Scientia Horticulturae 332 (2024) 113194

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Effects of cultivar, planting density and rootstock on long-term economic performance of apple orchards in the Northeastern U.S.

Shuay-Tsyr Ho [a], Luis Gonzalez Nieto [b,d,*], Bradley J. Rickard [c], Gemma Reig [d], Jaume Lordan [d], Brian T. Lawrence [b], Gennaro Fazio [b,e], Stephen A Hoying [b], Michael J. Fargione [b], Mario Miranda Sazo [b], Terence L. Robinson [b]

[a] Department of Agricultural Economics, National Taiwan University, Taipei, Taiwan
[b] School of Integrative Plant Sciences, Horticulture Section, New York State Agricultural Experiment Station, Cornell University, Geneva, NY, USA
[c] Dyson School of Applied Economics and Management, Cornell University, Ithaca, NY, USA
[d] Fruit Production Programme, Institute of Agrifood Research and Technology (IRTA), Lleida, Catalonia, Spain
[e] USDA ARS Plant Genetic Resources Unit, New York State Agricultural Experiment Station, Geneva, NY, United States

ARTICLE INFO

Keywords:
Net present value
Orchard design
Orchard profitability
Planting density
Sustainability, yield

ABSTRACT

An economic analysis of profitability using Net Present Value (NPV) was conducted using data from two long-term training system × rootstock field trials conducted in New York State from 2006 to 2016 (Dressel Farm in southeastern New York State and VandeWalle Farm in Western, New York State). We used trial data for the first 11 years and estimated values for years 12–20 using average data from the last 4 years of field data. The field trials compared four training systems with different planting densities (Slender Pyramid, 840 trees ha^{-1}; Vertical Axis, 1282 trees ha^{-1}; Slender Axis, 2244 trees ha^{-1}; and Tall Spindle, 3262 trees ha^{-1}) each evaluated with several rootstocks in an incomplete factorial treatment list and with two cultivars at each location. By the end of the trial (11 years) all combinations of planting density, rootstock and cultivar were profitable (NPV positive) at the VandeWalle site but at the Dressel site seven combinations of rootstock and planting density with 'Fuji' and two combinations with 'Gala' were not profitable. Projected profitability over 20 years using estimated yields and fruit quality for years 12–20 showed that all combinations would be profitable by year 20. Estimated 20-year NPV was greatest with the Tall Spindle system with the highest planting density compared to the other lower density systems. Economic performance was mostly driven by planting density, regardless of the rootstock selection. Among cultivars, 'Honeycrisp' had significantly higher profitability largely due to high fruit price). 'Gala' had intermediate profitability due to high yields and medium fruit price while 'Fuji' which had low fruit price had significantly lower profitability than 'Gala'. Among rootstocks, there was a significant interaction with training system and cultivar, so the same rootstock was not the most profitable with every cultivar and system. With 'Fuji' the most profitable combination was on G.16 rootstock planted at the highest density, however, it was not significantly better than with G.11 or M.9. With 'Gala' at Dressel farm the most profitable combination was on G.11 in the Tall Spindle system (planted at the highest density) but it was not significantly better than with G.16, G.41, M.9 or B.9. With 'Gala' at VandeWalle farm the most profitable combination was on G.41 planted at the highest density but it was not significantly better than on G.11, G.16, M.9 or B.9. With 'Honeycrisp' the most profitable combination was on M.9 planted at the highest density but it was not significantly better than G.11, G.16, G.41 or B.9. A sensitivity analysis showed that among economic parameters affecting the long-term profitability of an orchard, fruit price and yield were vastly more important than other factors. Of intermediate importance were the discount rate and labor costs while of much lesser importance were tree costs and land costs.

E-mail address: yusu135@gmail.com (L. Gonzalez Nieto).
* Corresponding author.

https://doi.org/10.1016/j.scienta.2024.113194
Received 4 October 2023; Received in revised form 3 April 2024; Accepted 4 April 2024

1. Introduction

Training system, cultivar and rootstock selection are three of the key investment decisions for successful orchard management. Several studies have documented the advantage of adopting new rootstocks in improving fruit yields and improving tree performance. Similarly, training system has been shown to have a large effect on orchard horticultural and economic performance (Gonzalez Nieto et al., 2023; Lordan et al., 2018a, b; Reig et al. 2019; Robinson et al., 2007a, b).

The selection of training system is a critical step in orchard design. Several new training systems have been developed over the last several decades including the Tall Spindle, Central Leader, Fruiting Wall, Palmette, Slender Pyramid, Slender Axis, Slender Spindle, Solaxe, Super Spindle, Vertical Axis, V shaped, Y-trellis (Reig et al., 2019; Robinson, 2003a). Modern orchard planting systems vary in specific tree-training recipes; tree shape, rootstock, and tree density which often results in differences in total light interception, light distribution within the canopy and the balance between vegetative growth and cropping (Robinson, 2003a).

Most studies featuring economic analyses of production systems and farm management systems have focused on evaluating orchard establishment costs (DeMarree et al., 2003; Robinson et al., 2007; White and DeMarree 1992) and the impacts of orchard design including optimal tree spacing. Lordan et al. (2019) compared the effects of various tree planting densities and training systems on the long-term economic performance for four apple cultivars. Bradshaw et al. (2016) evaluated the effects of different organic management systems on orchard horticultural performance. There has been much less work in the agricultural economics literature that has examined the effects of apple rootstock selection, and the economic implications of rootstock selection that also consider different planting densities, management system, cultivars, and regions. One notable exception is Lordan et al. (2018b) who evaluated the effect of five rootstocks and five planting densities on two cultivars, 'Honeycrisp' and 'McIntosh'. They found that the dwarfing rootstocks (M.9 and B.9) outperformed more vigorous rootstocks and one dwarfing rootstock (G.16) in terms of yield and long-run profitability for both cultivars under high and medium density systems.

The purpose of the present study was to use data from two experimental plantings to evaluate the economic benefits of seven Geneva® (disease-resistant) rootstocks (Fazio and Robinson, 2018; Robinson et al., 2003b) and four disease susceptible traditional rootstocks in four training systems across three apple cultivars ('Fuji', 'Gala', and 'Honeycrisp'). These cultivars are among the top 5 cultivars in terms of total production in the United States in recent years (AgMRC, 2018). We have previously published the horticultural performance of these two experimental plantings (Reig et al., 2019) and with this paper we present the economic implications of this long-term data set. The contribution of this study is expected to be two-fold. First, it aims to provide new information on the economic performance of important apple cultivars with a diverse set of rootstocks and a diverse set of training systems (each system planting at different tree density). Second, it explores how fluctuations in economic input and output factors influence the net returns for the various cultivars, rootstocks and training systems.

2. Materials and methods

2.1. Site description and experimental design

In 2006, two 1-ha replicated on-farm experiments were established at two locations in New York State: Dressel Farm in southeastern New York State and VandeWalle Farm in Western, New York State. The trials compared four training systems, eleven rootstocks and three scion cultivars ('Fuji', 'Gala', and 'Honeycrisp'). Rootstocks included four traditional rootstocks as controls and seven Geneva® rootstocks as treatment groups. The control rootstocks included B.9, M.7EMLA (M.7), M.9T337 (M.9), and M.26EMLA (M.26). The Geneva® rootstocks included G.11, G.16, G.30, G.41, G.935, and CG.4210. The four training systems were Slender Pyramid, (SP) (tree spaced at 2.44 $m \times 4.88$ m, 840 trees ha^{-1}), Vertical Axis, (VA) (tree spaced at 1.83 $m \times 4.27$ m, 1282 trees ha^{-1}), Slender Axis, (SA) (tree spaced at 1.22 $m \times 3.66$ m, 2244 trees ha^{-1}), and Tall Spindle, (TS) (tree spaced at 0.91 $m \times 3.35$ m, 3262 trees ha^{-1}) (Table 1). The details of the block locations, soil types and tree management protocols were published previously (Reig et al., 2019).

Each experimental trial used a split-split plot randomized block design with three replications. Within each block, the training system was the main plot, the cultivar was the sub-plot, and the rootstock was the sub-sub-plot. The treatment design at each site was an incomplete factorial of only 42 combinations out of a possible 132 combinations of 4 systems × 3 cultivars × 11 rootstocks. All three cultivars were not planted at both locations: 'Gala' and 'Fuji' apple cultivars were planted at the Dressel site while 'Gala' and 'Honeycrisp' were planted at the VandeWalle site. Both trials used fully feathered nursery trees which were propagated by Adams County Nursery (Aspers, PA). Virus free scion wood and rootstocks were used. At both sites, four training systems were compared, but the various rootstocks were assigned unevenly across the systems (Table 1). The Slender Pyramid system includes the three rootstocks, G.30, G.210, and M.7, that are not examined under other systems because their higher vigor characteristics were not compatible with high-density systems.

Trees at the Dressel site were irrigated each year through drip lines while the trees at the VandeWalle site were unirrigated. At both sites trees were supported by a trellis system. The SP and VA trees were supported by a steel conduit pipe which was supported by a single wire trellis while SA and TS trees were support by a 5-wire trellis. Pruning, thinning management, irrigation, fertilization, foliar micronutrients and phytosanitary treatments were described in Reig et al. (2019). Average annual rainfall for the Dressel site was 1000 mm and 990 mm at VandeWalle during the spring and summer months.

2.2. Yield, income and costs

Tree horticultural performance was evaluated for eleven years (2006–2016) after planting. Yield (kg) and the number of fruits were recorded annually from the second year (2007) onward. Average fruit size (weight) of the fruits was calculated from yield and fruit number. Annually, a 50 apple sample of representative fruits for each scion-rootstock-training system combination was collected at harvest and then classified by color and size as described in Reig et al. (2019). From these data, we calculated a simulated packout for each scion-rootstock-training system combination. We assigned a monetary value (Table 2) to each fruit size and quality category from the simulated packout using statewide average prices from the New York State apple industry in 2021. Overall, these prices show that 'Honeycrisp' is the cultivar with the highest revenues regardless of grade and fruit size. The economic values for each category were summed and a crop value per tree and per hectare were calculated and then used for the economic and sensitivity analyzes.

Tree price used in the analysis came from the published price list for apple trees from one large commercial Nursery in Washington state

Table 1
Training systems, spacings and rootstocks evaluated at two experimental trials in NY State.

System	Spacing and planting density	Rootstocks
Slender Pyramid	2.44 $m \times 4.88$ m, 840 trees•ha^{-1}	G.30, G.210, G.935, M.7, M.26
Vertical Axis	1.83 $m \times 4.27$ m, 1280 trees•ha^{-1}	G.16, G.41, G.935, M.9, M.26
Slender Axis	1.22 $m \times 3.66$ m, 2240 trees•ha^{-1}	B.9, CG.4210, G.11, G.16, G.41, M.9
Tall Spindle	0.91 $m \times 3.35$ m, 3280 trees•ha^{-1}	B.9, G.11, G.16, G.41, M.9

Table 2
Returns to apple growers by cultivar, grade, and fruit size, after subtracting storage and packing costs. These costs included packing charge, MCP (1-methylcyclopropene) treatment, and average cost between regular and CA storage. Values were taken from statewide averages of New York State apple industry.

		Grower returns ($/kg)								
		Fruit size (g)								
Color category	Cultivar	<128	128 <136	136 <153	153 <167	167 <190	190 <215	215 <238	238 <264	≥ 264
XX Fancy	Gala	0.09	0.18	0.88	0.88	0.88	1.05	1.10	1.16	1.16
	Fuji	0.09	0.17	0.79	0.79	0.79	0.94	1.00	1.05	1.05
	Honeycrisp	0.10	0.19	1.62	1.62	1.62	1.91	2.20	2.44	2.44
X Fancy	Gala	0.09	0.18	0.83	0.83	0.83	0.99	1.05	1.10	1.10
	Fuji	0.09	0.17	0.73	0.73	0.73	0.89	0.94	1.00	1.00
	Honeycrisp	0.10	0.19	1.45	1.45	1.45	1.74	2.03	2.32	2.32
Fancy	Gala	0.09	0.18	0.55	0.55	0.55	0.66	0.66	0.66	0.66
	Fuji	0.09	0.17	0.47	0.47	0.47	0.58	0.68	0.79	0.89
	Honeycrisp	0.10	0.19	1.16	1.16	1.16	1.45	1.57	1.68	1.68
No. 1	Gala	0.09	0.18	0.18	0.18	0.17	0.18	0.18	0.18	0.18
	Fuji	0.09	0.17	0.17	0.17	0.16	0.17	0.17	0.17	0.17
	Honeycrisp	0.10	0.19	0.19	0.19	0.17	0.19	0.19	0.19	0.19
Utility	Gala	0.09	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	Fuji	0.09	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
	Honeycrisp	0.10	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19

(Willow Drive Nursery, 2020). The tree price for 'Honeycrisp' ($7.5/tree (VA, SA, & TS) and $9/tree (SP) for traditional rootstocks ($8/tree (VA, SA, & TS) and $9.5/tree (SP) for Geneva rootstocks) was ≈$1/tree higher than that of trees for 'Fuji' and 'Gala' ($8.5/tree (VA, SA, & TS) and $10/tree (SP) for traditional rootstocks ($9/tree (VA, SA, & TS) and $10.5/tree (SP) for Geneva rootstocks). Labor time for pruning was recorded each year. Average values were used for those years when data was missing. Pruning and training costs were calculated as skilled labor at $15/h while harvest costs were taken from statewide averages and totaled $0.11/kg for 'Honeycrisp' and $0.08/kg for 'Gala' and 'Fuji' (Table 3). The cost of management by the owner/manager and an overhead charge for farm wide costs were also included as fixed costs (Table 3). The baseline parameter values in Table 3 were used to complete the calculation of NPV and the economic analysis under different hypothetical scenarios including changes in fruit price, yield level, labor cost, land value, and discount rate. Most of the parameters do not vary by cultivars, however, picking costs are higher for 'Honeycrisp'. Other costs for pest control, disease control, weed control, fertilization and chemical thinning were taken from statewide averages of New York State apple growers (Table 4). The variable costs for pest management, fruit nutrition, and tree maintenance, the IPM and nutrition costs do not vary by cultivar but increased over time. The thinning costs vary by cultivar and remain flat after year 5. 'Gala' incurs the highest thinning cost and 'Honeycrisp' has the lowest thinning costs.

Table 3
Costs and parameters used in the economic analysis.

Pre-plant and planting			
Land value ($/ha)	$12,500		
Land preparation ($/ha)	$1800		
Planting, training labor ($/ha)	$900		
Tree price ($/tree)	VA,SA & TS	SP	
Traditional rootstock (B and M clones)	$7.5 ~ $8.5	$9.0 ~ $10.0	
Geneva® clones	$8.0 ~ $9.0	$9.5 ~ $10.5	
Trellising			
Trellis material ($/ha)			
Slender Pyramid	~ $5376		
Vertical Axis	~ $6637		
Slender Axis	~ $8897		
Tall Spindle	~ $12,722		
Post pounding ($/ha)	$200		
Trellis install labor ($/ha)	$520		
Miscellaneous			
Irrigation material	$2500		
Irrigation install labor	$1000		
Financials			
Discount rate	5 %		
Annual fixed cost ($/ha)	$1500		
Wage rate ($/hour)			
Skilled labor	$15		
Unskilled labor	$12		
Picking/Harvest	Honeycrisp	Fuji	Gala
Base picking cost (per bin)	$35	$24	$24
Picking employer tax	15 %		
Total picking cost (per bin)	$40.3	$27.6	$27.6
Total picking cost (per kg)	$0.11	$0.08	$0.08

Source: Lordan et al., 2019. Values were estimated from statewide averages of New York State apple growers. Note: Assumptions for other items. Post cost: $20/post. Conduit/Stake cost: $3.0/stake. Wire cost: $0.33/m. Wires per row: 1 for SP, VA, SA; 5 for TS. Picking employer tax: 15 %.

2.3. Economic analysis

Net crop revenue was calculated by subtracting storage and packing related costs from gross crop revenue. Subsequently annual profit for each year was calculated by subtracting costs from net crop revenue and then the annual profit was discounted for each cultivar, rootstock and training system over 20 years. The 20-year analysis included costs and yields for the pre-plant year and the next 11 years from planting year 2006 to 2016 and the projected data from years 12–20.. Cash returns for year from 12 to 20 were predicted based on harvested quantities and prices between 2013 and 2016 (4 years); e.g., returns in the 12th year is the average of returns in 2013 through 2016 (4 years) and the returns in remaining years were calculated as the moving average in the same way. The economic analysis considered the time value of money using discounted annual cash flows (money today is worth more than that same amount in the future). NPV was calculated as the sum of discounted annual cash flows over 20 years using a fixed discount rate. The discount rate was estimated by subtracting the rate of inflation from the current interest rate to arrive at a real rate of interest. A discount rate of 5 % was used for our basic comparisons similar to Lordan et al. (2018b; 2019). NPV was obtained every year for each cultivar-rootstock-training system combination using the following formula:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

Where C_t = net cash inflow during period t; C_0 = total investment costs; r = discount rate; and t = number of time periods.

Table 4
Annual costs for IPM, fertilizer applications, and chemical thinning for different cultivars, over a 20-year orchard life. Values were estimated from statewide averages of New York State apple growers. We used average data from year 8–11 to estimate values for years 12- 20.

Year	Nº Year	IPM ($/ha)			Nutrition ($/ha)	Thinning ($/ha)		
		Disease	Weed	Insects		'Gala'	'Fuji'	'Honeycrisp'
2005	0	0	47	0	558	0	0	0
2006	1	0	47	0	558	0	0	0
2007	2	252	79	106	850	0	0	0
2008	3	346	84	105	205	0	0	0
2009	4	591	25	345	432	39	145	39
2010	5	638	86	558	353	213	158	105
2011	6	717	126	661	610	338	316	157
2012	7	600	42	808	413	338	316	157
2013	8	581	86	625	492	338	316	157
2014	9	729	124	463	531	338	316	157
2015	10	729	124	632	492	338	316	157
2016	11	729	124	632	413	338	316	157
2017	12	729	124	632	489	338	316	157
2018	13	729	124	632	489	338	316	157
2019	14	729	124	632	489	338	316	157
2020	15	729	124	632	489	338	316	157
2021	16	729	124	632	489	338	316	157
2022	17	729	124	632	489	338	316	157
2023	18	729	124	632	489	338	316	157
2024	19	729	124	632	489	338	316	157
2025	20	729	124	632	489	338	316	157

We also conducted a sensitivity analysis to evaluate how changes in selected cost and revenue variables affected the calculated NPVs for the different cultivars, rootstocks, and training systems. The sensitivity analysis included a range of scenarios using different values for key parameters in the budget model that calculates the NPV of an orchard. Our assumptions concerning the range of values for the parameters were based on the existing literature, field experience, and industry standards (Lordan et al., 2019). We considered a range of prices that were 10 % and 25 % higher and lower than those used in the baseline analysis. Average yields from those observed in the trials were adjusted for a 50 %, 75 %, 100 % and 150 % of the observed yields. Tree price increases of 10 %, 25 % and 50 % were simulated. We also modeled the impacts of higher labor costs (10 %, 25 %, and 50 % increases) and higher land costs using a land value of $25,000/hectare to simulate typical land prices in other apple producing regions which are typically significantly higher than those in New York State. The impact of higher discount rates (7 % and 9 %) were also considered in the sensitivity analysis. The impact of increased trellis costs and harvest costs which are both directly related to tree density were also modeled.

With NPV analysis, if the NPV of accumulated profit exceeds zero, the investment yields a positive rate of long-term return at the selected discount rate (White and DeMarree, 1992). The year that the NPV of accumulated profit reaches or exceeds zero is the year in which the investment has been recouped with interest (Gonzalez Nieto et al., 2023; Lordan et al., 2019, 2018b; Robinson et al., 2007a) and this point is depicted as the "break-even year" in our description below.

2.4. Statistical analysis

Data were analyzed by ANOVA with a linear mixed effects model (SAS institute, 2020) using a randomized split-split block design to determine the influence of cultivar, rootstock and training system on 20-year NPV. Explanatory variables included 21 Training System x Rootstock treatments as fixed factors, with replication and year as random factors. The interactions of cultivar and system*rootstock combination were all significant so the that final analysis was done by cultivar at each location. The final analysis of the cumulative NPV was performed with general linear model by ANOVA using SAS 9.4 (SAS Institute Inc., 2009) including all training systems and rootstocks (main treatment) in the same analysis for each cultivar. The statistical significance of treatment effects on the cumulative NPV for each cultivar at each trial location were estimated using the Fisher's LSD tests at $P < 0.05$. Regression analysis was used to determine relationships between NPV and planting density in selected years over the lifetime of the orchard for each apple variety and location.

3. Results

3.1. Net revenue effects

To understand the dynamics of cumulative NPV development over the life of the orchard, we plotted cumulative NPV from year 1 to 11 using trial data and from years 12 to 20. Using projected data. These cumulative NPV curves showed the typical initial decrease in NPV in the first three years of orchard life due to the investment required to establish the orchard after which all systems and rootstocks showed an upward slope to the NPV curves (Figs. 1-4). The SP system had the least negative NPV in the first 3 years followed by the VA and then the SA systems while the TS system reached a the most negative NPV in the first 3 years. However, the Tall Spindle System showed the most rapid rise in cumulative NPV from its most negative value compared to the other lower density systems. The cumulative NPV curves at the Dressel location showed more variability from year to year than at the VandeWalle farm. The cumulative NPV curves at Dressel farm showed a dip in the 8th year (2012) which was due to spring frosts which reduced yield significantly that year. This dip was more pronounced with 'Fuji' than with 'Gala'. After year 11 the curves show a constant slope since the data for years 12–20 was an estimated NPV derived from an average of the yields in years 8–11.

By the end of the trial (11 years) all combinations of planting density, rootstock and cultivar were profitable (NPV positive) at the VandeWalle site but at the Dressel site seven combinations of rootstock and planting density with 'Fuji' and two combinations with 'Gala' were not profitable (Figs. 1-4). Projections of profitability from year 11 through year 20 showed that the combinations of rootstock and planting density which were not profitable by the end of year 11 were all profitable by year 19 or earlier.

The shortest time to reach a NPV of zero (breakeven year) was 4 years with the combination 'Honeycrisp' grafted onto G.11, G.16, or M.9 trained as TS, and the maximum time was 19 years observed with Fuji/B.9 TS at Dressel farm (Table 5). With 'Fuji' the Slender Pyramid system reached the breakeven year between 9 and 16 years depending on

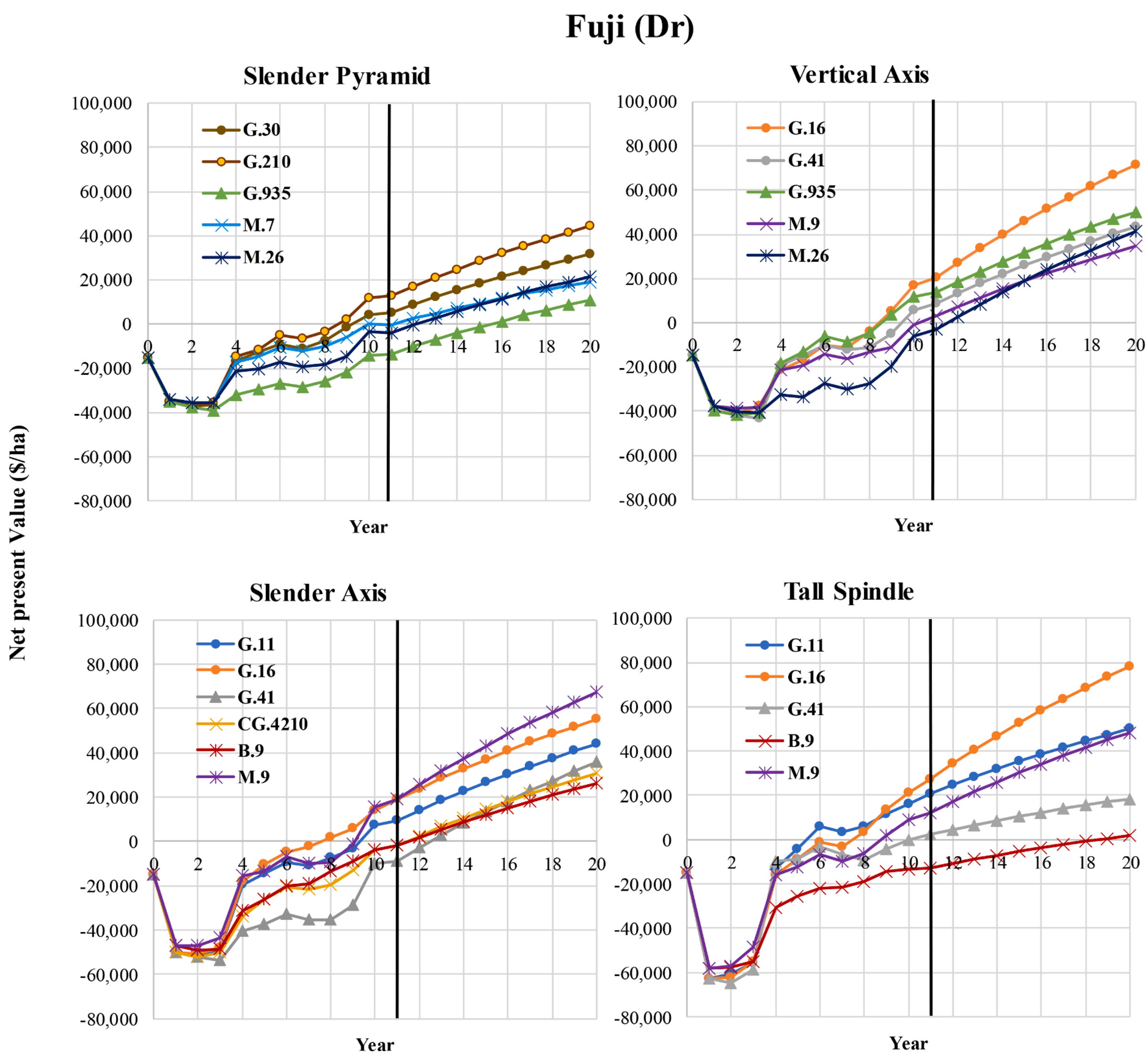

Fig. 1. Cumulative Net Present Value of net cash returns for 'Fuji' under various rootstocks and training systems at Dressel farm in southeastern New York state.

rootstock. With the Vertical Axis system, the breakeven year varied from year 9–13 while with the Slender Axis the breakeven year varied from year 8–12 and with the Tall Spindle system, the breakeven year varied from year 6–19. With 'Gala' at Dressel farm the breakeven year for the Slender Pyramid ranged from 9 to 12 years while with the Vertical Axis it ranged from 6 to 14 years. With the Slender Axis the breakeven year ranged from 6 to 9 and with the Tall Spindle the breakeven year ranged from 6 to 8. With 'Gala' at VandeWalle farm the breakeven year for the Slender Pyramid and the Vertical Axis ranged from 7 to 8 years while with the Slender Axis and the Tall Spindle the breakeven year ranged from 5 to 7. With 'Honeycrisp' the breakeven year for all four systems ranged from 4 to 7 years. In general, 'Honeycrisp' consistently led to a quicker break-even year than 'Gala' or 'Fuji' regardless of the system or rootstock. Also, in general, systems with lower planting densities had a later breakeven year than the higher density systems.

Projected profitability over 20 years using estimated yields and fruit quality for years 12–20 showed that cultivar, training system and rootstock all had significant effects on 20-year NPV (Table 6 for Dressel Farm and Table 7 for VandeWalle farm). Among cultivars, 'Honeycrisp' had the highest NPV while 'Fuji' had the lowest NPV averaged over all training systems and rootstocks. 'Gala' had intermediate NPV but 'Gala' at the VandeWalle site had higher NPV than at the Dressel site. Among training systems, the SP system was consistently the least profitable while the Tall Spindle system was consistently the most profitable (Tables 6 and 7). However, there was a significant interaction of cultivar and training system. With 'Fuji' (planted only at the Dressel site), the lowest profitability was with the B.9 in the Tall Spindle which was not significantly different than several other systems and rootstocks (G.935, M.7, M.26 and G.30 in the Slender Pyramid system, M.9, and M.26 in the Vertical Axis system, G.41, CG.4210, and B.9 in the Slender Axis system and G.41 in the Tall Spindle system) (Table 5). The greatest profitability was with G.16 in the Tall Spindle system, but it was not significantly greater than several other systems and rootstocks (M.9 and G.11 in the Tall Spindle system, M.9, G.16 and G.11 in the Slender Axis system, M.26, G.935, G41, and G.16 in the Vertical Axis system and G.210 in the Slender Pyramid system).

With 'Gala' at the Dressel site, G.41 in the Vertical Axis system had the lowest profitability but was not significantly different than several other systems and rootstocks (G.30, G.210, G.935, M.7 and M.26 in the Slender Pyramid system, G.16 and M.9 in the Vertical Axis system, CG.4210 and B.9 in the Slender Axis system) (Table 6). The greatest profitability was with G.41 in the Tall Spindle system, but it was not significantly greater than several other systems and rootstocks (G.11, G.16, M.9 and B.9 in the Tall Spindle system, or G.16 in the Slender Axis system). With 'Gala' at the VandeWalle site, G.210 in the Slender Pyramid system had the lowest profitability but was not significantly different than several other systems and rootstocks (G.30, G.935, M.26 in the Slender Pyramid system, or G.16, G.41 and M.26 in the Vertical

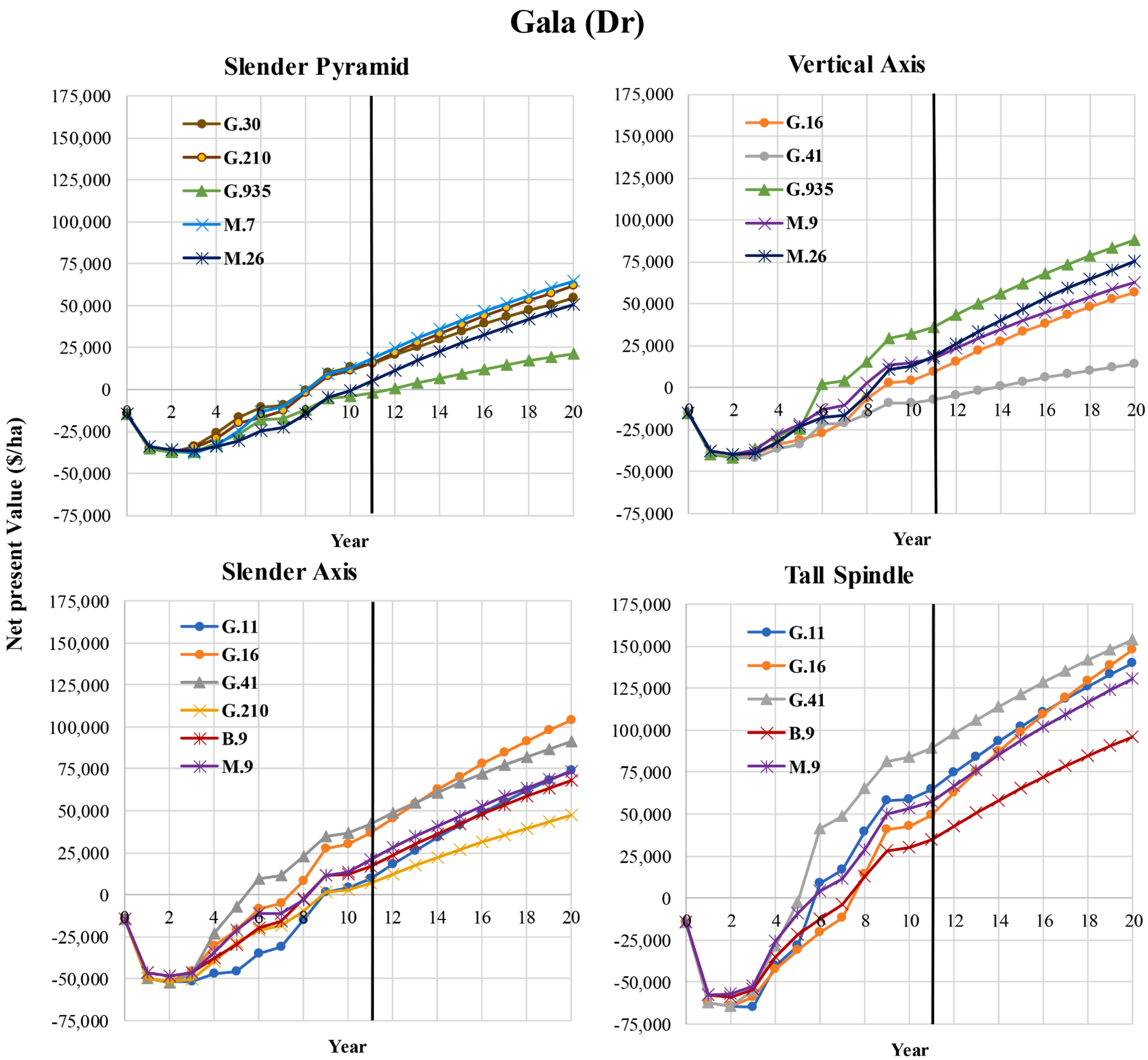

Fig. 2. Cumulative Net Present Value of net cash returns for 'Gala' under various rootstocks and training systems at Dressel farm in southeastern New York state.

Axis system) (Table 6). The greatest profitability was with M.9 in the Slender Axis system, but it was not significantly greater than several other systems and rootstocks (G.11, G.16, G.41, M.9 and B.9 in the Tall Spindle system, or G.11, G.16, G.41, CG.4210 or B.9 in the Slender Axis system).

With 'Honeycrisp' (planted only at the VandeWalle site) G.935 in the Slender Pyramid system had the lowest profitability but was not significantly different than several other systems and rootstocks (G.30, G.210, M7, M.26 in the Slender Pyramid system, G.16, G.935 in the Vertical Axis system or CG.4210 in the Slender Axis system) (Table 7). The greatest profitability was with G.11 in the Tall Spindle system, but it was not significantly greater than several other systems and rootstocks (G.16, G.41, M.9 and B.9 in the Tall Spindle system, G.11, G.16, G.41, M.9, in the Slender Axis system or M.26 in the Vertical axis system).

There were a number of inconsistencies in the performance of individual rootstocks. G.41 rootstock, which was among the group of highest NPV in the TS system with 'Gala' (at both locations) and 'Honeycrisp' at VandeWalle farm, has the lowest NPV with 'Fuji' in the Tall Spindle, at Dressel farm (Tables 6 and 7). B.9 also showed tremendous inconsistency with high NPV in the Tall Spindle systems with 'Honeycrisp' at VandeWalle and with 'Gala' at both locations while it had the absolute lowest profitability of any rootstock and system with 'Fuji' in the Tall Spindle system at Dressel farm. G.935, G.16, M.9, M.7, M.26 and B.9 also showed inconsistent performance while G.11 was consistently one of the top rootstocks regardless of training system or location. G.30 was also consistent in its performance but was not among the top rootstocks because it was only planted in the low-density Slender Pyramid system. CG.4210 consistently had low NPV except with 'Gala' at VandeWalle farm.

Overall, with 'Fuji' the most profitable combination was on G.16 rootstock in the Tall Spindle system, but it was not significantly better than several other rootstocks (Table 5). With 'Gala' at Dressel farm the most profitable combination was on G.41 in the Tall Spindle system but it was not significantly better than several other rootstocks (Table 5). With 'Gala' at the VandeWalle farm the most profitable combination was on M.9 in the Tall Spindle system but it was not significantly better several other rootstocks (Table 6). With 'Honeycrisp' the most profitable combination was on G.11 in the Tall Spindle system, but it was not significantly better several other rootstocks (Table 6). Thus, for all cultivars, the Tall Spindle system had the highest cumulative NPV but there was a different rootstock in the top spot for each cultivar (Tables 5 and 6).

3.2. *Effect of tree density on NPV*

We calculated the relationship of planting density and NPV for each

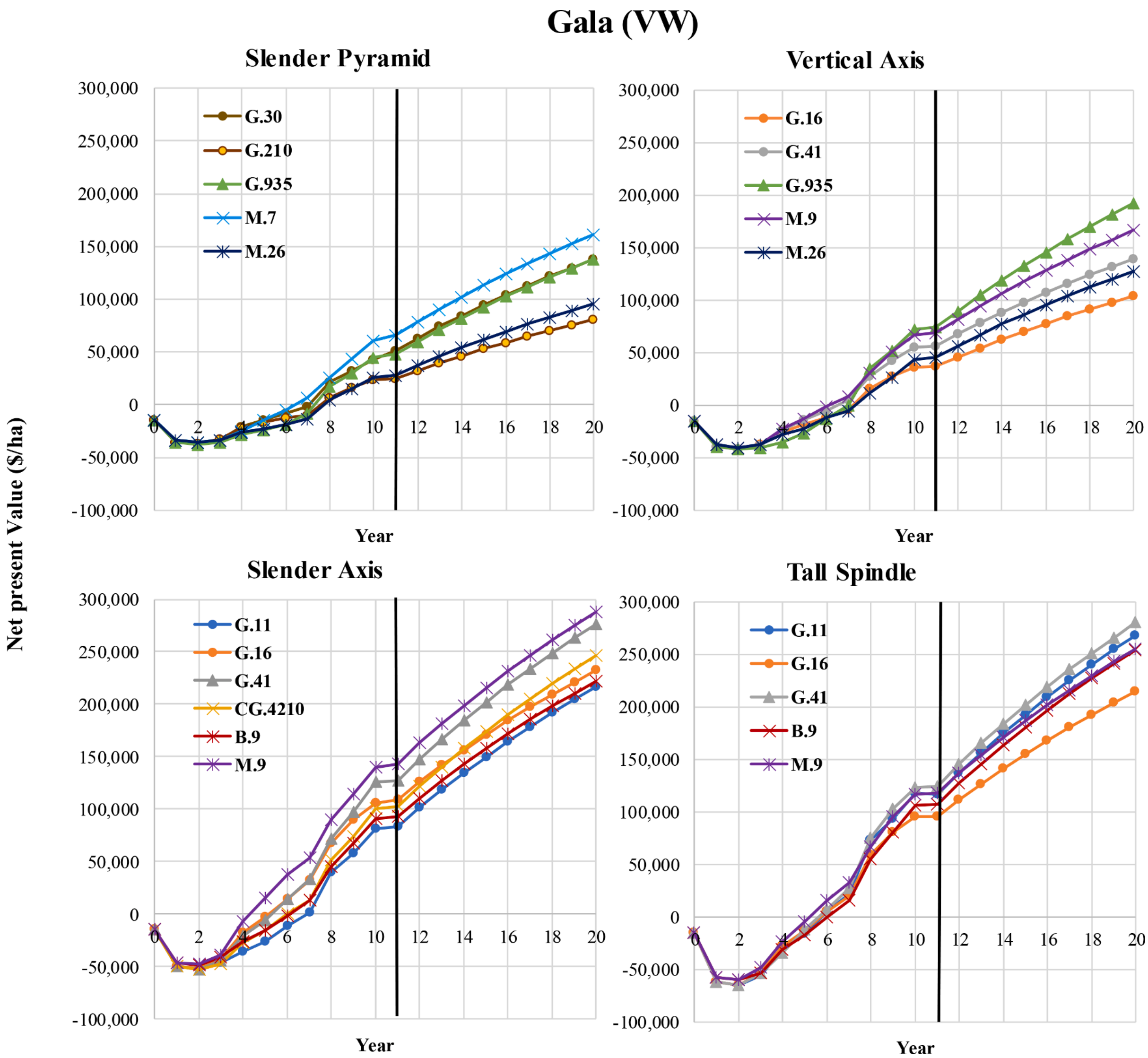

Fig. 3. Cumulative Net Present Value of net cash returns for 'Gala' under various rootstocks and training systems at VandeWalle farm in western New York state.

of the three rootstocks (M.9, G.41 and G.16) common to the Vertical Axis, Slender Axis and Tall Spindle systems at various timepoints in the orchard life. This analysis showed that profitability was related to planting density at the end of year 1, year 5, year 10, year 15 and year 20 (Figs. 5 and 6). At the end of the first year after planting there was a significant negative relationship between planting density and NPV with all systems having a negative NPV and the high-density system (TS) showing the most negative NPV. At 5 years after planting the relationship of planting density and NPV had a flat slope or a slight positive slope but all of systems still showed a negative NPV except 'Honeycrisp' in the VA, SA and TS systems. At 10, 15 and 20 years after planting the relationship was positive in all cases except with 'Fuji' on G.41 where the slope was negative. The relationships were generally quadratic with an optimum between 2500 and 3000 trees/ha. The exception was 'Fuji' with G.41 which had an optimum below 1000 trees/ha.

3.3. Sensitivity analysis

For all three cultivars, change in fruit prices and yield levels were the most influential factors that affected cumulative NPV's (Tables 8-11). Fruit price decreases resulted in a decrease in cumulative NPV. The magnitude of the reduction in NPV due to a reduction in fruit price was in most cases much greater than the magnitude of the reduction in fruit price (Tables 8 and 10). For 'Fuji' a reduction in fruit price of 25 % reduced NPV from 68 to 259 % depending on system and rootstock. An extreme exception was 'Fuji' on B.9 in the Tall Spindle system which had a 1912 % decrease in NPV with a 25 % decrease in fruit price. This was due to the very low NPV of this combination at the reference price. In general, fruit price reductions of 'Fuji' had similar large negative impacts on the low- and high-density systems. With 'Gala' at Dressel farm a reduction in fruit price of 25 % reduced NPV from 51 to 212 %. Specifically, with 'Gala' the G.41 rootstock in the Vertical Axis system, the G.935 rootstock in the Slender Pyramid system, and CG.4210 in the Slender Axis system were associated with the greatest losses under reductions in fruit price. In general, at the Dressel farm the reduction in fruit price 'Gala' had the greatest impact on the systems with the lowest planting density. For 'Gala' at the VandeWalle farm, a reduction on fruit price of 25 % reduced NPV from 37 to 53 % depending on system and rootstock. For 'Honeycrisp' a reduction on fruit price of 25 % reduced NPV from 32 to 40 %. In general, the impact of reduced fruit prices had a smaller relative effect on NPV at VandeWalle farm than at Dressel Farm and a smaller relative effect on NPV's of 'Honeycrisp', an intermediate effect on NPV's of 'Gala' and the largest effect on NPV'S of 'Fuji'. With 'Honeycrisp' there was little variation among rootstocks or training systems in their sensitivity to price decreases.

Changes in yields had a large impact on NPVs (Tables 8 and 10). For

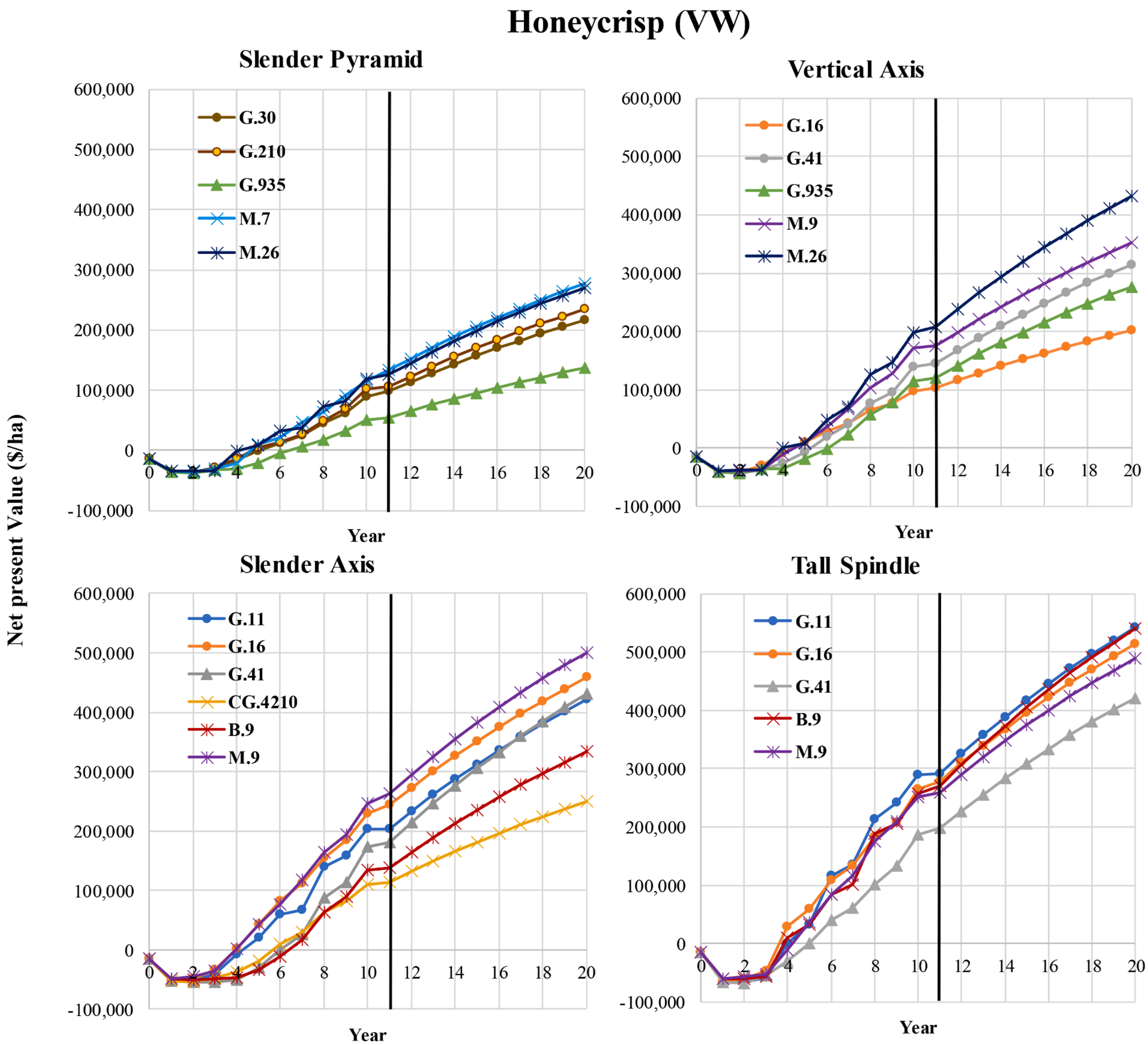

Fig. 4. Cumulative Net Present Value of net cash returns for 'Honeycrisp' under various rootstocks and training systems at VandeWalle farm in western New York state.

'Fuji' a 40 % increase in yield, increased NPV from 33 to 88 % depending on system and rootstock. An extreme exception was 'Fuji' on B.9 in the Tall Spindle system which had a 2357 % increase in NPV with a 40 % increase in yield. This was due to the very low reference NPV of this combination. For 'Gala' at Dressel farm a 40 % increase in yield increased NPV from 69 to 283 %. In general, at the Dressel farm increases in yield had the greatest impact on the systems with the lowest planting density. For 'Gala' at the VandeWalle farm, a 40 % increase in yield resulted in 55–80 % increase in NPV depending on system and rootstock. For 'Honeycrisp' a 40 % increase in yield resulted in a 48–64 % increase in NPV. In general, the impact of increased yield had a smaller relative effect on NPV at VandeWalle farm than at Dressel Farm and a smaller relative effect on NPV's of 'Honeycrisp', an intermediate effect on NPV's of 'Gala' and the largest effect on NPV's of 'Fuji'. With 'Honeycrisp' there was little variation among rootstock or training systems in their sensitivity to yield increases.

Changes in tree price had a relatively small effect (8–35 %) on cumulative NPV, even when the tree price increased by as much as 50 % (Tables 9 and 11). The greatest impact of increased tree cost was seen for 'Fuji' in the Tall Spindle system with either G.41 or B.9. This was due to the relatively low reference NPV of these two combinations.

Increased labor costs showed a modest impact on the NPV (Tables 9 and 11). An increase in labor costs of 50 % reduced NPV of 'Fuji' by 47–245 %. An extreme exception was 'Fuji' on B.9 in the Tall Spindle system which had a 1880 % decrease in NPV with a 50 % increase in labor cost. This was due to the very low reference NPV of this combination. For 'Gala' at Dressel farm NPV was reduced by 26–188 %. At VandeWalle farm 'Gala' NPV was reduced by 15–30 % with a 50 % increase in labor costs and with 'Honeycrisp' the reduction in NPV was 8–21 % when labor was increase 50 %. In general, there was less impact of higher labor costs with 'Honeycrisp', intermediate impact with 'Gala' and the largest impact with 'Fuji'. Among systems, the high-density systems were less impacted by increased labor costs than the low-density systems.

Land costs had a minor effect on NPV (Tables 9 and 11). A 100 % increase in land cost resulted in an 8–114 % reduction in NPV for 'Fuji'. An extreme exception was 'Fuji' on B.9 in the Tall Spindle system which had a 644 % decrease in NPV with a 100 % increase in land cost. With 'Gala' at Dressel farm a 100 % increase in land cost resulted in an 8–87 % decrease in NPV while at VandeWalle farm a 100 % increase in land cost resulted in a 4–15 % decrease in NPV for 'Gala' and a 2–9 % decrease in NPV with 'Honeycrisp'. The greatest impact of land cost was with 'Fuji' in the low-density system.

The discount rate had a relatively large impact on NPV (Tables 9 and

Table 5
Break-even year for positive NPV from various combinations of apple cultivars, training systems, rootstocks, and orchard locations. Within each cultivar, training systems are arranged in order of increasing tree planting density. Thus, with rootstocks which appear in more than one density, the effect of density can be observed by the change in breakeven year between systems. Cells colored green and yellow had short breakeven time period, orange and blue had intermediate breakeven time periods and pink and red had long breakeven time periods.

Location	Cultivar	Planting System	G.11	G.16	G.30	G.41	G.210	G.935	CG.4210	M.7	M.9	M.26	B.9
Dressel	Fuji	Slender Pyramid			10		9	16		11		13	
		Vertical Axis		9		10		9			11	12	
		Slender Axis	10	8		13			12		12		10
		Tall Spindle	6	8		11					9		19
	Gala	Slender Pyramid			9		9	12		9		11	
		Vertical Axis		9		14		6			8	9	
		Slender Axis	9	8		6			9		9		9
		Tall Spindle	6	8		6					6		8
VandeWalle	Gala	Slender Pyramid			8		8	8		7		8	
		Vertical Axis		8		7		8			7	8	
		Slender Axis	7	6		6			7		5		7
		Tall Spindle	6	6		6					6		7
	Honeycrisp	Slender Pyramid			6		5	7		5		5	
		Vertical Axis		5		6		6			5	4	
		Slender Axis	5	4		7			6		4		7
		Tall Spindle	4	4		6					4		5

Table 6
NPV of 20-year net cash returns of 'Fuji' and 'Gala' under various combinations of rootstocks and training systems at Dressel farm in southeastern New York state.

Dressel									
Cultivar	System & Rootstock		Cumulative NPV 20 years ($/ha)		Cultivar	System & Rootstock		Cumulative NPV 20 years ($/ha)	
Fuji	Slender Pyramid	G30	31,829	bcdef	Gala	Slender Pyramid	G30	54,392	efg
		G210	44,417	abcde			G210	61,793	efg
		G935	11,010	ef			G935	21,471	fg
		M7	19,235	def			M7	64,529	efg
		M26	21,472	def			M26	50,430	efg
	Vertical Axis	G16	71,305	ab		Vertical Axis	G16	57,095	efg
		G41	43,154	abcde			G41	14,354	g
		G935	49,971	abcde			G935	88,362	cde
		M9	34,711	bcdef			M9	62,504	efg
		M26	41,048	abcdef			M26	75,339	def
	Slender Axis	G11	43,751	abcde		Slender Axis	G11	73,800	def
		G16	54,954	abcd			G16	104,040	abcde
		G41	35,513	bcdef			G41	91,195	bcde
		CG4210	30,800	cdef			CG4210	47,113	efg
		M9	67,116	abc			M9	73,426	def
		B9	26,105	def			B9	68,302	efg
	Tall Spindle	G11	50,091	abcde		Tall Spindle	G11	140,144	abc
		G16	78,169	a			G16	147,549	ab
		G41	18,427	def			G41	153,552	a
		M9	48,347	abcde			M9	130,518	abcd
		B9	1,941	f			B9	96,088	abcde
		LSD P≤0.05	**39,557**				**LSD *P≤0.05***	**58,929**	

11). A discount rate of 9 % (an 80 % increase over the base rate of 5 %) resulted in a 49–143 % decrease in NPV for 'Fuji'. An extreme exception was 'Fuji' on B.9 in the Tall Spindle system which had a 658 % decrease in NPV with a 9 % discount rate. With 'Gala' at Dressel farm a discount rate of 9 % resulted in a 42–113 % decrease in NPV while at VandeWalle farm a 9 % discount rate resulted in a 37–47 % decrease in NPV for

Table 7
NPV of 20-year net cash returns of 'Gala', and 'Honeycrisp' under various combinations of rootstocks and training systems at VandeWalle farm in western New York state.

VandeWalle									
Cultivar	System & Rootstock		Cumulative NPV 20 years ($/ha)		Cultivar	System & Rootstock		Cumulative NPV 20 years ($/ha)	
Gala	Slender Pyramid	G30	137,885	def	Honeycrisp	Slender Pyramid	G30	216,092	efg
		G210	81,103	f			G210	234,361	efg
		G935	137,900	def			G935	136,441	g
		M7	161,182	cde			M7	276,638	efg
		M26	95,570	ef			M26	270,745	efg
	Vertical Axis	G16	103,627	ef		Vertical Axis	G16	201,607	fg
		G41	139,560	def			G41	314,834	def
		G935	192,238	bcd			G935	277,442	efg
		M9	166,480	cde			M9	351,928	bcde
		M26	127,814	def			M26	432,176	abcd
	Slender Axis	G11	216,238	abc		Slender Axis	G11	421,143	abcd
		G16	231,890	abc			G16	458,534	abc
		G41	276,570	a			G41	430,591	abcd
		CG4210	246,405	ab			CG4210	249,622	efg
		M9	288,048	a			M9	500,684	a
		B9	222,009	abc			B9	333,706	cdef
	Tall Spindle	G11	268,162	a		Tall Spindle	G11	543,084	a
		G16	214,421	abc			G16	514,214	a
		G41	279,944	a			G41	421,399	abcd
		M9	255,198	ab			M9	489,493	ab
		B9	254,355	ab			B9	541,239	a
		LSD *P*≤0.05	**74,772**				**LSD *P*≤0.05**	**142,161**	

'Gala', and a 35–42 % decrease in NPV for 'Honeycrisp'. With 'Fuji' the greatest negative effect of increased discount rate was with the low-density system.

4. Discussion

We evaluated the long-term economic performance of three apple cultivars, four training systems and various rootstocks using the cumulative net present value approach over 11 years using field plot data and then also projected profitability over 20 years representing the life of an orchard. The purpose for using cumulative discounted profits rather than annual profit was to allow the comparison of investment potential of each planting density (training system), rootstock, and cultivar over the expected lifetime of an orchard. Among cultivars, 'Honeycrisp' had significantly higher profitability than 'Gala' while 'Fuji' was significantly lower in profitability than 'Gala'. Other studies have also shown greater profitability with 'Honeycrisp' than 'McIntosh' (Lordan et al., 2018b) and greater profitability with 'Gala' than 'Fuji' (Lordan et al., 2019). In the present study the key difference between 'Fuji' and 'Gala' was significantly higher cumulative yield with 'Gala' (Reig et al., 2019) while the key difference between 'Gala' and 'Honeycrisp' was the much higher fruit price for 'Honeycrisp'.

Our primary objective was to evaluate the economic viability of the four systems we trialed. Overall, the Tall Spindle system performed better than the three other lower-density systems. Similar results were shown by Lordan et al. (2018b, 2019) who found an optimum profitability at a density similar to the Tall Spindle system. In the current study, the differences between the Tall Spindle and the Slender Axis were in some cases not statistically significant. However, since the systems differed in planting density (a continuous variable) we used regression analysis to estimate differences between systems by determining the relationship of tree density and profitability. In the present study the relationship of tree planting density and cumulative NPV was quadratic with a positive slope up to 2500–3000 trees/ha for all cultivars and systems except for 'Fuji' on G.41 where the relationship was negative. Lordan, et al. (2018b) also showed a positive linear relationship between tree planting density and cumulative NPV with 'Honeycrisp' and 'McIntosh' in a northern growing climate. However, Lordan, et al. (2019) in another study worked with a much wider range of densities (lower and higher) than we did in this study or Lordan et al. (2018b) did in their first study. The results of their second study showed a curvilinear relationship between tree planting density and cumulative NPV with an optimum density ~3000 trees per ha and lower profitability at lower and higher densities which is similar to the results of the present study. They interpreted their results as evidence of the law of diminishing returns where increasing tree planting density results in an increase in cumulative NPV up to the economic optimum density beyond which increasing tree planting density resulted in a decrease in cumulative NPV even though cumulative yield continued to increase up to the maximum density they evaluated. In the present study the maximum density we evaluated was near the optimum density in their study.

Among rootstocks, there was a significant interaction with planting density and cultivar, so the same rootstock was not the most profitable with every cultivar and system. Nevertheless, it appears that economic performance of the system was mostly driven by planting density, regardless of the rootstock selection. Each of the rootstocks we evaluated in the Tall Spindle system (B.9, G.11, G.16, G.41 and M.9) has been previously shown to be highly yield efficient (Autio et al., 2020a, 2020b; Marini et al., 2006; Reig, et al., 2018; Robinson et al., 2008a), thus it is reasonable that they all had high economic performance in the present study. A specific difference in performance between the present study and a previous report was with G.16 rootstock which was in the high

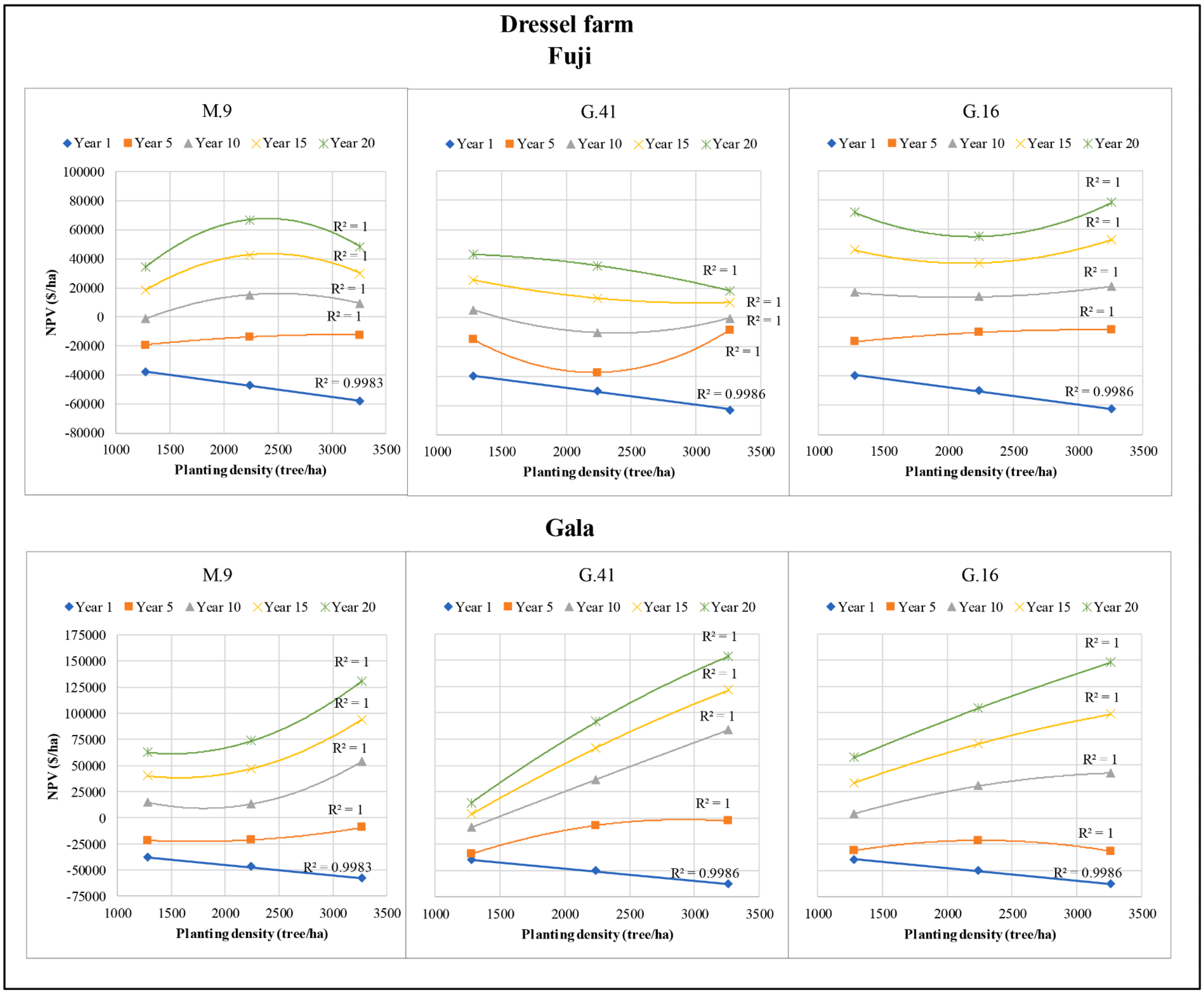

Fig. 5. Quadratic Regressions of tree planting density and cumulative net present value (NPV) for each cultivar ('Fuji' and 'Gala') and three rootstocks (M.9, G41 and G.16) common to the three systems (Vertical Axis = 1280 trees ha^{-1}, Slender Axis = 2240 trees•ha^{-1} and Tall Spindle = 3280 trees•ha^{-1}) at Dressel farm in New York state at various timepoints in the life of an orchard.

performing group of rootstocks in the present study while Lordan et al. (2018b) found that G.16 had inferior performance compared to M.9 and B.9 in a northern cold climate with 'McIntosh' and 'Honeycrisp' in terms of long-run profitability for both cultivars under high and medium density systems. Overall, the election of rootstock had an important effect on the investment return in this experiment, as also shown by Dallabetta et al. (2021) in Italy.

A notable result of this study was the inconsistent performance of several rootstocks. Marini et al. (2006, 2012) has shown that rootstock performance may vary greatly from one location to another with different soils, climates and management practices. In the present study the two trial locations showed quite different results with the Vande-Walle site performing better than the Dressel site. This variability justifies the application of "designer" rootstock principles when designing new orchards (Fazio and Robinson, 2021). However, even considering the differences between sites the inconsistent performance of G.41 and B.9 is difficult to explain. In the case of G.41, the rootstock liners were produced by stoolbeds in 2004 and had relatively few roots. This genotype is difficult to root in stoolbeds and since that time almost all of the G.41 rootstock production has been done by tissue culture which results in much better rooted rootstock liners (Adams, 2010). More recently planted rootstock trials have shown more consistent performance from this rootstock (Cline et al., 2021). In the case of B.9, the extremely poor performance with 'Fuji' in the Tall Spindle system at the Dressel Farm is unexplainable.

Another objective of our study was to estimate the break-even year to reach a positive NPV for each rootstock, tree type and cultivar. These calculations showed that the break-even year varied significantly for each rootstock, tree type and cultivar. Similar variations were shown by Lordan et al. (2019). Among cultivars our results showed the quickest investment pay off was for 'Honeycrisp', followed by 'Gala' and 'Fuji'. A study done by Lordan et al. (2019) showed longer times to reach the break-even year with 'Gala' and 'Fuji' while another study by Lordan et al. (2018b) showed shorter breakeven times for 'Honeycrisp' than 'McIntosh'. Badiu et al. (2015) observed payback periods for high density plantings similar to our results. Similarly Hassan et al. (2020b) reported the payback period was five years in high density trees compared with 11–12 years for traditional densities in India and Italy. In New Zealand, Cahn and Goedegebure, 1992 concluded that higher tree densities were more favorable for long-term profitability and earlier breakeven time. Among rootstocks, G.11 consistently had the shortest break-even year regardless of system or cultivar. Among systems the Tall Spindle had the shortest break-even year similar to other studies (Lordan et al., 2018b; 2019) which indicates the commercial value of this high-density system.

Our sensitivity analysis showed that among economic parameters affecting the long-term profitability of an orchard, fruit price and yield were vastly more important than other factors, concurring with results of Cahn et al. (1996) in New Zealand and Ucar et al., 2016 in Slovakia. Fruit price and marketable share can be vastly affected by quality of the

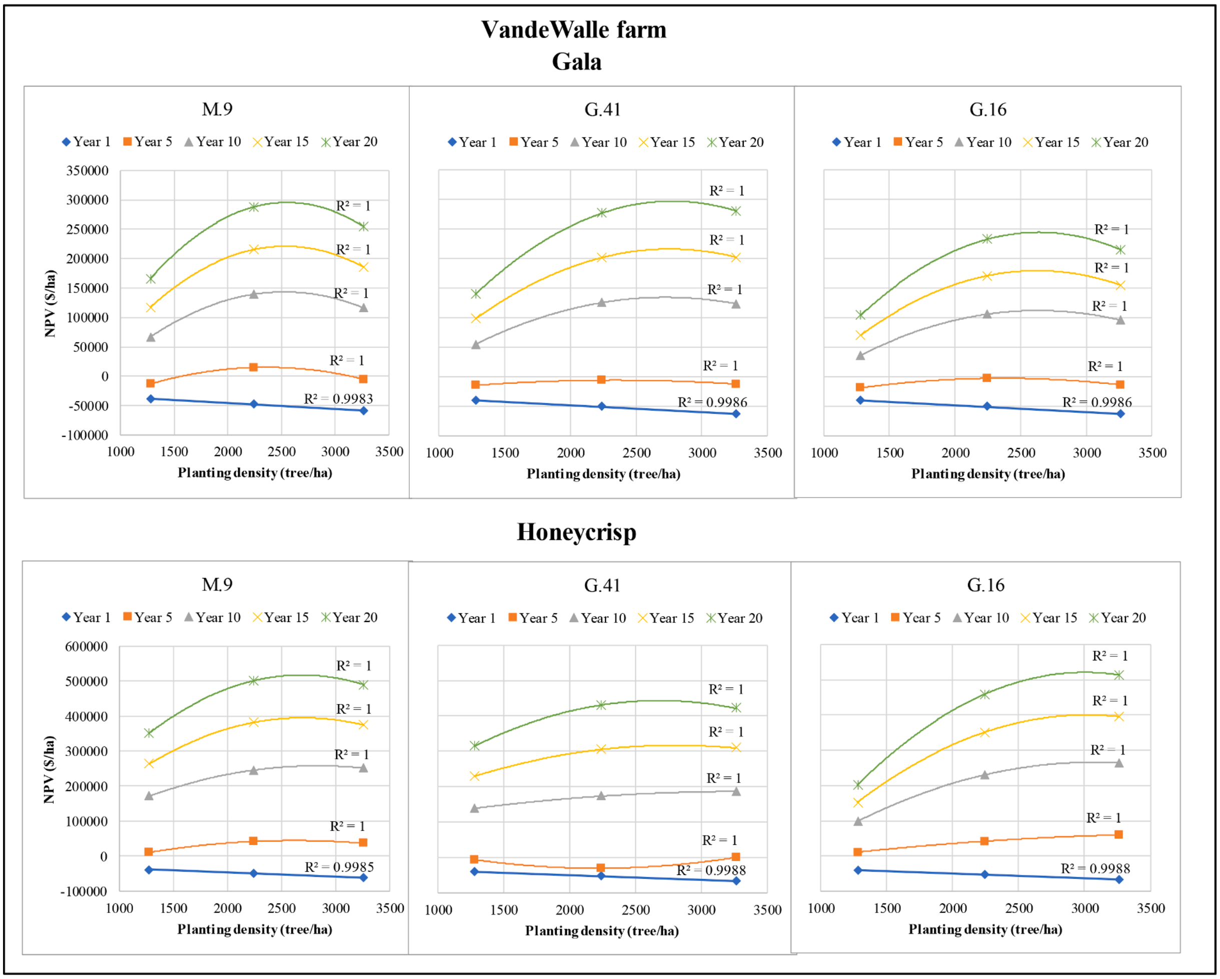

Fig. 6. Quadratic Regressions of tree planting density and cumulative net present value (NPV) for each cultivar ('Gala' and 'Honeycrisp') and three rootstocks (M.9, G41 and G.16) common to the three systems (Vertical Axis = 1280 trees ha^{-1}, Slender Axis = 2240 trees•ha^{-1} and Tall Spindle = 3280 trees•ha^{-1}) at VandeWalle farm in New York state at various timepoints in the life of an orchard.

fruit which in turn can be affected by rootstock choice as exemplified by rootstock induced bitter-pit in 'Honeycrisp' (Islam et al., 2022). For the individual grower, price and yields are not connected however for the apple industry as a whole yield and price are interconnected due to supply and demand forces. Thus, increases in yield by all growers of a particular cultivar might result in reduced price and profits. However, at the level of the individual grower, the investment decisions when planting a new orchard should be most heavily influenced by expected prices and expected yield. Bravin et al. (2009) concluded that fruit price and yield were the decisive starting-points for success. Similar to our study, Lordan et al. (2018b) reported that the most important variables that affected orchard NPV were fruit price and yield. Likewise, Hassan et al. (2020a) concluded that yield per hectare is one of the most important parameters to assess the performance of crops. Ekinci et al. (2020) also showed that fruit price and yield had the greatest impact on orchard profitability. In our study, the cultivar 'Fuji' (with the lowest fruit price) was more sensitive to fruit price and yield than 'Gala' or 'Honeycrisp'. Our results also suggested that sensitivity to changes in price and yield among rootstocks and tree types were smaller than among cultivars.

Of intermediate importance was the discount rate. The large effect of discount rate was due to the fact that it is applied to profits at each year of the 20-year life of an orchard. Our results suggested that when the discount rate is raised, orchard profitability was significantly lower. 'Fuji' profitability showed a higher dependance on discount rate compared to 'Gala' and 'Honeycrisp'. Robinson et al. (2007) and Galinato and Gallardo (2020) have also shown a large effect of discount rate on profitability.

Labor cost had a significant effect on NPV but was of much less importance than fruit price, yield and discount rate. Reig et al., showed that the higher density systems have higher labor costs than low density systems but from an investment perspective the increased labor costs are offset significantly by increased yield of the high density systems. Lordan et al. (2019) also found that labor cost had a significant effect on the cumulative NPV as this cost is applied to gross income every year of the life of an orchard. Of much less importance were tree costs and land costs. Robinson et al. (2007) also reported that land and tree price had a significant but small effect on orchard profitability of high-density orchards. These factors only occur in the first year of operation and thus it is somewhat expected that they would have a modest overall effect on NPV. The low sensitivity of cumulative NPV to tree prices provides the opportunity for expanding the use of different rootstocks without cost considerations.

5. Conclusions

The choice of cultivar has a very large effect on profitability because the fruit value (fruit price) of the cultivar is the most important factor affecting profitability. With cultivars like 'Honeycrisp' that have high fruit price, the investment is less risky because of the shorter breakeven time. Similarly high-density plantings in the Slender Axis and Tall Spindle systems (tree densities between 2240 and 3280 trees/ha) on

Table 8
Sensitivity of cumulative 20-year discounted net returns (NPV) of 'Fuji' and 'Gala' to changes in fruit price and yield at **Dressel farm** in southeastern New York State. Values under each scenario represent the percentage change from the baseline NPV which was calculated based on data from the trial. Red bars indicate negative change and green bars indicate positive change while yellow indicates a very small change in NPV. The intensity of green or red is related to the magnitude of the change in NPV.

Cultivar	System & Rootstock		Reference NPV	Fruit price -25%	Fruit price -15%	Fruit price +15%	Fruit price +25%	Yield 60%	Yield 80%	Yield 120%	Yield 140%
Fuji	SP	G.30	31,829	-111%	-66%	66%	111%	-144%	-72%	72%	144%
		G.210	44,417	-85%	-51%	51%	85%	-113%	-56%	56%	113%
		G.935	11,010	-259%	-155%	155%	259%	-333%	-167%	167%	333%
		M.7	19,235	-160%	-96%	96%	160%	-211%	-106%	106%	211%
		M.26	21,472	-145%	-87%	87%	145%	-189%	-95%	95%	189%
	VA	G.16	71,305	-68%	-41%	41%	68%	-88%	-44%	44%	88%
		G.41	43,154	-94%	-57%	57%	94%	-122%	-61%	61%	122%
		G.935	49,971	-87%	-52%	52%	87%	-111%	-55%	55%	111%
		M.9	34,711	-109%	-65%	65%	109%	-138%	-69%	69%	138%
		M.26	41,048	-99%	-60%	60%	99%	-124%	-62%	62%	124%
	SA	G.11	43,751	-107%	-64%	64%	107%	-132%	-66%	66%	132%
		G.16	54,954	-88%	-53%	53%	88%	-113%	-56%	56%	113%
		G.41	35,513	-121%	-73%	73%	121%	-153%	-76%	76%	153%
		CG.4210	30,800	-140%	-84%	84%	140%	-168%	-84%	84%	168%
		M.9	67,116	-77%	-46%	46%	77%	-96%	-48%	48%	96%
		B.9	26,105	-150%	-90%	90%	150%	-190%	-95%	95%	190%
	TS	G.11	50,091	-109%	-65%	65%	109%	-134%	-67%	67%	134%
		G.16	78,169	-78%	-47%	47%	78%	-100%	-50%	50%	100%
		G.41	18,427	-243%	-146%	146%	243%	-300%	-150%	150%	300%
		M.9	48,347	-105%	-63%	63%	105%	-129%	-64%	64%	129%
		B.9	1,941	-1912%	-1147%	1147%	1912%	-2357%	-1179%	1179%	2357%
Gala	SP	G.30	54,392	-62%	-37%	37%	62%	-99%	-50%	50%	99%
		G.210	61,793	-58%	-35%	35%	58%	-93%	-46%	46%	93%
		G.935	21,471	-119%	-71%	71%	119%	-190%	-95%	95%	190%
		M.7	64,529	-56%	-34%	34%	56%	-90%	-45%	45%	90%
		M.26	50,430	-64%	-39%	39%	64%	-103%	-52%	52%	103%
	VA	G.16	57,095	-76%	-45%	45%	76%	-100%	-50%	50%	100%
		G.41	14,354	-212%	-127%	127%	212%	-283%	-141%	141%	283%
		G.935	88,362	-59%	-35%	35%	59%	-79%	-40%	40%	79%
		M.9	62,504	-69%	-41%	41%	69%	-93%	-47%	47%	93%
		M.26	75,339	-63%	-38%	38%	63%	-86%	-43%	43%	86%
	SA	G.11	73,800	-72%	-43%	43%	72%	-94%	-47%	47%	94%
		G.16	104,040	-59%	-35%	35%	59%	-78%	-39%	39%	78%
		G.41	91,195	-63%	-38%	38%	63%	-85%	-43%	43%	85%
		CG.4210	47,113	-96%	-57%	57%	96%	-124%	-62%	62%	124%
		M.9	73,426	-68%	-41%	41%	68%	-91%	-46%	46%	91%
		B.9	68,302	-72%	-43%	43%	72%	-96%	-48%	48%	96%
	TS	G.11	140,144	-54%	-33%	33%	54%	-73%	-36%	36%	73%
		G.16	147,549	-52%	-31%	31%	52%	-71%	-35%	35%	71%
		G.41	153,552	-51%	-31%	31%	51%	-69%	-35%	35%	69%
		M.9	130,518	-53%	-32%	32%	53%	-72%	-36%	36%	72%
		B.9	96,088	-62%	-37%	37%	62%	-84%	-42%	42%	84%

dwarfing rootstocks are less risky because of the shorter breakeven time. A low number of years to recoup the investment gives growers flexibility to respond to changes in cultivar demand. Planting lower densities which require less initial investment may seem to be less risky since lower amounts of capital are put at risk, but they have lower yields and reach the breakeven year later thus are in reality more risky than high density orchards. From a practical perspective, our study indicates the most profitable option for new orchards is the Tall Spindle at 3230 trees/ha on any one of 5 dwarfing and efficient rootstocks (Robinson et al., 2008b). The estimated lifetime profitability levels we reported which

Table 9
Sensitivity of cumulative 20-year discounted net returns of 'Fuji' and 'Gala' to changes in tree price, labor costs, land cost, and discount rate at **Dressel farm** in southeastern New York State. Values under each scenario represent the percentage change from the baseline NPV which was calculated based on data from the trial. Red bars indicate negative change and green bars indicate positive change while yellow indicates a very small change in NPV. The intensity of green or red is related to the magnitude of the change in NPV.

Cultivar	System & Rootstock		Reference NPV	Tree price +15%	Tree price +25%	Tree price +50%	Labor cost +5%	Labor cost +15%	Labor cost +25%	Labor cost +50%	Land cost 25000 $/ha	DR 7%	DR 9%	Fruit price -25%
Fuji	SP	G.30	31,829	-4%	-6%	-12%	-9%	-28%	-47%	-93%	-39%	-34%	-61%	-111%
		G.210	44,417	-3%	-4%	-9%	-6%	-19%	-32%	-64%	-28%	-30%	-53%	-85%
		G.935	11,010	-10%	-17%	-35%	-24%	-73%	-122%	-245%	-114%	-81%	-143%	-259%
		M.7	19,235	-5%	-8%	-17%	-15%	-44%	-73%	-145%	-65%	-43%	-76%	-160%
		M.26	21,472	-4%	-7%	-15%	-13%	-38%	-64%	-128%	-58%	-46%	-80%	-145%
	VA	G.16	71,305	-2%	-4%	-8%	-5%	-14%	-23%	-47%	-18%	-28%	-50%	-68%
		G.41	43,154	-4%	-6%	-13%	-8%	-23%	-38%	-75%	-29%	-33%	-58%	-94%
		G.935	49,971	-3%	-5%	-11%	-7%	-21%	-34%	-69%	-25%	-30%	-53%	-87%
		M.9	34,711	-4%	-7%	-13%	-9%	-27%	-46%	-91%	-36%	-36%	-64%	-109%
		M.26	41,048	-3%	-6%	-11%	-8%	-25%	-42%	-83%	-30%	-39%	-69%	-99%
	SA	G.11	43,751	-7%	-11%	-22%	-9%	-26%	-44%	-88%	-29%	-33%	-59%	-107%
		G.16	54,954	-5%	-9%	-17%	-7%	-20%	-33%	-67%	-23%	-29%	-52%	-88%
		G.41	35,513	-8%	-14%	-27%	-10%	-30%	-50%	-99%	-35%	-46%	-81%	-121%
		CG.4210	30,800	-9%	-16%	-31%	-12%	-36%	-61%	-121%	-41%	-43%	-77%	-140%
		M.9	67,116	-4%	-6%	-12%	-6%	-17%	-28%	-56%	-19%	-29%	-51%	-77%
		B.9	26,105	-9%	-15%	-31%	-13%	-39%	-65%	-130%	-48%	-45%	-80%	-150%
	TS	G.11	50,091	-8%	-14%	-28%	-9%	-26%	-44%	-87%	-25%	-29%	-52%	-109%
		G.16	78,169	-5%	-9%	-18%	-6%	-17%	-28%	-56%	-16%	-28%	-49%	-78%
		G.41	18,427	-23%	-38%	-76%	-22%	-66%	-110%	-221%	-68%	-48%	-87%	-243%
		M.9	48,347	-7%	-12%	-24%	-8%	-24%	-41%	-82%	-26%	-32%	-57%	-105%
		B.9	1,941	-181%	-302%	-604%	-188%	-564%	-940%	-1880%	-644%	-367%	-658%	-1912%
Gala	SP	G.30	54,392	-2%	-3%	-7%	-4%	-12%	-20%	-41%	-23%	-29%	-51%	-62%
		G.210	61,793	-2%	-3%	-6%	-4%	-11%	-19%	-37%	-20%	-29%	-51%	-58%
		G.935	21,471	-5%	-9%	-18%	-10%	-29%	-48%	-97%	-58%	-46%	-81%	-119%
		M.7	64,529	-1%	-2%	-5%	-4%	-11%	-18%	-35%	-19%	-29%	-51%	-56%
		M.26	50,430	-2%	-3%	-6%	-4%	-13%	-22%	-44%	-25%	-34%	-59%	-64%
	VA	G.16	57,095	-3%	-5%	-10%	-5%	-16%	-27%	-53%	-22%	-32%	-57%	-76%
		G.41	14,354	-11%	-19%	-38%	-19%	-57%	-94%	-188%	-87%	-64%	-113%	-212%
		G.935	88,362	-2%	-3%	-6%	-4%	-11%	-18%	-37%	-14%	-25%	-44%	-59%
		M.9	62,504	-2%	-4%	-7%	-5%	-14%	-23%	-46%	-20%	-29%	-51%	-69%
		M.26	75,339	-2%	-3%	-6%	-4%	-13%	-21%	-42%	-17%	-29%	-50%	-63%
	SA	G.11	73,800	-4%	-7%	-13%	-5%	-15%	-25%	-49%	-17%	-33%	-58%	-72%
		G.16	104,040	-3%	-5%	-9%	-4%	-11%	-18%	-35%	-12%	-26%	-46%	-59%
		G.41	91,195	-3%	-5%	-11%	-4%	-12%	-20%	-40%	-14%	-24%	-43%	-63%
		CG.4210	47,113	-6%	-10%	-20%	-7%	-21%	-36%	-71%	-27%	-35%	-62%	-96%
		M.9	73,426	-3%	-5%	-11%	-4%	-13%	-22%	-44%	-17%	-29%	-51%	-68%
		B.9	68,302	-4%	-6%	-12%	-5%	-15%	-24%	-49%	-18%	-30%	-53%	-72%
	TS	G.11	140,144	-3%	-5%	-10%	-3%	-9%	-15%	-30%	-9%	-24%	-43%	-54%
		G.16	147,549	-3%	-5%	-10%	-3%	-8%	-14%	-27%	-8%	-26%	-46%	-52%
		G.41	153,552	-3%	-5%	-9%	-3%	-8%	-13%	-26%	-8%	-21%	-38%	-51%
		M.9	130,518	-3%	-4%	-9%	-3%	-8%	-14%	-28%	-10%	-24%	-42%	-53%
		B.9	96,088	-4%	-6%	-12%	-3%	-10%	-17%	-35%	-13%	-27%	-47%	-62%

resulted from the best apple cultivars and rootstocks planted at the highest. planting density, provide viable alternatives to apple growers seeking to plant new orchards.

CRediT authorship contribution statement

Shuay-Tsyr Ho: Writing – original draft, Data curation. **Luis Gonzalez Nieto:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bradley J. Rickard:** Project administration, Data curation. **Gemma Reig:** Writing – review & editing, Investigation, Data curation. **Jaume Lordan:** Writing – review & editing, Methodology, Investigation, Data curation. **Brian T. Lawrence:** Validation, Visualization. **Gennaro Fazio:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Stephen A Hoying:** Supervision, Resources, Methodology, Investigation. **Michael J. Fargione:** Resources, Methodology, Investigation, Conceptualization. **Mario Miranda Sazo:** Writing – review & editing, Supervision, Methodology, Investigation. **Terence L. Robinson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Table 10
Sensitivity of cumulative 20-year discounted net returns of 'Gala' and 'Honeycrisp' to changes in fruit price and yield at **VandeWalle farm** in western New York State. Values under each scenario represent the percentage change from the baseline NPV which was calculated based on data from the trial. Red bars indicate negative change and green bars indicate positive change while yellow indicates a very small change in NPV. The intensity of green or red is related to the magnitude of the change in NPV.

Cultivar	System & Rootstock		Reference NPV	Fruit price -25%	Fruit price -15%	Fruit price +15%	Fruit price +25%	Yield 60%	Yield 80%	Yield 120%	Yield 140%
Gala	SP	G.30	137,885	-40%	-24%	24%	40%	-64%	-32%	32%	64%
		G.210	81,103	-50%	-30%	30%	50%	-80%	-40%	40%	80%
		G.935	137,900	-40%	-24%	24%	40%	-64%	-32%	32%	64%
		M.7	161,182	-37%	-22%	22%	37%	-60%	-30%	30%	60%
		M.26	95,570	-46%	-27%	27%	46%	-73%	-37%	37%	73%
	VA	G.16	103,627	-53%	-32%	32%	53%	-74%	-37%	37%	74%
		G.41	139,560	-47%	-28%	28%	47%	-65%	-33%	33%	65%
		G.935	192,238	-41%	-25%	25%	41%	-58%	-29%	29%	58%
		M.9	166,480	-43%	-26%	26%	43%	-60%	-30%	30%	60%
		M.26	127,814	-48%	-29%	29%	48%	-67%	-33%	33%	67%
	SA	G.11	216,238	-42%	-25%	25%	42%	-59%	-30%	30%	59%
		G.16	231,890	-41%	-25%	25%	41%	-58%	-29%	29%	58%
		G.41	276,570	-39%	-23%	23%	39%	-55%	-27%	27%	55%
		CG.4210	246,405	-40%	-24%	24%	40%	-57%	-28%	28%	57%
		M.9	288,048	-38%	-23%	23%	38%	-54%	-27%	27%	54%
		B.9	222,009	-41%	-25%	25%	41%	-58%	-29%	29%	58%
	TS	G.11	268,162	-41%	-24%	24%	41%	-57%	-29%	29%	57%
		G.16	214,421	-44%	-27%	27%	44%	-61%	-31%	31%	61%
		G.41	279,944	-40%	-24%	24%	40%	-56%	-28%	28%	56%
		M.9	255,198	-41%	-24%	24%	41%	-57%	-28%	28%	57%
		B.9	254,355	-41%	-24%	24%	41%	-57%	-29%	29%	57%
Honeycrisp	SP	G.30	216,092	-34%	-21%	21%	34%	-55%	-28%	28%	55%
		G.210	234,361	-34%	-20%	20%	34%	-54%	-27%	27%	54%
		G.935	136,441	-40%	-24%	24%	40%	-64%	-32%	32%	64%
		M.7	276,638	-32%	-19%	19%	32%	-51%	-26%	26%	51%
		M.26	270,745	-32%	-19%	19%	32%	-52%	-26%	26%	52%
	VA	G.16	201,607	-39%	-23%	23%	39%	-57%	-28%	28%	57%
		G.41	314,834	-35%	-21%	21%	35%	-51%	-25%	25%	51%
		G.935	277,442	-36%	-22%	22%	36%	-52%	-26%	26%	52%
		M.9	351,928	-34%	-20%	20%	34%	-50%	-25%	25%	50%
		M.26	432,176	-32%	-19%	19%	32%	-48%	-24%	24%	48%
	SA	G.11	421,143	-34%	-20%	20%	34%	-50%	-25%	25%	50%
		G.16	458,534	-33%	-20%	20%	33%	-49%	-24%	24%	49%
		G.41	430,591	-34%	-20%	20%	34%	-50%	-25%	25%	50%
		CG.4210	249,622	-39%	-23%	23%	39%	-56%	-28%	28%	56%
		M.9	500,684	-33%	-20%	20%	33%	-48%	-24%	24%	48%
		B.9	333,706	-35%	-21%	21%	35%	-52%	-26%	26%	52%
	TS	G.11	543,084	-33%	-20%	20%	33%	-48%	-24%	24%	48%
		G.16	514,214	-33%	-20%	20%	33%	-49%	-24%	24%	49%
		G.41	421,399	-35%	-21%	21%	35%	-51%	-25%	25%	51%
		M.9	489,493	-34%	-20%	20%	34%	-49%	-24%	24%	49%
		B.9	541,239	-33%	-20%	20%	33%	-48%	-24%	24%	48%

Table 11
Sensitivity of cumulative 20-year discounted net returns of 'Gala' and 'Honeycrisp' to changes in tree price, labor costs, land cost, and discount rate at **VandeWalle farm** in western New York State. Values under each scenario represent the percentage change from the baseline NPV which was calculated based on data from the trial. Red bars indicate negative change and green bars indicate positive change while yellow indicates a very small change in NPV. The intensity of green or red is related to the magnitude of the change in NPV.

Cultivar	System & Rootstock		Reference NPV	Tree price +15%	Tree price +25%	Tree price +50%	Labor cost +5%	Labor cost +15%	Labor cost +25%	Labor cost +50%	Land cost 25000 $/ha	DR 7%	DR 9%
Gala	SP	G.30	137,885	-1%	-1%	-3%	-2%	-6%	-9%	-19%	-9%	-24%	-42%
		G.210	81,103	-1%	-2%	-5%	-3%	-9%	-15%	-29%	-15%	-27%	-47%
		G.935	137,900	-1%	-1%	-3%	-2%	-6%	-9%	-19%	-9%	-25%	-44%
		M.7	161,182	-1%	-1%	-2%	-2%	-5%	-8%	-16%	-8%	-23%	-41%
		M.26	95,570	-1%	-2%	-3%	-2%	-7%	-12%	-25%	-13%	-26%	-47%
	VA	G.16	103,627	-2%	-3%	-5%	-3%	-9%	-15%	-30%	-12%	-25%	-45%
		G.41	139,560	-1%	-2%	-4%	-2%	-7%	-12%	-24%	-9%	-24%	-42%
		G.935	192,238	-1%	-1%	-3%	-2%	-6%	-9%	-18%	-7%	-24%	-42%
		M.9	166,480	-1%	-1%	-3%	-2%	-6%	-10%	-20%	-8%	-23%	-41%
		M.26	127,814	-1%	-2%	-4%	-2%	-7%	-12%	-25%	-10%	-25%	-44%
	SA	G.11	216,238	-1%	-2%	-4%	-2%	-6%	-9%	-19%	-6%	-24%	-42%
		G.16	231,890	-1%	-2%	-4%	-2%	-5%	-9%	-18%	-5%	-22%	-38%
		G.41	276,570	-1%	-2%	-3%	-2%	-5%	-8%	-15%	-5%	-22%	-38%
		CG.4210	246,405	-1%	-2%	-4%	-2%	-5%	-9%	-17%	-5%	-23%	-40%
		M.9	288,048	-1%	-1%	-3%	-2%	-5%	-8%	-15%	-4%	-21%	-37%
		B.9	222,009	-1%	-2%	-4%	-2%	-5%	-9%	-18%	-6%	-23%	-40%
	TS	G.11	268,162	-2%	-3%	-5%	-2%	-5%	-8%	-16%	-5%	-22%	-40%
		G.16	214,421	-2%	-3%	-7%	-2%	-6%	-10%	-20%	-6%	-23%	-40%
		G.41	279,944	-2%	-3%	-5%	-2%	-5%	-8%	-16%	-4%	-22%	-39%
		M.9	255,198	-1%	-2%	-5%	-2%	-5%	-8%	-17%	-5%	-22%	-39%
		B.9	254,355	-1%	-2%	-5%	-2%	-5%	-8%	-16%	-5%	-23%	-40%
Honeycrisp	SP	G.30	216,092	-1%	-1%	-2%	-2%	-5%	-8%	-16%	-6%	-22%	-39%
		G.210	234,361	-1%	-1%	-2%	-1%	-4%	-7%	-15%	-5%	-22%	-38%
		G.935	136,441	-1%	-2%	-3%	-2%	-6%	-11%	-21%	-9%	-24%	-42%
		M.7	276,638	0%	-1%	-1%	-1%	-4%	-6%	-13%	-5%	-21%	-37%
		M.26	270,745	0%	-1%	-1%	-1%	-4%	-6%	-13%	-5%	-21%	-37%
	VA	G.16	201,607	-1%	-2%	-3%	-1%	-4%	-7%	-14%	-6%	-21%	-37%
		G.41	314,834	-1%	-1%	-2%	-1%	-3%	-5%	-11%	-4%	-21%	-38%
		G.935	277,442	-1%	-1%	-2%	-1%	-4%	-6%	-12%	-5%	-22%	-39%
		M.9	351,928	0%	-1%	-1%	-1%	-3%	-5%	-10%	-4%	-21%	-36%
		M.26	432,176	0%	-1%	-1%	-1%	-2%	-4%	-8%	-3%	-21%	-36%
	SA	G.11	421,143	-1%	-1%	-3%	-1%	-3%	-4%	-9%	-3%	-20%	-36%
		G.16	458,534	-1%	-1%	-2%	-1%	-3%	-5%	-9%	-3%	-20%	-35%
		G.41	430,591	-1%	-1%	-2%	-1%	-3%	-5%	-9%	-3%	-22%	-39%
		CG.4210	249,622	-1%	-2%	-4%	-1%	-4%	-7%	-15%	-5%	-22%	-39%
		M.9	500,684	-1%	-1%	-2%	-1%	-3%	-4%	-9%	-2%	-20%	-35%
		B.9	333,706	-1%	-1%	-3%	-1%	-3%	-5%	-11%	-4%	-23%	-40%
	TS	G.11	543,084	-1%	-1%	-3%	-1%	-2%	-4%	-8%	-2%	-20%	-35%
		G.16	514,214	-1%	-2%	-3%	-1%	-3%	-4%	-9%	-2%	-19%	-35%
		G.41	421,399	-1%	-2%	-4%	-1%	-3%	-5%	-10%	-3%	-21%	-38%
		M.9	489,493	-1%	-1%	-3%	-1%	-3%	-5%	-9%	-3%	-20%	-35%
		B.9	541,239	-1%	-1%	-2%	-1%	-2%	-4%	-8%	-2%	-20%	-36%

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Luis Gonzalez Nieto reports financial support was provided by Cornell AgriTech.

Data availability

The authors do not have permission to share data.

Acknowledgments

The authors wish to thank Rod Dressel Sr., Rod Dressel Jr., Sarah Dressel, Scott VandeWalle, Ken VandeWalle, and Marshall VandeWalle for all the help and resources invested over the 11 years of this study. Joe Whalen, Leo Dominguez, and Peter Herzeelle for plant material management in the orchard. This research was funded in part by a grant from the New York Apple Research and Development Program and by the USDA-NIFA SCRI grant Root to Fruit NYG-145543. The contents of this publication do not necessarily reflect the views or policies of the U.S. Department of Agriculture, nor does mention of trade names, commercial products, or organizations imply endorsement by the U.S. Government.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2024.113194.

References

Adams, R.R., 2010. Increasing the Rooting in Apple Rootstock Stoolbeds. Cornell University, Ithaca, NY. MS. Thesis.

Agricultural Marketing Resource Center (AgMRC). 2018. Access at: https://www.agmrc.org/commodities-products/fruits/apples.

Autio, W., Robinson, T., Black, B., Crassweller, R., Fallahi, E., Hoying, S., Parker, M., Parra-Quezada, R., Reig, G., Wolfe, D., 2020a. Budagovsky, Geneva, Pillnitz, and Malling apple rootstocks affect 'Fuji' performance over eight years in the 2010 NC-140 'Fuji' apple rootstock trial. J. Amer. Pomol. Soc. 74, 196–209.

Autio, W., Robinson, T., Blatt, S., Cochran, D., Francescato, P., Kushad, E., Lang, G., Lordan Sanahuja, J., Parra-Quezada, R., Stasiak, M., 2020b. Budagovsky, Geneva, Pillnitz, and Malling apple rootstocks affect 'Honeycrisp' performance over eight years in the 2010 NC-140 'Honeycrisp' apple rootstock trial. J. Amer. Pomol. Soc. 74, 182–195.

Badiu, D., Arion, F.H., Muresan, I.C., Lile, R., Mitre, V., 2015. Evaluation of economic efficiency of apple orchard investments. Sustainability. 7, 10521–10533.

Bradshaw, T.L., Berkett, L.P., Moran, R.E., Garcia, M.E., Darby, H.M., Parsons, R.L., Kingsley-Richards, S.L., Griffith, M.C., Bosworth, S.C., Gorres, J.H., 2016. Long-term economic evaluation of five cultivars in two organic apple orchard systems in Vermont, USA, 2006-2013. Acta Hortic. 1137, 315–322.

Bravin, E., Kilchenmann, A., Leumann, M., 2009. Six hypotheses for profitable apple production based on the economic work-package within the ISAFRUIT Project. J. Hort. Sci. Biotech. 84, 164–167.

Cahn, M.B., Goedegebure, J., 1992. Economic aspects of apple production in relation to tree density. N. Zealand J. Crop. Hortic. Sci. 20 (3), 289–296.

Cahn, M.B., Stevens, R.B., van de Klundert, A.C., 1996. Economic outcomes of early cropping and tree spacing decisions in braeburn apples on Malling 9 rootstock. Acta Hortic. 451, 551–558.

Cline, J.A., Autio, W., Clements, J., Cowgill, W., Crassweller, R., Einhorn, T., Fallahi, E., Francescatto, P., Hoover, E., Lang, G., Lordan, J., Moran, R., Muehlbauer, M., Musacchi, S., Stasiak, M., Quezada, R.Parra, Robinson, T., Serra, S., Sherif, S., Wiepz, R., Zandstra, J., 2021. Early performance of 'Honeycrisp' apple trees on several size-controlling rootstocks in the 2014 NC-140 rootstock trial. J. Amer. Pomol. Soc. 75, 189–202.

Dallabetta, N., Guerra, A., Pasqualini, J., Fazio, G., 2021. Performance of Semi-dwarf apple rootstocks in two-dimensional training systems. HortScience Horts 56, 234–241. https://doi.org/10.21273/HORTSCI15492-20.

DeMarree, A., Robinson, T., Hoying, S., 2003. Economics and the orchard system decision. Compact Fruit Tree 36, 42–49.

Ekinci, K., Demircan, V., Atasay, A., Karamursel, D., Sarica, D., 2020. Energy, economic and environmental analysis of organic and conventional apple production in Turkey. Erwerbs-Obstbau 62, 1–12.

Fazio, G., Robinson, T., 2018. GENEVA® apple rootstock comparison chart. https://ctl.cornell.edu/wp-content/uploads/plants/GENEVA-Apple-Rootstocks-Comparison-Chart.pdf . (Website checked in 2018).

Fazio, G., Robinson, T.L., 2021. Designer rootstocks: the basis for precision management of apple orchards. Acta Hortic. 1314, 275–286.

Galinato, S.P., Gallardo, R.K., 2020. 2019 Cost Estimates of Establishing, Producing, and Packing Honeycrisp Apples in Washington. Washington State University Extension. Technical Bulletin (Washington State University. Extension), 70E. https://hdl.handle.net/2376/17724.

Gonzalez Nieto, L., Reig, G., Lordan, J., Miranda Sazo, M., Hoying, S.A., Fargione, M.J., Reginato, G.H., Donahue, D.J., Francescatto, P., Casagrande Biasuz, E., Fazio, G., Lee Robinson, T., 2023. Long-term effects of rootstock and tree type on the economic profitability of 'Gala', 'Fuji' and 'Honeycrisp' orchards performance. Sci. Hortic. 318, 112129 https://doi.org/10.1016/j.scienta.2023.112129.

Hassan, B., Bhattacharjee, M., Wani, S.A., 2020a. Economic analysis of high-density apple plantation scheme in Jammu and Kashmir. Asian J. Agric. Rural Dev. 10, 379.

Hassan, B., Bhattacharjee, M., Wani, S., 2020b. Economics of high-density apple orchards: a comparative analysis of Jammu and Kashmir, India and Trentino-Alto-Adige, Italy. In: Glob. J. Hum.-Soc. Sci., 20, pp. 27–36.

Islam, M.T., Liu, J.Y., Das, P.R., Singh, A., Sherif, S.M., 2022. Rootstock effects on bitter pit incidence in 'Honeycrisp' apples are associated with changes in fruit's cell wall chemical properties. Front. Plant Sci. https://doi.org/10.3389/fpls.2022.1034664, 2022 13: 13 Accession Number: WOS:000875734700001.

Lordan, J., Wallis, A., Francescatto, P., Robinson, T.L., 2018a. Long-term effects of training systems and rootstocks on 'McIntosh' and 'Honeycrisp' performance, a 15-year study in a northern cold climate—Part 1: agronomic analysis. HortScience 53, 968–977.

Lordan, J., Wallis, A., Francescatto, P., Robinson, T.L., 2018b. Long-term effects of training systems and rootstocks on 'McIntosh' and 'Honeycrisp' performance, a 20-year study in a Northern Cold Climate—Part 2: economic analysis. HortScience 53, 978–992.

Lordan, J., Gomez, M., Francescatto, P., Robinson, T.L., 2019. Long-term effects of tree density and tree shape on apple orchard performance, a 20-year study–part 2, economic analysis. Sci. Hortic. 244, 435–444.

Marini, R.P., Anderson, J., Autio, W., Barritt, B., Cline, J., Cowgill, W., Crassweller, R., Garner, R., Gauss, A., Godin, R., 2006. Performance of 'Gala' Apple Trees on 18 dwarfing rootstocks: a ten-year summary of the 1994 NC-140 rootstock trial. J. Amer. Pomol. Soc. 60, 69.

Marini, R.P., Autio, W.R., Black, B., Cline, J.A., Cowgill Jr., W., Crassweller, R., Domoto, P., Hampson, C., Moran, R., Parra-Quezada, R.A., Robinson, T., Stasiak, M., Ward, D.L., Wolfe, D., 2012a. 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.

Reig, G., Lordan, J., Fazio, G., Grusak, M.A., Hoying, S., Cheng, L., Francescatto, P., Robinson, T., 2018. Horticultural performance and elemental nutrient concentrations on 'Fuji' grafted on apple rootstocks under New York State climatic conditions. Sci. Hortic. 227, 22–37.

Reig, G., Lordan, J., Miranda Sazo, M., Hoying, S., Fargione, M., Reginato, G., Donahue, D.J., Francescatto, P., Fazio, G., Robinson, T., 2019. Long-term performance of 'Gala', Fuji' and 'Honeycrisp' apple trees grafted on Geneva® rootstocks and trained to four production systems under New York State climatic conditions. Sci. Hortic. 244, 277–293.

Robinson, T., 2003a. Apple-Orchard Planting Systems. Apples; Botany, Production and Uses, DC Ferree and IJ Warrington. CABI publishing, Wallingford, Oxon, United Kingdom.

Robinson, T.L., Aldwinckle, H.S., Fazio, G., Holleran, T., 2003b. The Geneva series of apple rootstocks from Cornell: performance, disease resistance, and commercialization. Acta Hortic. 622, 513–520.

Robinson, T.L., 2007. Recent advances and future directions on orchard planting systems. Acta Hortic. 732, 367–381. https://doi.org/10.17660/ActaHortic.2007.732.57.

Robinson, T.L., DeMarree, A.M., Hoying, S.A., 2007a. An economic comparison of five high density apple planting systems. Acta Hortic. 732, 481–489. https://doi.org/10.17660/ActaHortic.2007.732.73.

Robinson, T., 2007b. Effect of tree density and tree shape on light interception, tree growth, yield and economic performance of apples. Acta Hortic. 732, 405–414.

Robinson, T., Hoying, S., Fazio, G., 2008a. Performance of Geneva® rootstocks in on-farm trials in New York State. Acta Hortic. 903, 249–255.

Robinson, T., Hoying, S., Reginato, G., 2008b. The tall spindle planting system: principles and performance. Acta Hortic. 903, 571–579.

Ucar, K., Palkovic, J., Engindeniz, S.J.J.A.F.U.U., 2016. Apple investment in Europe: a case study for Slovakia. J. Agric. Facul. Uludag Univ. 30, 152–157.

Willow Drive Nursery. 2020. Catalog and pricelists: 2020 catalog and fruit trees. Available at: http://www.willowdrive.com/home.

White, G.B., DeMarree, A., 1992. Economics of Apple Orchard Planting Systems.