Journal of the American Pomological Society 71(1): 34-46 2017

NC-140 Multi-State Research Project: Improving Economic and Environmental Sustainability in Tree-Fruit Production Through Changes in Rootstock Use

Winfred P. Cowgill, Jr.[1], Wesley R. Autio[2], Emily E. Hoover[3], Richard P. Marini[4], and Paul A. Domoto[5]

Additional index words: regional research, orchard

Abstract

The North Central Project 140 (NC-140) was established in the mid-1960s to facilitate evaluation of apple rootstocks and interstem trees in the north central region of the U.S. over the years, the project has grown to include cooperators from more than 20 states, four Canadian provinces and one Mexican state. The project played a major role in the rapid adoption of intensive orchard systems by the North American apple industry. This paper summarizes the history, accomplishments, participants, and potential future of the project.

History U.S. Rootstock Research Related to NC-140. The Morrill Act of 1862 established land grant universities to teach agriculture, mechanics, military science and classical studies.In 1887, the Hatch Act provided funds to the land grant institutions to establish agricultural experiment stations. The Research and Marketing Act of 1946 was passed by the U.S. Congress and signed into law by President Truman. The Act earmarked 25% of Federal Hatch funds to state experiment stations specifically for regional research. Effectively, this act resulted in the organization of the four regional experiment station associations: South (SAAED – 1946), Northeast (NERA – 1947), North-Central (NCRA – 1947), and Western (WAAESD – 1948). All Regional (now Multi-State) Projects are proposed, approved, and administered by one of the regional associations cooperatively with the Cooperative State Research, Education and Extension Service of the U.S. Department of Agriculture (CSREES, formerly CSRS).

The North Central Project 140 (NC-140) is one of many Multi-State projects authorized by CSREES. This project began in the mid 1960's when several scientists formed NC-78, a North-Central Region study to evaluate rootstocks for horticultural plants. NC-78 was approved for two cycles. However in 1970, the experiment station directors were concerned about approving projects knowing the proposed cooperative trials would extend well beyond the project period. Those researchers interested in rootstocks continued to meet under the structure of a North-Central Region coordinating committee, NCR-82, Stock/Scion Relations in Horticultural Plants, while working on a new project proposal. For six years, scientists from Alaska, Illinois, Indiana, Iowa, Kansas, Kentucky, Massachusetts, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, Vermont, and Wisconsin continued to meet annually. They also worked with the International Dwarf Fruit Tree Association (IDFTA) to further rootstock research

[1] New Jersey Agricultural Experiment Station, Rutgers University, New Brunswick, NU 08901
[2] Stockbridge School of Agriculture, University of Massachusetts, Amherst, MA 01003
[3] Department of Horticultural Science, University of Minnesota, Saint Paul, MN 55108
[4] Department of Plant Science, the Pennsylvania State University, University Park, PA 16802
[5] Department of Horticulture, Iowa State University, Ames, IA 50011

through the development of an IDFTA Rootstock Research Committee and annual funding in support of rootstock research.

NCR-82 initiated the first cooperative apple rootstock/interstem research trial planted at 10 locations in 1976. This lead to a successful proposal in 1977 for a full project called NC-140, entitled "Scion/Rootstock and Interstem Effects on Apple Tree Growth and Fruiting."

Dr. Richard Hayden from Purdue University chaired the first meeting of the NC-140 committee in August 1977 with Dr. James Cummins from Cornell University hosting at the New York State Agricultural Experiment Station in Geneva, NY. Members included scientists from Illinois, Indiana, Iowa, Kansas, Kentucky, Massachusetts, Michigan, Missouri, New York, Ohio, and Wisconsin. Arkansas, Minnesota, Oregon, and Vermont participated at the beginning but became members in subsequent years. Cooperators from Ontario and Quebec, Canada, also participated at the beginning of the project. See Table 1 for committee membership throughout its history.

The NC-140 committee coordinated the trial established under NCR-82. It included 'Delicious' and 'Empire' on M.9 interstems with Antonovka, MM.111, and Ottawa 11 as rootstocks. Uniform protocols for tree management and data collection were developed, and all data were compiled and analyzed by Drs. David Ferree and Bert Bishop at The Ohio State University.

At the first meeting in 1977, planning began for a uniform apple rootstock trial, scheduled for planting in 1980. It was successfully implemented and has led to 20 additional apple rootstock/interstem trials under the direction of the NC-140 committee. The first renewal of the NC-140 proposal (1982-87) expanded the objectives to include stone fruit, with the first uniform NC-140 peach trial planted in 1984. Four additional peach trials have been established. Uniform sweet and sour cherry rootstock trials were planted in 1987, a pear rootstock trial was planted in 1988, and a plum rootstock trial was planted in 1990. Four additional uniform cherry and three additional pear trials have been established. The NC140 project, to date, has established 38 uniform trials over the 30 years of its existence.

The current NC-140 project, "Improving Economic and Environmental Sustainability in Tree-Fruit Production Through Changes in Rootstock Use," has 40 regular participants from 22 states, 2 USDA facilities, 2 Mexican locations, 3 Canadian provinces, and Chile joined in 2015. In 1987, two NC-140 members edited and led a group of authors in writing a book on rootstocks where much of the information was a culmination of knowledge gained from NC-140 trials (Rom and Carlson, 1987). Seven of the 15 authors contributing to this book, titled "Rootstocks for Fruit Crops", were NC-140 members.

NC-140 Objectives at the Beginning and Now. Prior to the first NC-140 project, knowledge of rootstock performance was based upon unrelated studies. Results often varied from state to state, and there was little chance of isolating the influences of climate, soil and tree management. NC140's founders wished to shorten and greatly enhance the evaluation process through the uniform testing of rootstocks over a wide range of climatic and soil conditions. They recognized a burgeoning interest among orchardists in trees on dwarfing rootstocks; however, they were particularly interested in finding a rootstock or interstem that would result in a free-standing, semi-dwarf to dwarf sized tree. They also were looking for rootstocks that were easy for the nursery to propagate and ones that tolerated biotic and abiotic stresses in the orchard. The first NC-140 project (1977-82) had three specific objectives:

1. To evaluate the production efficiency of rootstock and interstem materials now available and any additional such materials which may become available which are potentially precocious, dwarfing, free standing, easy to propagate, disease re-

sistant, and adapted over the wide range of climatic conditions which exist in the many fruit areas of the United States.
2. To determine the propagation practicability of new rootstock and interstem material and to ascertain the anatomical factors in plant material combinations that are associated with compatibility.
3. To ascertain the cause and prevent the decline of apple trees on new and existing rootstocks and interstems and to evaluate the influence of various cultural practices on rootstock survival and performance.

In 30 years, the orchard industry has changed dramatically. Utilization of full-dwarfing rootstocks with support is commonplace and the desire for free-standing dwarf trees has diminished. Orchardists have embraced new training and management systems and are interested in fine-tuning rootstock choices to best fit those systems. NC-140 objectives are similar to the earlier ones, but have changed as orchard management has evolved. Further, objectives on rootstock development and on the physiology of the rootstock/scion interaction have been added. Still, the uniform testing of rootstocks under different climatic and soil conditions remains the backbone of NC-140's research effort. Objectives of the current NC-140 project (2012-2017) are as follows:

1. To evaluate the influence of rootstocks on temperate-zone fruit tree characteristics grown under varying environments using sustainable management systems.
2. To develop improved rootstocks for temperate-zone fruit trees using state-of-the-art genomic tools in breeding programs.
3. To accelerate adoption of new rootstocks (a) by improving propagation techniques and (b) by acquiring new rootstocks from worldwide sources.
4. To better understand the impacts of biotic and abiotic stresses on scion/rootstock combinations in temperate-zone fruit trees.
5. To enhance the sustainability of temperate fruit farming through development and distribution of research-based information utilizing eXtension.

Specific Accomplishments of NC-140. During the past 30 years 38 trials have been conducted by NC140. Upon completion of a project, the data are published in peer-reviewed and trade journals. Approximately 125 peer-reviewed articles have resulted directly from NC-140 trials, and more than 1,500 related articles have been published by NC-140 cooperators. Below is an abbreviated list of information resulting from the project:

- The length of time required to evaluate rootstocks has been reduced tremendously. The uniform trials expose a new rootstock to an extremely wide range of climates and soils, so a new rootstock can be recommended for commercial trial in less than 10 years. Before NC-140 different researchers used different cultivars, tree spacings, training systems, and collected different types of data to evaluate rootstocks, so it was impossible to compare rootstock performance from one location to another. For these reasons, M.9 was still being evaluated in the 1970s although it was brought to North America in the 1920s.
- MARK rootstock was identified as a potential dwarfing rootstock in certain regions of North America, but it performed very poorly in hot arid regions (NC-140, 1991; Marini et al., 2006).
- Budagovski 9 (B.9) was identified as a possible replacement for M.9. Final tree size varies depending upon location. B.9 is quite resistant to fireblight and imparts some resistance to the scion. This led to additional research on genetic control of rootstock/scion interactions (Ferree et al., 2002; Jensen et al., 2012; Gardener et al., 2012)
- Fireblight screening to gauge resistance has been modified. At one time, the bacterium was injected into growing shoot

tips and researchers assumed the amount of dieback was indicative of relative susceptibility. This test indicated that B.9 was quite susceptible, but field observations gave contradictory results. More recently we have learned that young shoots collected from the stool bed and older budded trees may not always respond similarly to inoculation tests. As a result, fireblight screening protocols have been modified (Johnson et al., 2000).

- Seven M.9 clones have been evaluated with clones varying in vigor control. Nic 29 and Pajam 2 are nearly as vigorous as M.26, but Fleuren 56 is more dwarfing than NAKBT337, which is the most widely planted clone of M.9. Therefore growers need to know which clone they are ordering. Additionally, obtaining a range of tree sizes can be accomplished by using various clones of M.9 thus avoiding the use of M.26, which has higher tree mortality in most trials Marini et al., 2006; Autio et al., 2008).
- Nineteen rootstocks from the Cornell-Geneva (G) program have been evaluated. G.30 requires more support than most other rootstocks in that size category. If support is not adequate the trees break at the bud union, especially with brittle cultivars such as 'Gala.' G.41 and G.35 also produce weak bud unions when budded with brittle cultivars.
- The Vineland (V) series may have commercial potential, especially in the southeast because tree survival was much better on V.1 and V.3 than on the Malling (M) rootstocks. This was surprising, because they were selected for northern growing conditions (Marini et al., 2006).
- Apple cultivar-by-rootstock interaction is small. The relative tree size differences among rootstocks are similar regardless of the scion. Therefore, cultivar selection for rootstock studies need not be limited to those varieties which are grown in a specific region (Autio et al., 2001).
- The Gisela series of cherry rootstocks was first tested by NC-140 and Gisela 6 has become the most widely-planted sweet cherry rootstock in the Pacific Northwest. Research results by NC-140 members have been used to develop the information used by growers interested in producing cherries in high tunnels.
- NC-140 research guided propagation of fruit trees by nurseries, allowing them to tailor their production to grower demands and to avoid problematic rootstocks. As an example, a series of cherry rootstocks from Russia were gaining a great deal of interest, but NC-140 workers found them to be hypersensitive to *Prunus* Necrotic Ringspot virus, reducing their suitability for U.S. production.
- Through experience, we have modified the protocols, experimental designs and statistical analyses of our trials to enhance efficiencies in rootstock evaluation.
- Extension and outreach is integral to the NC-140 project. Therefore, research plantings serve as the focus of field days, and results are disseminated quickly and widely as soon as they are available. As an example of the outreach effort, nearly 200 grower-oriented publications were developed, about 450 talks were given, nearly 150 field days were conducted, and more than 50,000 grower contacts were made in the last 5 years to disseminate information from NC-140 projects. The NC-140 website (NC140.org) is another vehicle for distributing rootstock information, and attracts over 20,000 hits per year. Because of the extensive output of NC-140 and the widespread participation, all modern North American recommendations regarding rootstocks, tree training and orchard systems for fruit crops have their basis in NC-140.
- NC-140 has become an important organization for training future generations of pomologists. Graduate students often attend the annual meeting of the NC-140 technical committee and often collect and analyze data associated with NC-140 tri-

als. These activities provide a unique opportunity for young pomologists to network with more experienced pomologists and to learn about fruit production and research activities at the international level.

Impacts of NC-140. It is difficult to quantify impacts of a large project such as NC-140, particularly since they touch every state where temperate tree fruit are grown, the southern Canadian provinces and some areas in Mexico. Further, NC-140 is a major source of rootstock information worldwide. Reasonable estimates of NC-140 impacts are:

- Overall, the work of NC-140 resulted in recommendations and educational programs which guided planting of 170,000 acres of fruit trees over the last five years in the U.S.
- Growers have realized significantly earlier returns on investments related to tree establishment.
- Yields have increased on average 20% per acre in mature orchards, fruit size has improved by10%, and the percentage of fruit meeting the highest grade category increased by 20%.
- The financial benefit to U.S. fruit growers from earlier returns, greater yield, and higher fruit quality was $200,000,000 over the 5-year period.
- Because most new plantings have been primarily in the dwarf category (with a substantially reduced canopy volume per acre), pesticide usage on the new acreage was reduced by nearly 40%, with the associated environmental benefit plus $100,000,000 saved over the 5-year period in pesticide cost and application.
- Tree losses declined by 10% over the 5-year period due to the introduction and planting of disease-resistant rootstocks.
- Individuals from Canada and Mexico are integral to NC-140, therefore expanding its influence throughout the Americas. The project and its output, however, are valued worldwide.
- NC-140 continues to develop advanced experimental design approaches to reduce the costs of rootstock research. Recently we learned that six to seven years are required to accurately assess rootstock vigor rather than the 10-year period that was formerly used (Marini et al. 2016).
- NC-140 cooperators introduced molecular approaches to the breeding programs, enhancing the efficiency of development and selection of the next generations of fruit tree rootstocks.
- Cumulative state and federal investment in NC-140 for the last 5 years was about $5,000,000. Cumulative, measurable benefits to the U.S. temperate tree-fruit industries were more than $300,000,000. Less easily measured benefits, such as averted losses and enhanced environmental quality, certainly increase the financial value of NC-140 to well beyond $300,000,000 in the last 5 years.
- Through links to cooperative extension programs, information generated by NC-140 is rapidly available to fruit growers. Many of the technical committee members have extension appointments and provide information to stakeholders in their states and provinces. In 2013 alone, NC-140 members presented information related to the project at more than 140 grower meetings (http://www.nc140.org/2013/annualreport.pdf). NC-140 has a long-standing close relationship with the International Fruit Tree Association (formerly International Dwarf fruit Tree Association). Many members of the NC-140 have presented updates on rootstock performance at annual meetings of IFTA and have received funding for uniform trials (tree costs) and support of critical research for independent studies on rootstock issues. NC-140 developed a website (http:///www.nc140.org/) more than 15 years ago to make results from the project widely available. The eXtension website (http://www.extension.org/pages/60760/apples-community-

information#,VGzEBckXLlg) was developed by NC-140 members to archive information from NC-140 and apple cultivar trials to make research-based information available to the general public.

In recognition of NC-140's exceptional collaboration and research impacts, NC-140 received the 2015 Experiment Station Section Excellence in Multistate Research Award from the Experiment Station Committee on Organization and Policy.

Future of NC-140 and Other Pomological Research. Due to declining state and federal support for state agricultural experiment stations, applied agricultural research is in jeopardy. Land grant university colleges of agriculture around the country now expect faculty members to externally fund their research. About 10 years ago NC-140 members estimated the cost of maintaining an acre of rootstock plantings at about $4,000 per year. This value was probably conservative because it did not include costs for office space, salaries and fringe benefits, office supplies, staff support, creation and maintenance of the NC-140 website, transportation of cooperators to meetings, and page charges for publishing. Without support from national and international organizations, such as the International Fruit Tree Association (formerly IDFTA), applied research on fruit crops will decline rapidly. As college and department administrators consider replacing vacated pomology positions, one criterion that will be used is the ability to attract grant funding for a world-class research program. If support is not deemed adequate then faculty positions focusing on more basic research may be considered. These positions might be of little immediate help to the industry. Over the next decade we will likely see the number of pomologists decline across the United States, particularly in states where the fruit industry is small or fail to provide substantial research support. States with relatively small fruit industries provide the variety of climatic conditions needed to rapidly test rootstocks. If rootstock research is limited to the major fruit-growing regions, evaluation of new rootstocks to withstand environmental stresses as the climate changes will take much longer.

Literature Cited

Autio, W.R., J.L. Anderson, J.A. Barden, G.R. Brown, R.M. Crassweller, P.A. Domoto, A. Erb, D.C. Ferree, A. Gaus, P. M. Hirst, C.A. Mullins, and J.R. Schupp. 2001. Performance of 'Golden Delicious', 'Jonagold', 'Empire', and 'Rome Beauty' apple trees on five rootstocks over ten years in the 1990 NC-140 cultivar/rootstock trial. J. Amer. Pomol. Soc. 55:131-137.

Autio, W., T. Robinson, W. Cowgill, Jr., C. Hampson, M. Kushad, J. Masabni, R. Quezada, R. Perry and C. Rom. 2008. Performance of 'Gala' apple on Supporter 4, P.14, and different strains of B.9, M.9, and M.26 rootstocks: a five year report on the 2002 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 62:119-128.

Ferree, D. C., J.C. Schmid, and B.L. Bishop. 2002. Survival of apple rootstocks to natural infections of fire blight. HortTechnology 12:239-241.

Gardner,S., J. Norelli, N. de Silva, G. Fazio, A. Peill, M. Malnoy, M. Horner, D. Bowatte, C. Carlise, C. Wiedow, Y. Wan, C. Bassett, A. Baldo, J. Celton, K. Richter, H. Aldwinckle, and B. Bus. 2012. Putative resistance gene markers associated with quantitative trait loci for fire blight resistance in Malus 'Robusta 5' accessions. BMC Genet. 2012 Apr 3;13:25. doi: 10.1186/1471-2156-13-25.

Jensen, P.J., N. Halbrendt, G. Fazio, I. Makalowska, N. Altman, C. Praul, S. Maximova, H. Ngugi, R. Crassweller, J. Travis, and T. McNellis. 2012. Rootstock-regulated gene expression patterns associated with fire blight resistance in apple. BMC Genomics. 1012 Jan. 9. doi: 10.1186/1471-2164-13-9.

Johnson, W.C., HS. Aldwinkle, J.L. Norelli and H.T. Holleran. 2000. Screening for fire blight resistance in apple rootstock breeding. HortScience 35:477.

Marini, R.P., J.L. Anderson, W.R. Autio, B.H. Barritt, J. Cline, W.P. Cowgill, Jr., R.C. Crassweller, R.M. Garner, A. Gauss, R. Godin, G.M. Greene, C. Hampson, P. Hirst, M.M. Kushad, J. Masabni, E. Mielke, R. Moran, C.A. Mullins, M. Parker, R.L. Perry, J.P. Prive, G.L. Reighard, T. Robinson, C.R. Rom, T. Roper, J.R. Schupp, E. Stover, and R. Unrath. 2006. Performance of 'Gala' apple trees on 18 dwarfing rootstocks: ten-year summary of the 1994 NC-140 rootstock trial. J. Amer. Pomol. Soc. 60:69-83.

Marini, R., W.R. Autio, B. Black, J. Cline, W.P. Cowgill, Jr., R.M. Crassweller, C. Hampson, M.M. Kushad, R. Moran, M. Parker, R.L. Perry, G.L. Reighard, T. Robinson, and D. Wolfe. 2016. Time required for classifying rootstock vigor in multi-location rootstock trials. J. Amer. Pomol. Soc. 70:82-91.

NC-140.1991. Performance of 'Starkspur Supreme Delicious' apple on 9 rootstocks over 10 years in NC-140 cooperative planting. Fruit Var. J. 45:192-199.

Rom, R.R. and R. F. Carlson. 1987. Rootstocks for fruit crops. Wiley-Interscience, ????

Table 1. Administrative advisors and NC-140 participants.

Location	Name of Members	Location	Name of Members
CREES Advisors		*North Central Administrative Advisors*	
		MN	K.A. Huston
USDA	D.R. Tompkins	MI	Ian Gray
USDA	C. Stushnoff	MN	D.A. Holt
USDA	S.C. Wiggans	MN	R.G. Gast
USDA	T. Bewick	MN	R.W. Hougas
		OH	B. Randal
		MI	R. Perry
Participants for more than 3 years			
AL	E. Coneva	NC	S. McArtney, E. Young, M. Parker
AR	R. Rom, C. Rom	NE	W.A. Gustafson
CA	T. DeJong, S. Johnson, R. Elkins, W. Micke	NJ	R. Marini, W. Cowgill, R. Belding, E. Durner, D. Ward
CO	A. Gaus, H. Larsen, K.S. Yu, G. Litus	NM	S. Yao
GA	K. Taylor, T. Beckman, S.C. Myers, D. Chavez	NY	G. Fazio, J. Cummins, R.L. Anderson, T. Robinson
IA	P. Domoto, D. Cochran	OH	D.C. Ferree, D. Miller
ID	E. Fallahi	OR	A. Azarenko, M.N. Westwood, P. Lombard, E. Mielke, T. Einhorn
IL	M. Kushad, R. Simons, D.B. Meador	PA	G. Green, L.D. Tukey, R. Crassweller, R. Marini, J. Schupp
IN	R. Hayden, P. Hirst	SC	W. Olien, G. Reighard
KY	G. Brown, D. Wolfe	SD	A. Fennell
KS	F. Morrison, A. Erb	TN	C.A. Mullins, D. Lockwood
MA	W. Lord, W. Autio, J. Clements	TX	J. Worthington
MD	C.S. Walsh, M. Newell	UT	L. Anderson, B. Black, T. Lindstrom, D.R. Walker
ME	W. Olien, J. Schupp, R. Moran	VA	J. Barden, R. Marini, G. Peck, K. Yoder
MI	R. Carlson, R. Perry, G. Lang	WA	B.H. Barritt, G. Lang, S. Muscchi
MO	T. Hopfinger, M. Warmund	WV	T. Baugher
MT	N.W. Callan	WI	F.A. Gilbert, T. Roper, M. Stasiak
International Participants			
B.C., CA	C. R. Hampson, H Quammer, F. Kappel, D. Neilsen	N.S., CA	C. Embry, S. Blatt
N.B., CA	J.P. Prive	QUE, CA	G.L. Rousselle, R.L. Granger
ONT., CA	Hutchinson, D. Elfving, G. Tehrani, R.E.C. Layne, J. Cline	CAEF, Chile	C. Munoz, F. Gainza
CHIH, Mexico	R. Quezada		

Table 2. NC-140 trials, including the name of the trial, the trial coordinator and cooperating locations.

Year	Name of Trial	coordinator	Collaborating locations
1977	1976 Apple Interstem	David Ferree	IA, IL, IN, KS, KY, OH, MA, MO, MI
1980	1980-81 Apple Rootstock	David Ferree	AR, CA, GA, IL, IN, WI, KS, KY, MA, MI, MN, NC, NY, OH, OR, ON, PA, QUE, TN, UT, SC,VA, WA, WI
1984	1984 Apple Rootstock	David Ferree	
1984	1984 Peach Rootstock	Ronald Perry	AR, CA, GA, VA, MO, NY, MI, UT, PA, OH, KY, CO, NJ, KS, IL, ON
1987	1987 Tart and Sweet Cherry Rootstock	Ronald Perry	*Bing* -- BC, CA, CO, OR, UT, WA; *Hedelfingen* -- MD, MI, NY, ON; *Montmorency* -- AR, KS, MI, NJ, NY, ON, OR, PA, UT, WI
1988	1988 Pear Rootstock	Anita Miller/ Eugene Mielke	AR, BC, CO, KY, MD, NS, NY, OH, ON, OR, WA, WV
1990	1990 Apple Orchard Systems	Bruce Barritt/Richard Marini	IL, MI, MN, NC, NY, ON, QUE, VA, WA
1990	1990 Gala Apple Rootstock	Bruce Barritt/Richard Marini	IL, MI, MN, NC, NY, ON QUE, VA, WA
1990	1990 Apple Cultivar/Rootstock	Wesley Autio	AR, CO, GA, IA, IN, KS, KY, MA, ME, MI, NC, OH, PA, QUE, TN, UT, VA
1990	1990 Plum Rootstock	Gus Tehrani/Robert Anderson/Joseph Masabni	CA, GA, KY, IN, MI, NY, ON, OR, QUE
1992-93	1992-93 Apple Rootstock	James Cummins/Terrence Robinson	AR, CA, CO, IA, IN, ME, MI, NC, NY, OH, PA, WA
1994	1994 Peach Rootstock	Gregory Reighard	AR, CO, GA, IL, IN, KS, KY, MD, MS, MI, MO, NJ, NY, OH, ON, SC, TN, UT
1994	1994 Dwarf Apple Rootstock	Richard Marini	AR, CO, GA, IA, IL, IN, KY, MA, ME, MO, NY, OH, ON, OR, PA, WA, MI, MN, NC, NJ, NS, QC, SD, WI, VA, SC
1994	1994 Semidwarf Apple Rootstock	Richard Marini	AR, CO, GA, IA, IL, IN, KY, MA, ME, MO, NY, OH, ON, OR, PA, WA, MI, MN, NC, NJ, NS, QC, SD, WI, VA, SC
1998	1998 Apple Rootstock	Terrence Robinson	BC, MA, MI, MO, NC, NJ, NS, NY, OH, UT, WA

Table 2. *continued*

1998	1998 Tart Cherry Rootstock	Frank Kappel/Gregory Lang	MI, NY, ON, PA, UT, WI
1998	1998 Sweet Cherry Rootstock	Frank Kappel/Gregory Lang	*Hedelfingen* -- MI, NY, ON, PA, SC *Bing* -- BC, CA, OR, UT, WA
1999	1999 Semidwarf Apple Rootstock	Wesley Autio	*Fuji* -- CA, IN, KY, MO, NC, OH, PA, UT, SC, WA; *McIntosh* -- MA, MI, MN, NS, NY, ON, PA, VT
1999	1999 Dwarf Apple Rootstock	Wesley Autio	*Fuji* -- CA, IN, KY, MO, NC, OH, PA, SC, UT, WA *McIntosh* -- MA, MI, MN, NY, NS, ON, PA, VT
2001	2001 Peach Rootstock	Gregory Reighard	*Redtop* -- CA, GA, MD GA *Redhaven* -- IN, MI, MO, NJ, ONT, UT *Cresthaven* – CO, IL, WA, TX
2002	2002 Apple Rootstock	Wesley Autio	AR, BC, IL, IN, KY, MA, MI, NJ, NY, OH, Mexico
2002	2002 Peach Physiology	Scott Johnson	CA, GA, MD, NJ, NY, SC, WA
2002	2002 Peach Rootstock	Scott Johnson	*Redhaven* – CA, GA, MA, MD, MX, MO, OH, ONT, PA, SC; *Cresthaven* – CO, IL, MO, NJ, NY, TX, UT, WA, MX
2002	2002 Pear Rootstock	Eugene Milke/ Steve Castagnoli	WA
2002	2002 New Jersey-Massachusetts Rootstock	Winfred Cowgill	NJ, MA
2003	2003 Apple Rootstock	Richard Marini	AR, BC, CA, GA, IA, KY, ME, MI, NY, OH, PA, UT WI
2003	2003 Apple Physiology	Richard Marini	AR, BC, CA, GA, IA, IN, KY, MA, ME, MI, MX, NJ, NY, NS, OH, ONT, PA, UT, WI
2004	2004 Pear Rootstock	Steve Castagnoli	NY, WA, NS
2005	2005 Pear Rootstock	Steve Castagnoli	CA, MX, NY, OR, WA
2006	2006 Apple Replant	Terence Robinson	CA, NY, OR, WA, Mexico
2009	2009 Peach Rootstock	Greg Reighard	SC & MA
2010	2010 Sweet Cherry Rootstock 7 Training Systems	Greg Lang	BC, MI, NY, NC
2010	2010 Apple rootstock	Wesley Autio	*HoneyCrisp*-- BC, CO, IL, IN, IA, MA, MN, MI, MX, NJ, NS, NY-G, OH, UT, WI. *Fuji* -- ID, KY, MX, NC, NY-HV, PA, UT
2013	Pear Training/Spacing/Rootstock	Todd Einhorn	NY, OR, CA
2014	2014 Apple Rootstock	John Cline	AL, ID, IN, MA, ME, MN, NC, NJ, NY, ON, PA, SC, UT, VA, WA, WI
2015	Organic Apple Rootstock	Terence Robinson & Wesley Autio	CA, CO, ID, IA, MA, MI, NJ, NM, MX, NS, NY, VA, VT, WI

Table 3. Refereed journal articles resulting from NC-140 trials.

Autio, W. R., J. A. Barden, and G.R. Brown. 1991. Rootstock affects ripening, size, mineral composition, and storability of 'Starkspur Supreme Delicious' in the 1980-81 NC-140 cooperative planting. Fruit Var. J. 45:247-251.

Autio, W., R. Hayden, W. Micke, and G. Brown. 1996. Rootstock affects ripening, color and shape of Starkspur Supreme Delicious' apples in the 1984 NC-140 cooperative planting. Fruit Va. J. 51:45-53.

Autio, W.R., J.L. Anderson, J.A. Barden, G.R. Brown, R.M. Crassweller, P.A. Domoto, A. Erb, D.C. Ferree, A. Gaus, P.M. Hirst, C.A. Mullins, and J.R. Schupp. 2001. Performance of 'Golden Delicious,' 'Jonagold,' 'Empire,' and 'Rome Beauty' apple trees on five rootstocks over ten years in the 1990 NC-140 cultivar/rootstock trial. J. Amer. Pomol. Soc. 55:131-137.

Autio, W.R., J.L. Anderson, J.A. Barden, G.R. Brown, R.M. Crassweller, P.A. Domoto, A. Erb, D.C. Ferree, A. Gaus, and P.M. Hirst. 2001. Location affects performance of 'Golden Delicious', 'Jonagold', 'Empire', and 'Rome Beauty' apple trees on five rootstocks over ten years in the 1990 NC-140 cultivar/rootstock trial. J. Amer. Pomol. Soc. 55:138-145.

Autio, W., T. Robinson, D. Archbold, W. Cowgill, C. Hampson, R. Parra Quezada, and D, Wolfe. 2013. 'Gala' apple trees on supporter 4, P.14, and different strains of B.9, M.9 and M.26 rootstocks: final 10-year report on the 2002 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 67:62-71.

Autio, W. R.,T.L. Robinson, B.H. Barritt, J.A. Cline, R. M. Crassweller, C.G. Embree, D.C. Ferree, M.E. Garcia, G.M. Greene, E.E. Hoover, R.S. Johnson, K. Kosola, J. Masabni, M.L. Parker, R.L. Perry, G.L. Reighard, S.D. Seeley, and M. Warmund. 2005. Performance of 'Fuji' and 'McIntosh' apple trees after 5 years as affected by several semi dwarf rootstocks in the 1999 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 59:192-201.

Autio, W. R., T.L. Robinson, B.H. Barritt, J.A. Cline, R. M. Crassweller, C.G. Embree, D.C. Ferree, M.E. Garcia, G.M. Greene, E.E. Hoover, R.S. Johnson, K. Kosola, J. Masabni, M.L. Parker, R.L. Perry, G.L. Reighard, S.D. Seeley, and M. Warmund. 2005. Performance of 'Fuji' and 'McIntosh' apple trees after 5 years as affected by several dwarf rootstocks in the 1999 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 59:202-214.

Autio, W.R., T.L. Robinson, B. Black, T. Bradshaw, J.A. Cline, R.M. Crassweller, C.G. Embree, E.E. Hoover, S.A. Hoying, K.A. Iungerman, R.S. Johnson, G. Lang, M.L. Parker, R.L. Perry, G.L. Reighard, J.R. Schupp , M. Stasiak, M. Warmund, and D. Wolfe. 2011. Performance of 'Fuji' and 'McIntosh' apple trees after 10 years as affected by several dwarf rootstocks in the 1999 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 65:2-20.

W.R. Autio, T.L. Robinson, B. Black, T. Bradshaw, J.A. Cline, R.M. Crassweller, C.G. Embree, E.E. Hoover, S.A. Hoying, K.A. Iungerman, R.S. Johnson, G. Lang, M.L. Parker, R.L. Perry, G.L. Reighard, M. Stasiak, M. Warmund, and D. Wolfe. 2011. Performance of 'Fuji' and 'McIntosh' apple trees after 10 years as affected by several semidwarf rootstocks in the 1999 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 65:21-38.

Autio, W., T. Robinson, W. Cowgill, C. Hampson, M. Kushad, J. Masabni, R. Parra Quezada, R. Perry and C. Rom. 2008. Performance of 'Gala' apple trees on Supporter 4, P.14, and different strains of B.9, M.9 and M.26 rootstocks: A five-year report on the 202 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 62:119-129.

Domoto, P.A., W.R. Autio, G.R. Brown, D.C. Ferree, P.M. Hirst, C.A. Mullins, and J.R. Schupp. 2001. Blackheart injury in 'Golden Delicious', 'Jonagold', 'Empire', and 'Rome Beauty' apple trees on five rootstocks in the 1990 NC-140 cultivar/rootstock trial. J. Amer. Pomol. Soc. 55:146-153.

Ferree, D. C. 1981. Cooperative apple rootstock studied in North America. Chronica Horticulturae 21(1):6.

Ferree, D.C. 1982. Multi-state cooperative apple interstem planting established in 1976. Fruit Var. J. 36:3-6.

Ferree, D. C. 1982. Multi-state cooperative apple interstem planting established in 1976. Fruit Var. J. 36:206.

Ferree, D. C. and R. L. Perry. 1988. Rootstock evaluation through the NC-140 cooperative project. HortScience 23:102-104.

Hirst, P.M., W.R. Autio, J.A. Barden, G.R. Brown, R.M. Crassweller, P.A. Domoto, and J.R. Schupp. 2001. Performance of trees in the 1990 NC-140 apple cultivar/rootstock planting: additional cultivars and rootstocks. J. Amer. Pomol. Soc. 55:178-184.

Johnson, S., R. Andersen, W. Autio, T. Beckman, B. Black, P. Byers, J. Cline, C. Chavez-Gonzalez, W. Cowgill, R. Godin, G. Greene, M. Kaps, J. Kamas, H. Larsen, T. Lindstrom, D. Miller, M. Newell, D. Ophardt, D. Ouellette, R. Parra-Quezada, R. Pokharel, G. Reighard, T. Robinson, J. Schupp, L. Stein, K. Taylor, C. Walsh, D. Ward, M. Warmund and M. Whiting. 2011. Performance of the 2002 NC-140 cooperative peach rootstock planting. J. Amer. Pomol. Soc. 65:17-25.

Kappel, F., G. Lang, A. Azarenko, T. Facteau, A. Gaus, R. Godin, T. Lindstrom, R. Nuñez-Elisea, R. Pokharel, M. Whiting and C. Hampson. 2013. Performance of sweet cherry rootstocks in the 1998 NC-140 regional trial in Western North America. J. Amer. Pomol. Soc. 67:186-195.

Marini, R. P., J. L. Anderson, B. H. Barritt, G. R. Brown, J. Cline, W. P. Cowgill, Jr., P. A. Domoto, D. C. Ferree, J. Garner, G. M. Greene, C. Hampson, P. Hirst, M. M. Kushad, E. Mielke, C. A. Mullins, M. Parker, R. L. Perry, J. P. Prive, G. L. Reighard, T. Robinson, C. R. Rom, T. Roper, J. R. Schupp, E. Stover, and R. Unrath. 2000. Performance of 'Gala' apple on four semi-dwarf rootstocks: a five-year summary of the 1994 NC-140 semi-dwarf rootstock trial. J. Amer. Pomol. Soc. 54:84-91.

Marini, R. P. J. L. Anderson, W. R. Autio, B. H. Barritt, G. R. Brown, J. A. Cline, W. P. Cowgill, Jr., R. M. Crassweller, P. A. Domoto, D. C. Ferree, J. Garner, A. Gaus, G. M. Greene, C. Hampson, P. Hirst, M. M. Kushad, E. Mielke, C. A. Mullins, M. Parker, R. L. Perry, J. P. Prive, G. L. Reighard, T. Robinson, C. R. Rom, T. Roper, J. R. Schupp, E. Stover and R. Unrath. 2000. Performance of 'Gala' apple on 18 dwarf rootstocks: five-year summary of the 1994 NC-140 dwarf rootstock trial. J. Amer. Pomol. Soc. 54:92-107.

Marini, R.P., J.L. Anderson, W.R. Autio, B.H. Barritt, J.A. Cline, W.P. Cowgill, Jr., R.M. Crassweller, P.A. Domoto, D.C. Ferree, J. Garner, A. Gaus, G.M. Greene, C. Hampson, P. Hirst, M.M. Kushad, E. Mielke, C.A. Mullins, M. Parker, R.L. Perry, J.P. Prive, G.L. Reighard, T. Robinson, C.R. Rom, T.R. Roper, J.R. Schupp, E. Stover, and R. Unrath. 2006a. Performance of Gala apple on 18 dwarf rootstocks: Ten-year summary of the 1994 NC-140 dwarf rootstock Trial. J. Amer. Pomol. Soc. 60:69-83.

Marini, R.P., J.L. Anderson, J.A. Barden, B.H. Barritt, G.R. Brown, J. Cline, W.P. Cowgill, Jr., P.A. Domoto, D.C. Ferree, R.M. Garner, G.M. Greene, C. Hampson, P. Hirst, M.M. Kushad, J. Masabni, E. Mielke, R. Moran, C.A. Mullins, M. Parker, R.L. Perry, J.P. Prive, G.L. Reighard, T. Robinson, C.R. Rom, T. Roper, J.R. Schupp, E. Stover, and R. Unrath. 2006b. Performance of 'Gala' on four semi-dwarf rootstocks: A ten-year summary of the 1994 NC-140 semi-dwarf rootstock trial. J. Amer. Pomol. Soc. 60:58-68.

Marini, R.P., W.R. Autio, B. Black, J.A. Cline, W. Cowgill, Jr., R. Crassweller, P. Domoto, C. Hampson, R. Moran, R.A. Parra-Quezada, T. Robinson, M. Stasiak, D.L. Ward and D. Wolfe. 2012. Summary of the NC-140 apple physiology trial: the relationship between 'Golden Delicious' fruit weight and crop density at 12 locations as influenced by three dwarfing rootstocks. J. Amer. Pomol. Soc. 66:78-90.

Marini, R.P., W.R. Autio, B. Black, J.A. Cline, W. Cowgill, Jr., R. Crassweller, P. Domoto, C. Hampson, R. Moran, R.A. Parra-Quezada, T. Robinson, M. Stasiak, D.L. Ward and D. Wolfe. 2012. The influence of crop density on annual trunk growth of 'Golden Delicious' apple trees on three dwarfing rootstocks at 11 locations. J. Amer. Pomol. Soc. 66:183-195.

Marini, R.P., W.R. Autio, B. Black, J. Cline, W.R. Cowgill, Jr., R.M. Crassweller, P.A. Domoto, C. Hampson, R. Moran, R.A. Quezada, T. Robinson, D.L. Ward, and D. Wolfe. 2013. Return bloom on 'Golden Delicious' apple trees as affected by previous season's crop density on three rootstocks at 11 locations. J. Amer. Pomol. Soc. 67:72-79.

Marini, R.P., J.A. Barden, J.A. Cline, R.L. Perry, and T. Robinson. 2002. Effect of apple rootstocks on average 'Gala' fruit weight at four locations after adjusting for crop load. J. Amer. Soc. Hort. Sci. 127:749-753.

Marini, R.P., B.H. Barritt, J.A. Barden, J. Cline, R.L. Granger, M.M. Kushad, M. Parker, R.L. Perry, T. Robinson, and S. Khanizadeh. 2001. Performance of 'Gala' apple on eight dwarf rootstocks: ten-year summary of the 1990 NC-140 rootstock trial. J. Amer. Pomol. Soc. 55:197-204.

Marini, R.P., B.H. Barritt, J.A. Barden, J. Cline, E.E. Hoover, R.L. Granger, M.M. Kushad, M. Parker, R.L. Perry, T. Robinson, S. Khanizadeh, and C.R. Unrath. 2001. Performance of ten apple orchard systems: ten-year summary of the 1990 NC-140 systems trials. J. Amer. Pomol. Soc. 55:222-238.

Marini, R.P., B. Black, R.M. Crassweller, P.A. Domoto, C. Hampson, S. Johnson, K. Kosola, S. McArtney, J. Masabni, R. Moran, R.P. Quezada, T. Robinson and C.R. Rom. 2009. Performance of 'Golden Delicious' apple on 23 rootstocks at 12 locations: a five-year summary of the 2003 NC-140 dwarf rootstock trial. J. Amer. Pomol. Soc. 63:115-127.

Marini, R.P., B. Black, R.M. Crassweller, P.A. Domoto, C. Hampson, R. Moran, T. Robinson, M. Stasiak, and D. Wolfe. 2014. Performance of 'Golden Delicious' apple on 23 rootstocks at eight locations: a ten-year summary of the 2003 NC-140 dwarf rootstock trial. J. Amer. Pomol. Soc. 68:54-68.

Marini, R.P., R. Moran, C. Hampson, M. Kushad, R.L. Perry, T.L. Robinson. 2008. Effect of dwarf apple rootstocks on average 'Gala' fruit weight at six locations over three seasons. J. Amer. Pomol. Soc. 62:129-137.

Marini. RP. And D. Ward. 2012. Using analysis of covariance with unequal slopes to increase efficiency and information obtained from designed experiments. J. Amer. Pomol. Soc. 66:78-90.

Masabni, J.G., P. Hirst, G. Brown, D. Wolfe, R. Perry, R. Andersen, J. Freer, T. Robinson, A. Azarenko, E. Mielke, B. McCluskey, G. Tehrani and W. Lay. 2007. Performance of plum rootstocks with 'Stanley', 'Valor', and 'Veeblue' as the scion in the 1990 NC-140 multi-location plum trial. J. Amer. Pomol. Soc. 61:196-207.

McArtney, S. and J.D. Obermiller. 2011. Effect of dwarfing rootstocks on low temperature tolerance of 'Golden Delicious' apple trees during winter 2008-2009. J. Amer. Pomol. Soc. 65:178-184.

NC-140. 1987. Growth and production of 'Starkspur Supreme Delicious' on 9 rootstocks in the NC-140 cooperative planting. Fruit Var. J. 41:31-39.

NC-140. 1990. Early performance of 'Starkspur Supreme Delicious' on 16 rootstocks in the NC-140 cooperative planting. Fruit Var. J. 44:225-235.

NC-140. 1991. Performance of 'Starkspur Supreme Delicious' on 9 rootstocks over 10 years in the 1980 NC-140 Cooperative Planting. Fruit Var. J. 45:192-199.

NC-140. 1991. Performance of 'Starkspur Supreme Delicious' on 9 rootstocks at 27 sites over 10 years. Fruit Var. J. 45:200-208.

NC-140. 1991. Abnormalities in 'Starkspur Supreme Delicious' on nine rootstocks in the 1980-81 NC-140 cooperative planting. Fruit Var. J. 45:213-219.

NC-140. 1996a. Performance of the NC-140 cooperative rootstock planting: I. Survival, tree size, yield and fruit size. Fruit Var. J. 50:6-11.

NC-140. 1996b. Performance of the NC-140 cooperative rootstock planting: II. A 10-year summary of TCA, yield and yield efficiency at 31 sites. Fruit Var. J. 50:11-18.

NC-140. 1996c. Horticultural characteristics of 'Starkspur Supreme Delicious' apple on 15 rootstocks at 24 sites. Fruit Var. J. 50:18-24.

NC-140. 1996d. Rootstock and scion cultivar interact to affect apple tree performance: A five-year summary of the 1990 NC-140 cultivar/rootstock trial. Fruit Var. J. 50:175-187.

Olien, W.C., D. C. Ferree, and B. L. Bishop. 1991. Long-term performance potential and stability across 10 environments for nine apple rootstocks tested in the 1980-81 NC-140 trial. Fruit Var. J. 45:208-212.

Perry, R., G. L. Reighard, D. Ferree, J. Barden, T. Beckman, G. Brown, J. Cummins, E. Durner, G. Greene, S. Johnson, R. Layne, F. Morrison, S. Myers, W. R. Okie, C. Rom, R. Rom, B. Taylor, D. Walker, M. Warmund, and K. Yu. 2001. Performance of the 1984 NC-140 cooperative peach rootstock planting. J. Amer. Pomol. Soc. 54:6-10.

Reighard, G., J. Anderson, R. Andersen, W. Autio, T. Beckman, T. Baker, R. Belding, G. Brown, P. Byers, W. Cowgill, D. Deyton, E. Durner, A. Erb, D. Ferree, A. Gaus, P. Hirst, M. Kaps, N. Miles, F. Morrison, S. Myers, D. Ouellette, R. Perry, C. Rom, W. Shane, B. Taylor, K. Taylor, C. Walsh, and M. Warmund. 2004. Eight-year performance of 19 peach rootstocks at 20 locations in North America. J. Amer. Pomol. Soc. 58:174-2002.

Reighard, G.L., T. Beckman, R. Belding, B. Black, P. Byers, J. Cline, W. Cowgill, R. Godin, R.S. Johnson, J. Kamas, M. Kaps, H. Larsen, T. Lindstrom, M. Newell, D. Ouellette, R. Pokharel, L. Stein, K. Taylor, C. Walsh, D. Ward and M. Whitingerica. J. Amer. Pomol. Six-year performance of 14 *Prunus* rootstocks at 11 sites in the 2001 NC-140 peach trial. J. Amer. Pomol. Soc. 65:26-41.

Reighard, G.L., T. Beckman, R. Belding, B. Black, J. Cline, W. Cowgill, R. Godin, M. Kaps, T. Lindstrom, D. Ouellette, L. Stein, K. Taylor, C. Walsh, M. Whiting and T. Robinson. 2006. Performance of *Prunus* Rootstocks in the 2001 NC-140 Peach Trial. Sodininkyste Ir Darzinninkyste. 25:327-333.

Robinson, T., D. Wolfe, J. Masabni, R. Andersen, A. Azarenko, J. Freer, G. Reighard, P. Hirst, R. Hayden and B. McCluskey. 2010. Performance of plum rootstocks with 'Stanley', 'Valor', Veeblue' and 'Santa Rosa' as the scions in the 1991 NC-140 multi-state plum trial. J. Amer. Pomol. Soc. 64:173-184.

Simons, R., R. Hayden, P. Domoto, F. Morrison, W. Lord, R. Perry, M. Warmund, D. Ferree, and E. Stang. 1986. NC-140 1976 Cooperative apple interstem planting. Fruit Var. J. 40:108-115.

Warmund, M. R., D. C. Ferree, P. Domoto, J. A. Barden, C. A. Mullins, and R. L. Granger. 1991. Blackheart injury in 'Starkspur Supreme Delicious' on nine rootstocks in the 1980-81 NC-140 cooperative planting. Fruit Var. J. 45:219-223.

Warmund, M.R., W.R. Autio, J.A. Barden, J.N. Cummins, P.A. Domoto, C.G. Embree, R.L. Granger, F.D. Morrison, J.R. Schupp, and E. Young. 1996. Blackheart injury in 'Starkspur Supreme Delicious' on 15 rootstocks in the 1984 NC-140 cooperative planting. Fruit Var. J. 50:55-62.

Warmund, M., G. Reighard, and D. Ferree. 2002. Low temperature susceptibility of Redhaven peach floral buds on various rootstocks in the 1994 NC-140 trial. J. Amer. Pomol. Soc. 56:235-241.