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Estimated economic impact of fire blight on long-term orchard economic performance with susceptible and resistant rootstocks

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ABSTRACT

We estimated the economic impact of theoretical fire blight induced tree loss using data from two long-term field trials in NY State. An economic analysis of profitability using Net Present Value (NPV) was conducted with three cultivars, eleven rootstocks and four planting systems. The impact of fire blight was modeled in terms of both the severity of the disease and the year of infection. We considered a range of scenarios with different infection rates (10 %, 50 %, 80 % and 100 %) of all the trees planted and different timings when the infection took place including the 1st year (prior to production), 5th year, 10th year and the 15th year during the life cycle of an orchard. The analysis showed that the smallest impact of fire blight induced losses on lifetime NPV occurred when the fire blight infection and tree death occurred in year 1 and was greatest when infection and tree death occurred in year 10. If the infection occurred in year 15 then the losses in NPV were less. As expected, the analysis showed that a low percentage of tree loss due to fire blight at any given year of the orchard life resulted in a low impact on lifetime NPV while greater levels of infection and tree loss were associated with higher losses in NPV. The use of fire blight resistant rootstocks dramatically reduced the negative impact of fire blight induced tree losses on NPV. With susceptible rootstocks (M.9 and M.26), the reduction in NPV with high levels of tree infection was as high as 70 % which would render the planting unprofitable, while with resistant rootstocks the losses in NPV were lower (<30 %) and the orchard would still be profitable. High-density orchard systems like the Tall Spindle system had less sensitivity to fire blight induced losses than lower density systems. Cultivar also had an important effect on the level of fire blight induced losses of NPV. With a high priced cultivar like ‘Honeycrisp’ the percentage loss in NPV was less than with the lower priced cultivars like ‘Fuji’ and ‘Gala’.

1. Introduction

Fire blight (*Erwinia amylovora*) outbreaks have become more common and more severe in apple (Malus × domestica Borkh.) orchards in New York (USA) in recent years (Milkovich, 2022; Robbins, 2019). The pathogen caused significant economic distress for apple producers in 2012 in the Hudson Valley, in 2016 in the Champlain Lake Valley and Western New York (Aćimović et al., 2019, 2021; Robbins, 2019), and then again in 2020 and 2022 in Western New York. Damage estimates to producers from the 2016 epidemic exceed $16 million in the Champlain Lake Valley. These sudden fire blight outbreaks can cause over 50 % apple tree losses in young, recently planted orchards (Breth 2008). The most severe symptom behind tree death is the girdling effect of a fire blight canker on susceptible rootstock (Aćimović et al., 2023). Tree death occurs when the bacteria infect flowers on the scion and then the bacteria moves symptomless internally down the tree to the rootstock where the bacteria kills the rootstock cambium resulting in the death of the tree (Aldwinckle et al., 2004). Fire blight resistant rootstocks reduce or eliminate infection of the rootstock shank and subsequent tree death (Aldwinckle et al., 2004, Norelli et al., 2003, Russo et al., 2007)

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The use of fire blight resistant rootstocks has been shown to decrease the severity of the disease in susceptible scions (Jensen et al., 2011, 2012) possibly by changing the expression of genes during the infection (Baldo et al., 2011). The Geneva® rootstocks, developed by a partnership between Cornell University and the United States Department of Agriculture-Agricultural Research Service, were selected to increase resistance to fire blight (Aldwinckle et al., 2001; Fazio, et al., 2013; Norelli et al., 2003). Many traditional rootstocks are sensitive to fire blight (Malling 9 clones (M.9), Malling 26 (M.26), Ottawa 3 (O.3), etc.) resulting in the death of the tree once the rootstock is infected. Genetic resistance to *E. amylovora* was observed in wild apple species, and this natural resistance was utilized by conventional breeding to develop apple rootstocks genetically resistant to fire blight (Geneva (G) rootstocks (G.65, G.11, G.16, G.30, G.202, G.41, G.935, G.213, G.214, G.969, G.890, G.222 and G.210), Budagovsky 9 (B.9) and Vineland 1 (V.1)). The characteristics of these rootstocks have been described by Fazio and Robinson (2018). They have been extensively evaluated over the last 25 years. (Autio et al., 2020a, 2020b; Auvil et al., 2011; Marini et al., 2006; Robinson et al., 2007b, 2008). In addition to the Geneva® rootstocks Budagovsky 9 rootstock although not being resistant to fire blight has shown field tolerance with few tree deaths in the field (Ferree et al., 2002; LoGiudice et al., 2006). Older Malling rootstocks like M.7 also have shown field tolerance to fire blight (Russo et al., 2007).

Several studies have documented the economic advantage of adopting new rootstocks for improving fruit yields and economic performance (Lordan et al., 2018a, 2018b; 2019; Robinson et al., 2007a). The economic impact of using fire blight resistant rootstocks as a defense against fire blight induced tree loses was recently evaluated by Rickard et al. (2023) using hypothetical scenarios for yield and fruit quality. However, no one has yet evaluated the economic that impact of new fire blight resistant rootstocks which also impart greater tree survival under different levels of fire blight pressure using actual tree performance data. Previous economic analyses of orchard system performance have shown that fruit price and yield are the primary factors affecting long-term profitability of an orchard (DeMarree et al., 2003; Gallardo and Garming, 2017; Gonzalez, et al., 2022; Ho et al., 2024; Lordan, et al., 2018b, 2019; Robinson et al., 2007a; White and DeMarree 1992). Fire blight induced tree death has a direct impact on yield and thus on profitability. The purpose of this study was to use data from two experimental plantings to evaluate the economic benefits of nine disease-resistant rootstocks, two susceptible rootstocks in four planting systems across three apple cultivars ('Fuji', 'Gala', and 'Honeycrisp') when affected by different severity and frequency of fire blight induced tree deaths over the life span of an orchard. We have evaluated several scenarios of fire blight induced tree death and have modeled the economic consequences of using resistant rootstocks versus susceptible rootstocks using long-term field plot data of tree performance on various rootstocks and planting systems of different densities.

2. Materials and methods

2.1. Site description and experimental design

In 2006, two 1-ha replicated experiments were established at two commercial orchards in New York state, USA: Dressel Farm in southeastern New York State and VandeWalle Farm in Western, New York State. The trials compared four planting 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 traditional rootstocks included B.9, M.7EMLA (M.7), M.9T337 (M.9), and M.26EMLA (M.26). The Geneva® stocks included G.11, G.16, G.30, G.41, G.935 and CG. 4210. The four planting systems were Slender Pyramid (SP), Vertical Axis (VA), Slender Axis (SA) and Tall Spindle (TS) (Table 1). The details of the block locations, soil types and tree management protocols were published previously (Reig, et al., 2019).

Table 1
Orchard 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

Each experimental trial used a split-split plot randomized block design with three replicates. Within each block, the planting system was the main plot, the cultivar was the sub-plot, and the rootstock was the sub-sub-plot. Cultivar sub plots were whole rows while rootstock sub-sub plots were composed of a row section 12 m long with either thirteen trees for TS, ten trees for SA, seven trees for VA and five trees for SP. 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 varieties 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 planting systems were compared, but the various rootstocks were assigned unevenly across the four systems (Table 1).

Trees at the Dressel site were irrigated each year through drip lines and supported by a trellis system while the trees at the VandeWalle site were unirrigated. 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 during the spring and summer months for the Dressel site from 2006 to 2016 was 1000 mm and 990 mm at VandeWalle. Weekly rainfall averaged about 25 mm per week.

2.2. Yield, income and costs

Tree horticultural performance was evaluated for eleven years (2006–2016) after planting. Yield (kg) and the number of fruit were recorded annually from the second year (2007) onward. Average fruit size (weight) of the fruit was calculated from yield and fruit number. Annually, a 50 apple sample of representative fruits for each scion-rootstock-planting system combination was collected at harvest and then classified by color and size as described by Reig et al. (2019). From these data, we calculated a simulated packout for each scion-rootstock-planting system combination. A monetary value was assigned to each fruit size and quality category from the simulated packout using statewide average prices from the New York State apple industry in 2021 (Ho et al., 2024). The prices were highest for 'Honeycrisp' intermediate for 'Gala' and lowest for 'Fuji'. 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 analysis.

The details of the costs used in our economic analysis including tree costs, establishment costs, trellising costs, pruning and training costs, labor costs, management costs, overhead costs and costs for pest control, disease control, weed control, fertilization and chemical thinning were published previously (Ho et al., 2024).

2.3. Economic analysis

The parameters used in the Net Present Value (NPV) economic analysis were published previously (Ho et al., 2024). In summary, gross crop revenue was calculated by subtracting storage and packing related costs from total revenue (price multiplied by yield). Subsequently annual profit for each year was calculated by subtracting costs from gross crop revenue and then the annual profit was discounted using NPV for each cultivar, rootstock and orchard system over 20 years. The 20-year analysis included the pre-plant year and the next 20 years from planting. Cash returns for years 12–20 were estimated without observations but instead were predicted based on harvested quantities and prices between years 8–11; e.g., return in year 12 is the average of returns 8–12 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). The NPV values for each combination of cultivar, planting system and rootstock was designated as the baseline NPV.

2.4. Analysis of estimated economic impacts of fire blight

We modeled the impact of fire blight in terms of both the severity of the disease and the year of infection on cumulative NPV over the 20-year orchard life. A range of scenarios were considered with infection rates of 10 %, 50 %, 80 % and 100 % of all the trees planted and a range of timings when the infection took place including the 1st year (prior to production), 5th year, 10th year and the 15th year during the 20-year life cycle of an orchard. There were a total of 16 combinations for this hypothetical setting: 4 tree infection rates $\times$ 4 infection year timings. For the scenarios that included M.9 or M.26 rootstocks which are extremely susceptible to fire blight, we assumed that fire blight infection killed the tree due to rootstock infection and girdling requiring replanting of the tree the next year. The yield of an infected tree was assumed to be reduced by 100 % in the year of infection and then the newly replanted tree on a fire blight resistant rootstock was assumed to begin its yield development curve in a similar manner to the original tree but beginning the year after infection. Labor costs for tree pruning were increased by 50 % during the year of infection and subsequently the pruning costs of the replacement tree were assumed to be similar to the early years of the original tree.

The most notable assumption built into this modeling work is that resistant rootstocks (all Geneva® rootstocks, B.9 and M.7) protect trees from fire blight induced death after infection of the scion and the infection in the scion could be managed via pruning. In the scenarios we considered, infected trees on resistant rootstocks were pruned back (resulting in a 2-year slowdown in productivity). The yield of an infected tree on a resistant rootstock was assumed to be reduced by 50 % in the year of infection and by 50 % in the year following infection. The second year after infections yield was estimated to be 75 % of a non-infected tree after which yield was assumed to return to the normal production of a non-infected tree. Pruning costs of an infected tree were increased by 50 % during the year of infection but in subsequent years pruning costs returned to the pruning cost of the non-infected tree.

The calculated NPV's under each scenario were compared to the baseline NPV without fire blight and a percentage reduction in NPV was calculated for each scenario. This analysis of economic impact of fire blight allowed an evaluation the economic value of disease resistant rootstocks.

2.5. 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 planting system on 20-year NPV. Explanatory variables included 21 Planting System $\times$ Rootstock treatments as fixed factors, with replication and year as random factors. The statistical significance of treatment effects on the cumulative NPV for each cultivar at each trial location were estimated using Least Significant Difference method.

3. Results

3.1. Baseline NPV values

Cultivar, training system and rootstock all had significant effects on the baseline 20-year Net Present Value of Profits (NPV) (Tables 2 and 3 for the Dressel Farm and Tables 4 and 5 for the VandeWalle farm). Among cultivars, 'Honeycrisp' had significantly higher baseline profitability than 'Gala' while 'Fuji' had significantly lower profitability than 'Gala'. With 'Fuji' at the Dressel farm, cumulative NPV over 20-years ranged from a low of $6678 to $78,169 per hectare. With 'Gala' at the Dressel farm NPV varied from $11,435 to $153,343 per hectare. With 'Gala at the VandeWalle farm, NPV varied from $72,262 to $288,605. With 'Honeycrisp' at the VandeWalle farm NPV varied from $141,983 to $542,875. Among systems, baseline economic profitability over 20 years was greatest with the Tall Spindle system compared to the other lower density systems. Economic performance was mostly driven by planting density, regardless of the rootstock selection. 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 the G.16 rootstock in the Tall Spindle system, however, it was not significantly better than G.11 or M.9. For 'Gala' at the Dressel farm, the most profitable combination was G.11 in the Tall Spindle system but again it was not significantly better than several other rootstocks including G.16, G.41, M.9 or B.9. The most profitable combination with 'Gala' at the VandeWalle farm was G.41 in the Tall Spindle system 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 in the Tall Spindle system but it was not significantly better than G.11, G.16, G.41 or B.9.

3.2. Fire blight impact on orchard profitability

Fire blight infections of susceptible and resistant rootstocks reduced cumulative NPV for all cultivars, planting systems and rootstocks (Tables 2-5). However, the negative impact of fire blight infection on cumulative NPV was much greater for susceptible rootstocks than resistant rootstocks. A 10 % fire blight infection rate of trees generated the least amount of NPV losses while 50 %, 80 % and 100 % infection rate caused increasingly greater losses of NPV regardless of the year for which the fire blight event occurred. Furthermore, the magnitude of loss was least when the infection occurred in year 1 and was greatest when the infection occurred in year 10. If the fire blight infection occurred in year 15, the reduction in NPV was less than if the infection occurred in year 10 and similar to the losses if the infection occurred in year 5. Across the scenarios considered, the 100 % fire blight infection rate in year 10 led to the worst-case scenario for NPV while a 10 % infection rate in year 1 had the least impact on lifetime orchard profitability.

There was a significant interaction of cultivar, training system and rootstock on the level of NPV loss caused by fire blight infection. Next, we highlight the main effects of cultivar, planting system and rootstocks before addressing the important interactions.

When results were averaged over all systems and rootstocks at each location, fire blight induced losses in NPV were greater at the Dressel farm than at the VandeWalle farm (Fig. 1). At the Dressel farm, the worst case scenario was with high infection rate at year 10 which resulted in approximately a 60 % reduction in lifetime NPV while at the VandeWalle farm the worst case scenario at year 10 resulted in approximate loss of 25 % in NPV. When comparing the performance of the two

Table 2
Effects of a fire blight infection in year 1, 5, 10 or 15 on NPV of 20-year net returns for 'Fuji' at the Dressel Farm of 4 training systems (SP=Slender Pyramid, VA=Vertical Axis, SA=Slender Axis and TS=Tall Spindle) on several rootstocks in New York State USA.

			Percentatge loss of NPV							
			Year 1				Year 5			
System	Stock	0 %	10 %	50 %	80 %	100 %	10 %	50 %	80 %	100 %
SP	G.30	31,621 bcdef	-1.3 % a	-6.7 % a	-10.6 % a	-13.3 % a	-3.1 % a	-15.5 % a	-24.9 % a	-31.1 % a
SP	G.210	44,208 abcdef	-0.4 % a	-2.1 % a	-3.4 % a	-4.3 % a	-1.4 % a	-7.2 % a	-11.5 % a	-14.4 % a
SP	G.935	10,801 ef	-2.4 % ab	-12.1 % ab	-19.4 % ab	-24.3 % ab	-26.8 % b	-134.1 % b	-214.6 % b	-268.3 % b
SP	M.7	19,026 def	-1.4 % a	-7.1 % a	-11.3 % a	-14.2 % a	-5.8 % a	-28.8 % a	-46.1 % a	-57.6 % a
SP	M.26	21,263 def	-5.8 % bc	-28.9 % bc	-46.3 % bc	-57.9 % bc	-5.8 % a	-28.8 % a	-46.1 % a	-57.6 % a
VA	G.16	71,096 ab	-0.4 % a	-2.0 % a	-3.2 % a	-4.0 % a	-1.5 % a	-7.6 % a	-12.1 % a	-15.1 % a
VA	G.41	42,945 abcdef	-0.2 % a	-1.1 % a	-1.7 % a	-2.1 % a	-2.0 % a	-9.9 % a	-15.8 % a	-19.8 % a
VA	G.935	49,762 abcde	-0.3 % a	-1.7 % a	-2.7 % a	-3.3 % a	-2.7 % a	-13.6 % a	-21.7 % a	-27.1 % a
VA	M.9	34,502 bcdef	-6.8 % c	-34.0 % c	-54.5 % c	-68.1 % c	-8.0 % a	-40.2 % a	-64.3 % a	-80.4 % a
VA	M.26	40,839 abcdef	-5.7 % bc	-28.3 % bc	-45.4 % bc	-56.7 % bc	-12.8 % ab	-63.9 % ab	-102.2 % ab	-127.7 % ab
SA	G.11	43,543 abcdef	-0.6 % a	-3.2 % a	-5.2 % a	-6.5 % a	-2.4 % a	-12.0 % a	-19.1 % a	-23.9 % a
SA	G.16	54,745 abcd	-0.5 % a	-2.3 % a	-3.7 % a	-4.7 % a	-1.9 % a	-9.5 % a	-15.1 % a	-18.9 % a
SA	G.41	35,305 bcdef	-0.2 % a	-1.2 % a	-1.9 % a	-2.3 % a	-2.8 % a	-14.0 % a	-22.5 % a	-28.1 % a
SA	CG.4210	30,591 cdef	-0.7 % a	-3.5 % a	-5.6 % a	-7.0 % a	-3.2 % a	-16.1 % a	-25.8 % a	-32.2 % a
SA	B.9	29,599 cdef	-0.7 % a	-3.4 % a	-5.5 % a	-6.9 % a	-5.9 % a	-29.4 % a	-47.1 % a	-58.9 % a
SA	M.9	63,205 abc	-5.7 % bc	-28.5 % bc	-45.7 % bc	-57.1 % bc	-5.3 % a	-26.7 % a	-42.7 % a	-53.4 % a
TS	G.11	49,882 abcde	-1.0 % a	-5.1 % a	-8.1 % a	-10.1 % a	-3.1 % a	-15.6 % a	-25.0 % a	-31.3 % a
TS	G.16	77,960 a	-0.7 % a	-3.7 % a	-5.9 % a	-7.4 % a	-1.8 % a	-9.2 % a	-14.7 % a	-18.4 % a
TS	G.41	18,218 def	-5.1 % bc	-25.4 % bc	-40.6 % bc	-50.7 % bc	-16.2 % ab	-81.2 % ab	-129.9 % ab	-162.3 % ab
TS	B.9	6,628 f	-2.5 % ab	-12.3 % ab	-19.7 % ab	-24.7 % ab	-6.8 % a	-33.8 % a	-54.1 % a	-67.6 % a
TS	M.9	43,243 abcdef	-8.5 % c	-42.3 % c	-67.7 % c	-84.7 % c	-5.4 % a	-26.9 % a	-43.1 % a	-53.9 % a
	LSD	39,557	3.6 %	17.8 %	28.5 %	35.7 %	16.5 %	82.5 %	132.0 %	165.0 %
			Year 10				Year 15			
System	Stock	0%	10.0 %	50.0 %	80.0 %	100.0 %	10.0 %	50.0 %	80.0 %	100.0 %
SP	G.30	31,621 bcdef	-9.7 % a	-48.3 % a	-77.3 % a	-96.6 % a	-8.5 % a	-42.7 % a	-68.4 % a	-85.5 % a
SP	G.210	44,208 abcdef	-2.5 % a	-12.6 % a	-20.1 % a	-25.2 % a	-1.9 % a	-9.3 % a	-14.9 % a	-18.7 % a
SP	G.935	10,801 ef	-56.2 % b	-281.1 % b	-449.7 % b	-562.2 % b	-40.8 % b	-204.2 % b	-326.7 % b	-408.3 % b
SP	M.7	19,026 def	-6.1 % a	-30.3 % a	-48.4 % a	-60.5 % a	-5.5 % a	-27.5 % a	-44.0 % a	-55.0 % a
SP	M.26	21,263 def	-7.8 % a	-38.8 % a	-62.1 % a	-77.6 % a	-5.7 % a	-28.4 % a	-45.5 % a	-56.9 % a
VA	G.16	71,096 ab	-1.8 % a	-8.8 % a	-14.0 % a	-17.5 % a	-1.5 % a	-7.3 % a	-11.7 % a	-14.6 % a
VA	G.41	42,945 abcdef	-2.8 % a	-13.8 % a	-22.0 % a	-27.5 % a	-1.8 % a	-9.2 % a	-14.7 % a	-18.3 % a
VA	G.935	49,762 abcde	-2.6 % a	-12.8 % a	-20.4 % a	-25.5 % a	-2.1 % a	-10.5 % a	-16.7 % a	-20.9 % a
VA	M.9	34,502 bcdef	-11.1 % a	-55.5 % a	-88.7 % a	-110.9 % a	-6.5 % a	-32.5 % a	-52.0 % a	-64.9 % a
VA	M.26	40,839 abcdef	-14.0 % a	-70.0 % a	-112.0 % a	-140.0 % a	-9.9 % a	-49.7 % a	-79.6 % a	-99.5 % a
SA	G.11	43,543 abcdef	-2.1 % a	-10.7 % a	-17.1 % a	-21.3 % a	-2.2 % a	-11.2 % a	-17.9 % a	-22.3 % a
SA	G.16	54,745 abcd	-1.9 % a	-9.6 % a	-15.4 % a	-19.2 % a	-1.5 % a	-7.4 % a	-11.8 % a	-14.8 % a
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SA	B.9	29,599 cdef	-9.6 % a	-48.0 % a	-76.7 % a	-95.9 % a	-10.3 % a	-51.3 % a	-82.1 % a	-102.6 % a
SA	M.9	63,205 abc	-8.1 % a	-40.4 % a	-64.6 % a	-80.8 % a	-4.7 % a	-23.4 % a	-37.4 % a	-46.7 % a
TS	G.11	49,882 abcde	-2.0 % a	-9.9 % a	-15.8 % a	-19.7 % a	-1.5 % a	-7.5 % a	-12.0 % a	-15.0 % a
TS	G.16	77,960 a	-1.8 % a	-9.1 % a	-14.5 % a	-18.1 % a	-1.4 % a	-7.2 % a	-11.6 % a	-14.5 % a
TS	G.41	18,218 def	-11.3 % a	-56.4 % a	-90.3 % a	-112.9 % a	-9.0 % a	-45.1 % a	-72.1 % a	-90.2 % a
TS	B.9	6,628 f	-3.9 % a	-19.5 % a	-31.1 % a	-38.9 % a	-4.4 % a	-22.0 % a	-35.2 % a	-43.9 % a
TS	M.9	43,243 abcdef	-7.4 % a	-37.1 % a	-59.3 % a	-74.1 % a	-4.5 % a	-22.4 % a	-35.9 % a	-44.8 % a
	LSD	39,557	31.5 %	157.4 %	251.8 %	314.8 %	23.3 %	116.4 %	186.3 %	232.9 %

*Values under each scenario represent the percentage change from the baseline NPV which is calculated based on actual yield at the trial. Green indicates a reduction of NPV less than 15 %, yellow indicates a reduction of NPV between 15 and 50 %, and red indicates a reduction of NPV greater than 50 %. Column 0 % green indicates a higher NPV, followed by orange, yellow and lower red.

cultivars from the trial at the Dressel farm, NPV with 'Gala' was greater than 'Fuji' across the various fire blight infection scenarios. At the VandeWalle farm, the reductions in NPV due to fire blight infection across all fire blight scenarios for 'Gala' were less than those at the Dressel farm. The magnitude of NPV losses due to fire blight with 'Honeycrisp' were less severe compared to either 'Gala' or 'Fuji'. For each cultivar, losses in NPV showed the same pattern with respect to the year in which infection occurred where the smallest losses from fire blight infection occurred in year one with increasing losses at year 5 and the greatest losses at year 10 followed by lesser losses in year 15.

Among training systems, (averaged over all cultivars and rootstocks) the NPV losses under the Tall Spindle or the Slender Axis system, regardless of the infection year or the percentage of tree infected, were much smaller than losses with the Vertical Axis, or the Slender Pyramid systems (Fig. 2). The maximum reduction of lifetime NPV from fire blight infection with the 2 high density systems was 25 % while with the Vertical Axis system the maximum loss was 60 % and the maximum loss with the Slender Pyramid systems was 50 %.

Among rootstocks, (averaged over all cultivars and systems) the fire blight susceptible rootstocks (M.9 and M.26) had much greater losses in NPV due to fire blight infection than the resistant rootstocks (Geneva's®, B.9 and M.7) (Fig. 3). With a low percentage of infection (10

Table 3
Effects of a fire blight infection in year 1, 5, 10 or 15 on NPV of 20-year net returns for 'Gala' at the Dressel Farm of 4 training systems (SP=Slender Pyramid, VA=Vertical Axis, SA=Slender Axis and TS=Tall Spindle) on several rootstocks in New York State USA..

			Percentatge loss of NPV							
			Year 1				Year 5			
System	Stock	0 %	10 %	50 %	80 %	100 %	10 %	50 %	80 %	100 %
SP	G.30	43,022 fghi	-0.4 % ab	-2.1 % ab	-3.3 % ab	-4.2 % ab	-2.0 % a	-10.2 % a	-16.3 % a	-20.4 % a
SP	G.210	49,088 efghi	-0.3 % a	-1.7 % a	-2.8 % a	-3.4 % a	-1.7 % a	-8.5 % a	-13.7 % a	-17.1 % a
SP	G.935	11,435 i	-1.0 % ab	-5.0 % ab	-8.0 % ab	-10.0 % ab	-9.5 % ab	-47.5 % ab	-76.0 % ab	-95.0 % ab
SP	M.7	53,072 efghi	-0.1 % a	-0.4 % a	-0.6 % a	-0.8 % a	-2.8 % ab	-14.2 % ab	-22.8 % ab	-28.5 % ab
SP	M.26	38,508 ghi	-9.1 % d	-45.3 % d	-72.5 % d	-90.6 % d	-22.0 % c	-109.8 % c	-175.7 % c	-219.7 % c
VA	G.16	56,887 efghi	-0.3 % a	-1.3 % a	-2.0 % a	-2.5 % a	-1.5 % a	-7.7 % a	-12.4 % a	-15.5 % a
VA	G.41	14,146 hi	-0.4 % a	-2.0 % a	-3.2 % a	-4.0 % a	-3.6 % ab	-18.1 % ab	-28.9 % ab	-36.2 % ab
VA	G.935	88,153 cdefg	-0.7 % ab	-3.4 % ab	-5.4 % ab	-6.8 % ab	-8.7 % ab	-43.4 % ab	-69.4 % ab	-86.8 % ab
VA	M.9	62,295 efghi	-3.4 % abc	-17.1 % abc	-27.4 % abc	-34.2 % abc	-7.3 % ab	-36.5 % ab	-58.5 % ab	-73.1 % ab
VA	M.26	75,130 defg	-3.8 % abc	-19.1 % abc	-30.6 % abc	-38.2 % abc	-9.1 % ab	-45.3 % ab	-72.5 % ab	-90.6 % ab
SA	G.11	73,591 defg	-0.2 % a	-0.9 % a	-1.4 % a	-1.7 % a	-2.5 % ab	-12.5 % ab	-19.9 % ab	-24.9 % ab
SA	G.16	103,831 abcde	-0.3 % a	-1.7 % a	-2.7 % a	-3.4 % a	-1.8 % a	-8.8 % a	-14.1 % a	-17.7 % a
SA	G.41	90,987 bcdefg	-0.4 % ab	-2.2 % ab	-3.5 % ab	-4.4 % ab	-2.6 % ab	-12.9 % ab	-20.7 % ab	-25.9 % ab
SA	CG.4210	46,904 efghi	-0.3 % a	-1.6 % a	-2.6 % a	-3.2 % a	-2.8 % ab	-14.1 % ab	-22.5 % ab	-28.2 % ab
SA	B.9	70,337 defgh	-0.3 % a	-1.4 % a	-2.2 % a	-2.8 % a	-2.4 % ab	-12.1 % ab	-19.4 % ab	-24.3 % ab
SA	M.9	70,974 defgh	-6.8 % cd	-34.0 % cd	-54.3 % cd	-67.9 % cd	-11.5 % b	-57.6 % b	-92.2 % b	-115.3 % b
TS	G.11	139,935 abc	-0.1 % a	-0.6 % a	-1.0 % a	-1.3 % a	-2.6 % ab	-13.2 % ab	-21.1 % ab	-26.4 % ab
TS	G.16	147,341 ab	-0.2 % a	-1.0 % a	-1.5 % a	-1.9 % a	-1.1 % a	-5.4 % a	-8.6 % a	-10.8 % a
TS	G.41	153,343 a	-0.3 % a	-1.4 % a	-2.3 % a	-2.9 % a	-2.8 % ab	-14.2 % ab	-22.7 % ab	-28.3 % ab
TS	B.9	97,642 abcdef	-0.4 % ab	-2.1 % ab	-3.3 % ab	-4.2 % ab	-2.2 % ab	-11.1 % ab	-17.7 % ab	-22.2 % ab
TS	M.9	128,546 abcd	-4.4 % bc	-21.9 % bc	-35.0 % bc	-43.8 % bc	-6.1 % ab	-30.4 % ab	-48.6 % ab	-60.7 % ab
	LSD	58,586	4.0 %	19.8 %	31.7 %	39.6 %	9.3 %	46.6 %	74.6 %	93.3 %

			Year 10				Year 15			
System	Stock	0 %	10 %	50 %	80 %	100 %	10 %	50 %	80 %	100 %
SP	G.30	43,022 fghi	-1.4 % a	-7.1 % a	-11.4 % a	-14.2 % a	-1.7 % ab	-8.6 % ab	-13.7 % ab	-17.1 % ab
SP	G.210	49,088 efghi	-1.6 % a	-7.9 % a	-12.6 % a	-15.8 % a	-1.7 % ab	-8.5 % ab	-13.6 % ab	-17.0 % ab
SP	G.935	11,435 i	-6.4 % ab	-32.0 % ab	-51.3 % ab	-64.1 % ab	-7.0 % b	-35.2 % b	-56.3 % b	-70.4 % b
SP	M.7	53,072 efghi	-1.6 % a	-8.2 % a	-13.1 % a	-16.4 % a	-1.6 % ab	-8.2 % ab	-13.1 % ab	-16.3 % ab
SP	M.26	38,508 ghi	-19.0 % c	-94.8 % c	-151.7 % c	-189.6 % c	-15.5 % c	-77.6 % c	-124.2 % c	-155.3 % c
VA	G.16	56,887 efghi	-1.5 % a	-7.6 % a	-12.2 % a	-15.3 % a	-1.7 % ab	-8.5 % ab	-13.6 % ab	-17.1 % ab
VA	G.41	14,146 hi	-1.6 % a	-7.8 % a	-12.5 % a	-15.7 % a	-1.7 % ab	-8.7 % ab	-13.9 % ab	-17.4 % ab
VA	G.935	88,153 cdefg	-1.0 % a	-5.1 % a	-8.2 % a	-10.2 % a	-1.2 % a	-5.8 % a	-9.3 % a	-11.7 % a
VA	M.9	62,295 efghi	-4.8 % ab	-24.0 % ab	-38.3 % ab	-47.9 % ab	-4.8 % ab	-23.9 % ab	-38.2 % ab	-47.7 % ab
VA	M.26	75,130 defg	-7.0 % ab	-35.2 % ab	-56.3 % ab	-70.4 % ab	-6.1 % ab	-30.3 % ab	-48.5 % ab	-60.6 % ab
SA	G.11	73,591 defg	-1.8 % a	-8.9 % a	-14.2 % a	-17.7 % a	-1.9 % ab	-9.3 % ab	-14.9 % ab	-18.7 % ab
SA	G.16	103,831 abcde	-1.1 % a	-5.6 % a	-9.0 % a	-11.2 % a	-1.3 % a	-6.3 % a	-10.0 % a	-12.5 % a
SA	G.41	90,987 bcdefg	-1.4 % a	-6.8 % a	-10.8 % a	-13.5 % a	-1.3 % a	-6.4 % a	-10.2 % a	-12.7 % a
SA	CG.4210	46,904 efghi	-2.2 % a	-10.9 % a	-17.4 % a	-21.7 % a	-2.2 % ab	-11.1 % ab	-17.7 % ab	-22.1 % ab
SA	B.9	70,337 defgh	-1.5 % a	-7.4 % a	-11.9 % a	-14.9 % a	-1.6 % ab	-7.8 % ab	-12.5 % ab	-15.7 % ab
SA	M.9	70,974 defgh	-10.6 % b	-53.1 % b	-84.9 % b	-106.2 % b	-7.1 % b	-35.7 % b	-57.1 % b	-71.4 % b
TS	G.11	139,935 abc	-1.1 % a	-5.5 % a	-8.9 % a	-11.1 % a	-1.2 % a	-5.8 % a	-9.3 % a	-11.6 % a
TS	G.16	147,341 ab	-1.0 % a	-4.8 % a	-7.7 % a	-9.6 % a	-1.2 % a	-5.9 % a	-9.5 % a	-11.8 % a
TS	G.41	153,343 a	-0.8 % a	-4.1 % a	-6.5 % a	-8.1 % a	-0.8 % a	-4.2 % a	-6.8 % a	-8.4 % a
TS	B.9	97,642 abcdef	-1.3 % a	-6.5 % a	-10.4 % a	-13.0 % a	-1.3 % a	-6.5 % a	-10.4 % a	-13.0 % a
TS	M.9	128,546 abcd	-3.0 % a	-15.0 % a	-24.0 % a	-30.0 % a	-3.5 % ab	-17.5 % ab	-28.0 % ab	-34.9 % ab
	LSD	58,586	7.1 %	35.3 %	56.4 %	70.5 %	5.7 %	28.6 %	45.7 %	57.1 %

* Values under each scenario represent the percentage change from the baseline NPV which is calculated based on actual yield of the trial. Green indicates a reduction of NPV less than 15 %, yellow indicates a reduction of NPV between 15 and 50 %, and red indicates a reduction of NPV greater than 50 %. Column 0 % green indicates a higher NPV, followed by orange, yellow and lower red.

%) the worst case scenario with the resistant rootstocks was a 3 % reduction in NPV and with the susceptible stocks there was a 7 % reduction in NPV. With a 50 % infection rate the susceptible stocks showed a worst case scenario of a 35 % reduction in NPV, while the resistant stocks showed only a 15 % reduction in NPV. With a 100 % infection rate the susceptible stocks showed a worst case scenario of a 70 % reduction in NPV while the resistant stocks showed only a 30 % reduction in NPV.

The significant interaction of cultivar, planting system and rootstock was caused by a number of inconsistencies in the performance of individual rootstocks. G.41 rootstock was among the group of highest NPV in the TS system with 'Gala' (at both locations) and with 'Honeycrisp' at the VandeWalle farm but had the lowest NPV with 'Fuji' in the Tall Spindle, at the Dressel farm (Tables 2-5). B.9 also showed tremendous inconsistency with high NPV in the Tall Spindle systems with 'Honeycrisp' at the VandeWalle farm 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 the Dressel farm. G.935, G.16, M.9, M.7 and M.26 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 the VandeWalle farm. The inconsistencies in NPV outlined above

Table 4
Effects of a fire blight infection in year 1, 5, 10 or 15 on NPV of 20-year net returns for 'Gala' at the VandeWalle Farm of 4 training systems (SP=Slender Pyramid, VA=Vertical Axis, SA=Slender Axis and TS=Tall Spindle) on several rootstocks in New York State USA..

			Percentatge loss of NPV							
			Year 1				Year 5			
System	**Stock**	**0 %**	**10 %**	**50 %**	**80 %**	**100 %**	**10 %**	**50 %**	**80 %**	**100 %**
SP	G.30	126,166 fghi	-0.2 % a	-1.0 % a	-1.6 % a	-1.9 % a	-0.8 % a	-3.9 % a	-6.3 % a	-7.8 % a
SP	G.210	72,262 i	-0.6 % a	-2.8 % a	-4.4 % a	-5.5 % a	-1.1 % ab	-5.4 % ab	-8.6 % ab	-10.7 % ab
SP	G.935	127,524 fghi	-0.1 % a	-0.7 % a	-1.1 % a	-1.4 % a	-0.7 % a	-3.7 % a	-5.9 % a	-7.4 % a
SP	M.7	150,849 efgh	-0.1 % a	-0.6 % a	-0.9 % a	-1.1 % a	-1.0 % ab	-4.8 % ab	-7.7 % ab	-9.6 % ab
SP	M.26	86,508 hi	-2.5 % d	-12.5 % d	-20.0 % d	-25.0 % d	-6.4 % e	-31.9 % e	-51.1 % e	-63.8 % e
VA	G.16	103,418 ghi	-0.3 % a	-1.3 % a	-2.1 % a	-2.6 % a	-1.3 % ab	-6.3 % ab	-10.0 % ab	-12.6 % ab
VA	G.41	139,352 fghi	-0.2 % a	-0.9 % a	-1.4 % a	-1.8 % a	-1.1 % ab	-5.7 % ab	-9.1 % ab	-11.4 % ab
VA	G.935	192,029 cdef	-0.1 % a	-0.6 % a	-0.9 % a	-1.2 % a	-1.0 % ab	-4.9 % ab	-7.8 % ab	-9.8 % ab
VA	M.9	166,271 defg	-1.9 % bc	-9.6 % bc	-15.4 % bc	-19.3 % bc	-5.2 % d	-25.8 % d	-41.3 % d	-51.6 % d
VA	M.26	127,605 fghi	-2.5 % d	-12.5 % d	-20.0 % d	-25.0 % d	-6.0 % e	-30.2 % e	-48.4 % e	-60.5 % e
SA	G.11	216,029 abcde	-0.2 % a	-0.9 % a	-1.4 % a	-1.7 % a	-1.2 % ab	-6.0 % ab	-9.6 % ab	-11.9 % ab
SA	G.16	231,682 abcd	-0.2 % a	-0.9 % a	-1.5 % a	-1.8 % a	-1.2 % ab	-6.1 % ab	-9.8 % ab	-12.2 % ab
SA	G.41	276,362 ab	-0.1 % a	-0.7 % a	-1.1 % a	-1.4 % a	-1.2 % ab	-5.8 % ab	-9.3 % ab	-11.7 % ab
SA	CG.4210	246,196 abc	-0.1 % a	-0.6 % a	-1.0 % a	-1.3 % a	-1.1 % ab	-5.3 % ab	-8.5 % ab	-10.7 % ab
SA	B.9	221,034 abcde	-0.2 % a	-0.9 % a	-1.5 % a	-1.8 % a	-1.1 % ab	-5.3 % ab	-8.4 % ab	-10.5 % ab
SA	M.9	288,605 a	-1.7 % b	-8.5 % b	-13.6 % b	-17.0 % b	-3.9 % c	-19.5 % c	-31.3 % c	-39.1 % c
TS	G.11	267,953 ab	-0.2 % a	-1.1 % a	-1.8 % a	-2.2 % a	-1.2 % ab	-6.2 % ab	-9.9 % ab	-12.4 % ab
TS	G.16	214,212 bcde	-0.3 % a	-1.6 % a	-2.5 % a	-3.1 % a	-1.4 % b	-7.0 % b	-11.1 % b	-13.9 % b
TS	G.41	279,735 ab	-0.2 % a	-1.1 % a	-1.8 % a	-2.2 % a	-1.1 % ab	-5.3 % ab	-8.6 % ab	-10.7 % ab
TS	B.9	254,811 abc	-0.2 % a	-0.9 % a	-1.5 % a	-1.9 % a	-1.0 % ab	-5.2 % ab	-8.4 % ab	-10.5 % ab
TS	M.9	254,324 abc	-2.3 % cd	-11.5 % cd	-18.3 % cd	-22.9 % cd	-4.6 % d	-23.2 % d	-37.1 % d	-46.4 % d
	LSD	74,271	0.4 %	2.2 %	3.5 %	4.4 %	0.6 %	3.0 %	4.8 %	6.0 %
			Year 10				Year 15			
System	**Stock**	**0 %**	**10 %**	**50 %**	**80 %**	**100 %**	**10 %**	**50 %**	**80 %**	**100 %**
SP	G.30	126,166 fghi	-1.2 % ab	-6.1 % ab	-9.8 % b	-12.3 % b	-1.2 % a	-5.8 % a	-9.4 % a	-11.7 % a
SP	G.210	72,262 i	-2.0 % bc	-9.9 % bc	-15.8 % bc	-19.8 % bc	-2.1 % b	-10.6 % b	-16.9 % b	-21.1 % b
SP	G.935	127,524 fghi	-1.1 % ab	-5.4 % ab	-8.7 % ab	-10.9 % ab	-1.1 % a	-5.7 % a	-9.1 % a	-11.4 % a
SP	M.7	150,849 efgh	-1.1 % ab	-5.4 % ab	-8.7 % ab	-10.9 % ab	-1.0 % a	-5.1 % a	-8.1 % a	-10.1 % a
SP	M.26	86,508 hi	-5.6 % f	-28.0 % f	-44.7 % f	-55.9 % f	-4.8 % f	-24.1 % f	-38.6 % f	-48.3 % f
VA	G.16	103,418 ghi	-1.0 % a	-5.0 % a	-8.0 % a	-10.0 % a	-1.2 % a	-5.9 % a	-9.4 % a	-11.7 % a
VA	G.41	139,352 fghi	-0.9 % a	-4.7 % a	-7.6 % a	-9.5 % a	-1.0 % a	-5.2 % a	-8.3 % a	-10.4 % a
VA	G.935	192,029 cdef	-1.0 % a	-4.8 % a	-7.6 % a	-9.5 % a	-1.0 % a	-5.0 % a	-8.1 % a	-10.1 % a
VA	M.9	166,271 defg	-4.0 % e	-19.8 % e	-31.7 % e	-39.7 % e	-3.6 % de	-17.8 % de	-28.5 % de	-35.6 % de
VA	M.26	127,605 fghi	-4.6 % ef	-23.2 % ef	-37.0 % ef	-46.3 % e	-4.1 % e	-20.3 % e	-32.6 % e	-40.7 % e
SA	G.11	216,029 abcde	-0.5 % a	-2.7 % a	-4.2 % a	-5.3 % a	-1.0 % a	-5.0 % a	-8.0 % a	-10.0 % a
SA	G.16	231,682 abcd	-0.6 % a	-2.8 % a	-4.4 % a	-5.6 % a	-0.9 % a	-4.4 % a	-7.0 % a	-8.7 % a
SA	G.41	276,362 ab	-0.4 % a	-2.0 % a	-3.2 % a	-4.0 % a	-0.9 % a	-4.3 % a	-6.9 % a	-8.7 % a
SA	CG.4210	246,196 abc	-0.5 % a	-2.4 % a	-3.9 % a	-4.8 % a	-0.9 % a	-4.7 % a	-7.5 % a	-9.4 % a
SA	B.9	221,034 abcde	-0.5 % a	-2.4 % a	-3.9 % a	-4.9 % a	-1.0 % a	-4.8 % a	-7.7 % a	-9.6 % a
SA	M.9	288,605 a	-2.6 % cd	-13.1 % cd	-20.9 % cd	-26.1 % cd	-2.5 % bc	-12.6 % bc	-20.2 % bc	-25.3 % bc
TS	G.11	267,953 ab	-0.4 % a	-2.1 % a	-3.3 % a	-4.2 % a	-0.9 % a	-4.5 % a	-7.2 % a	-9.0 % a
TS	G.16	214,212 bcde	-0.5 % a	-2.6 % a	-4.2 % a	-5.2 % a	-0.9 % a	-4.6 % a	-7.4 % a	-9.2 % a
TS	G.41	279,735 ab	-0.5 % a	-2.3 % a	-3.7 % a	-4.7 % a	-0.9 % a	-4.4 % a	-7.0 % a	-8.8 % a
TS	B.9	254,811 abc	-0.5 % a	-2.5 % a	-4.0 % a	-5.0 % a	-0.9 % a	-4.6 % a	-7.3 % a	-9.1 % a
TS	M.9	254,324 abc	-3.0 % d	-14.9 % d	-23.8 % d	-29.8 % d	-3.0 % cd	-15.0 % cd	-23.9 % cd	-29.9 % cd
	LSD	74,271	1.0 %	4.8 %	7.7 %	9.6 %	0.7 %	3.5 %	5.6 %	7.0 %

* Values under each scenario represent the percentage change from the baseline NPV which is calculated based on actual yield of the trial. Green indicates a reduction of NPV less than 15 %, yellow indicates a reduction of NPV between 15 and 50 %, and red indicates a reduction of NPV greater than 50 %. Column 0 % green indicates a higher NPV, followed by orange, yellow and lower red.

resulted in anomalies in the percentage reduction in NPV due to fire blight with some rootstock and system combinations especially with 'Fuji'. In Table 2 which presents the 'Fuji' results, the number of fire blight induced losses of greater than 50 % (red cells) is scattered through all the systems and several are in the high density Tall Spindle system. However, with 'Gala' at the Dressel Farm (Table 3) or the two cultivars at the VandeWalle farm (Tables 4 and 5) there are not severe losses in the high density systems. Because of the inconsistencies of the NPV performance of some rootstock and system combinations, our conclusion is driven from the results concerning the main effects of cultivar, system and rootstock selection in the presence of fire blight.

4. Discussion

4.1. Validity of assumptions

The primary assumption behind our work is that fire blight infection of the scion results in tree death when the rootstock is highly susceptible to fire blight as are M.9 and M.26. This assumption is supported by the work of Aldwinckle et al. (2004) who showed that the fire blight bacteria once inside the plant can move symptomless down the plant to the rootstock which if susceptible causes the death of the rootstock cambium and girdling of the tree followed by subsequent tree death. This result was demonstrated in grafted plants by Aldwinckle et al. (2001); Norelli et al. (2003); and Russo et al. (2007). In all three studies artificial infection of the scion with fire blight bacteria resulted in tree death of

Table 5
Effects of a fire blight infection in year 1, 5, 10 or 15 on NPV of 20-year net returns for 'Honeycrisp' at the VandeWalle Farm of 4 training systems (SP=Slender Pyramid, VA=Vertical Axis, SA=Slender Axis and TS=Tall Spindle) on several rootstocks in New York State USA..

			Percentatge loss of NPV							
			Year 1				Year 5			
System	Stock	0 %	10 %	50 %	80 %	100 %	10 %	50 %	80 %	100 %
SP	G.30	228,093 ghi	-0.2 % bcde	-0.9 % bcde	-1.5 % bcde	-1.9 % bcde	-0.9 % ab	-4.7 % ab	-7.5 % ab	-9.4 % ab
SP	G.210	246,906 ghi	-0.2 % bcde	-0.9 % bcde	-1.5 % bcde	-1.9 % bcde	-0.9 % a	-4.3 % a	-6.9 % a	-8.6 % a
SP	G.935	141,983 i	-0.2 % de	-1.2 % de	-2.0 % de	-2.5 % de	-1.3 % abcd	-6.7 % abcd	-10.7 % abcd	-13.4 % abcd
SP	M.7	288,754 efgh	-0.1 % abc	-0.5 % abc	-0.9 % abc	-1.1 % abc	-1.1 % abc	-5.5 % abc	-8.9 % abc	-11.1 % abc
SP	M.26	287,221 fgh	-1.4 % f	-6.9 % f	-11.0 % f	-13.8 % f	-3.7 % e	-18.5 % e	-29.5 % e	-36.9 % e
VA	G.16	201,398 hi	-0.3 % e	-1.4 % e	-2.3 % e	-2.8 % e	-1.4 % bcd	-7.0 % bcd	-11.2 % bcd	-14.0 % bcd
VA	G.41	314,625 defgh	-0.1 % abc	-0.5 % abc	-0.7 % abc	-0.9 % abc	-1.0 % abc	-5.2 % abc	-8.3 % abc	-10.3 % abc
VA	G.935	277,233 ghi	-0.1 % abcd	-0.7 % abcd	-1.2 % abcd	-1.5 % abcd	-1.0 % abc	-5.2 % abc	-8.2 % abc	-10.3 % abc
VA	M.9	351,720 bcdefg	-1.4 % f	-6.8 % f	-10.9 % f	-13.7 % f	-4.1 % e	-20.4 % e	-32.6 % e	-40.8 % e
VA	M.26	431,967 abcd	-1.3 % f	-6.6 % f	-10.6 % f	-13.3 % f	-3.9 % e	-19.4 % e	-31.0 % e	-38.7 % e
SA	G.11	420,934 abcdef	-0.2 % abcd	-0.8 % abcd	-1.2 % abcd	-1.5 % abcd	-1.1 % abc	-5.4 % abc	-8.7 % abc	-10.9 % abc
SA	G.16	458,325 abc	-0.2 % cde	-1.0 % cde	-1.6 % cde	-2.0 % cde	-1.2 % abc	-5.9 % abc	-9.4 % abc	-11.8 % abc
SA	G.41	430,382 abcde	-0.1 % a	-0.3 % a	-0.4 % a	-0.5 % a	-1.1 % abc	-5.5 % abc	-8.8 % abc	-11.0 % abc
SA	CG.4210	249,413 ghi	-0.1 % abcd	-0.7 % abcd	-1.2 % abcd	-1.4 % abcd	-1.5 % cd	-7.5 % d	-12.0 % cd	-15.0 % cd
SA	B.9	334,561 cdefgh	-0.1 % ab	-0.4 % ab	-0.6 % ab	-0.7 % ab	-1.1 % abc	-5.3 % abc	-8.5 % abc	-10.7 % abc
SA	M.9	499,412 a	-1.4 % f	-6.9 % f	-11.1 % f	-13.8 % f	-3.7 % e	-18.7 % e	-30.0 % e	-37.5 % e
TS	G.11	542,875 a	-0.1 % abc	-0.5 % abc	-0.8 % abc	-1.0 % abc	-1.8 % d	-8.8 % d	-14.1 % d	-17.7 % d
TS	G.16	514,005 a	-0.2 % cde	-1.0 % cde	-1.5 % cde	-1.9 % cde	-1.2 % abc	-5.9 % abc	-9.4 % abc	-11.7 % abc
TS	G.41	421,190 abcdef	-0.1 % abcd	-0.7 % abcd	-1.1 % abcd	-1.4 % abcd	-1.2 % abc	-5.8 % abc	-9.3 % abc	-11.7 % abc
TS	B.9	541,544 a	-0.1 % abc	-0.5 % abc	-0.8 % abc	-1.0 % abc	-1.1 % abc	-5.6 % abc	-8.9 % abc	-11.1 % abc
TS	M.9	488,770 ab	-1.6 % g	-8.0 % g	-12.7 % g	-15.9 % g	-3.9 % e	-19.4 % e	-31.1 % e	-38.9 % e
	LSD	143,056	0.1 %	0.6 %	0.9 %	1.2 %	0.5 %	2.6 %	4.2 %	5.3 %

			Year 10				Year 15			
System	Stock	0 %	10 %	50 %	80 %	100 %	10 %	50 %	80 %	100 %
SP	G.30	228,093 ghi	-1.2 % bc	-5.9 % bc	-9.4 % bc	-11.7 % bc	-0.9 % a	-4.5 % a	-7.2 % a	-9.0 % a
SP	G.210	246,906 ghi	-1.1 % bc	-5.4 % bc	-8.6 % bc	-10.8 % bc	-0.9 % a	-4.4 % a	-7.0 % a	-8.7 % a
SP	G.935	141,983 i	-1.3 % c	-6.3 % c	-10.2 % c	-12.7 % c	-1.0 % a	-5.1 % a	-8.2 % a	-10.2 % a
SP	M.7	288,754 efgh	-1.0 % bc	-5.2 % bc	-8.3 % bc	-10.4 % bc	-0.8 % a	-4.0 % a	-6.4 % a	-8.0 % a
SP	M.26	287,221 fgh	-3.7 % f	-18.7 % f	-29.9 % f	-37.4 % f	-2.8 % c	-14.0 % c	-22.4 % c	-28.0 % c
VA	G.16	201,398 hi	-1.0 % abc	-4.8 % abc	-7.7 % abc	-9.7 % abc	-0.8 % a	-4.0 % a	-6.4 % a	-7.9 % a
VA	G.41	314,625 defgh	-1.1 % bc	-5.3 % bc	-8.5 % bc	-10.6 % bc	-0.8 % a	-4.2 % a	-6.6 % a	-8.3 % a
VA	G.935	277,233 ghi	-1.1 % bc	-5.3 % bc	-8.6 % bc	-10.7 % bc	-0.9 % a	-4.4 % a	-7.0 % a	-8.8 % a
VA	M.9	351,720 bcdefg	-3.1 % ef	-15.7 % ef	-25.1 % ef	-31.4 % ef	-2.7 % c	-13.6 % c	-21.8 % c	-27.3 % c
VA	M.26	431,967 abcd	-3.6 % ef	-17.8 % ef	-28.5 % ef	-35.6 % ef	-2.9 % c	-14.5 % c	-23.2 % c	-29.0 % c
SA	G.11	420,934 abcdef	-0.3 % a	-1.3 % a	-2.0 % a	-2.5 % a	-0.8 % a	-3.9 % a	-6.3 % a	-7.9 % a
SA	G.16	458,325 abc	-0.6 % abc	-3.0 % abc	-4.8 % abc	-6.0 % abc	-0.7 % a	-3.6 % a	-5.7 % a	-7.1 % a
SA	G.41	430,382 abcde	-0.5 % abc	-2.6 % abc	-4.1 % abc	-5.1 % abc	-0.9 % a	-4.5 % a	-7.1 % a	-8.9 % a
SA	CG.4210	249,413 ghi	-0.5 % abc	-2.6 % abc	-4.2 % abc	-5.2 % abc	-0.9 % a	-4.4 % a	-7.1 % a	-8.9 % a
SA	B.9	334,561 cdefgh	-0.4 % ab	-2.2 % ab	-3.4 % ab	-4.3 % ab	-0.9 % a	-4.5 % a	-7.2 % a	-9.0 % a
SA	M.9	499,412 a	-2.9 % de	-14.6 % de	-23.3 % de	-29.1 % de	-2.4 % b	-11.8 % b	-19.0 % b	-23.7 % b
TS	G.11	542,875 a	-0.3 % a	-1.3 % a	-2.0 % a	-2.5 % a	-0.7 % a	-3.5 % a	-5.5 % a	-6.9 % a
TS	G.16	514,005 a	-0.5 % abc	-2.6 % abc	-4.1 % abc	-5.1 % abc	-0.7 % a	-3.5 % a	-5.5 % a	-6.9 % a
TS	G.41	421,190 abcdef	-0.6 % abc	-2.8 % abc	-4.5 % abc	-5.6 % abc	-0.8 % a	-4.0 % a	-6.4 % a	-8.0 % a
TS	B.9	541,544 a	-0.5 % ab	-2.5 % ab	-4.0 % ab	-5.0 % ab	-0.7 % a	-3.7 % a	-6.0 % a	-7.5 % a
TS	M.9	488,770 ab	-2.3 % d	-11.6 % d	-18.5 % d	-23.1 % d	-2.3 % b	-11.7 % b	-18.7 % b	-23.3 % b
	LSD	143,056	0.8 %	3.8 %	6.1 %	7.6 %	0.3 %	1.7 %	2.7 %	3.4 %

* Values under each scenario represent the percentage change from the baseline NPV which is calculated based on actual yield of the trial. Green indicates a reduction of NPV less than 15 %, yellow indicates a reduction of NPV between 15 and 50 %, and red indicates a reduction of NPV greater than 50 %. Column 0 % green indicates a higher NPV, followed by orange, yellow and lower red.

susceptible rootstocks but not with resistant rootstocks. Thus, if there is an infection of the scion regardless of whether the visible infection progresses to the main leader of the tree, the symptomless movement of the bacteria in the tree can still result in tree death if the rootstock is susceptible. A second assumption is that cultivars have similar tree death rates when infected by fire blight. This assumption is likely not totally valid since 'Honeycrisp' is less susceptible to fire blight than is 'Gala'. However, lacking quantitative data on the relative level of tree death for a given level of infection for difference scions, we chose to evaluate tree death and its effect on lifetime NPV at various levels of infection. Thus, the reader can judge the impact of a of a given level of infection by assuming his own opinion of the resulting level of tree death by viewing the figures at that level of tree death.

4.2. Implications of our results

We estimated the impact of theoretical fire blight induced tree losses on the economic performance of three cultivars, various rootstocks and four planting systems using the baseline cumulative 20-year net present value method. We used field performance data from two long-term field trials conducted in NY state (USA). The horticultural performance and the economic performance of these trials was published previously (Reig et al., 2019 and Ho et al., 2024). The current analysis was conducted to estimate the economic impact of fire blight induced tree losses and whether fire blight resistant rootstocks could reduce the economic risk associated with fire blight. Using numerous scenarios of the severity and timing of fire blight infections and estimating the impact on lifetime profitability of an orchard we have shown several important findings

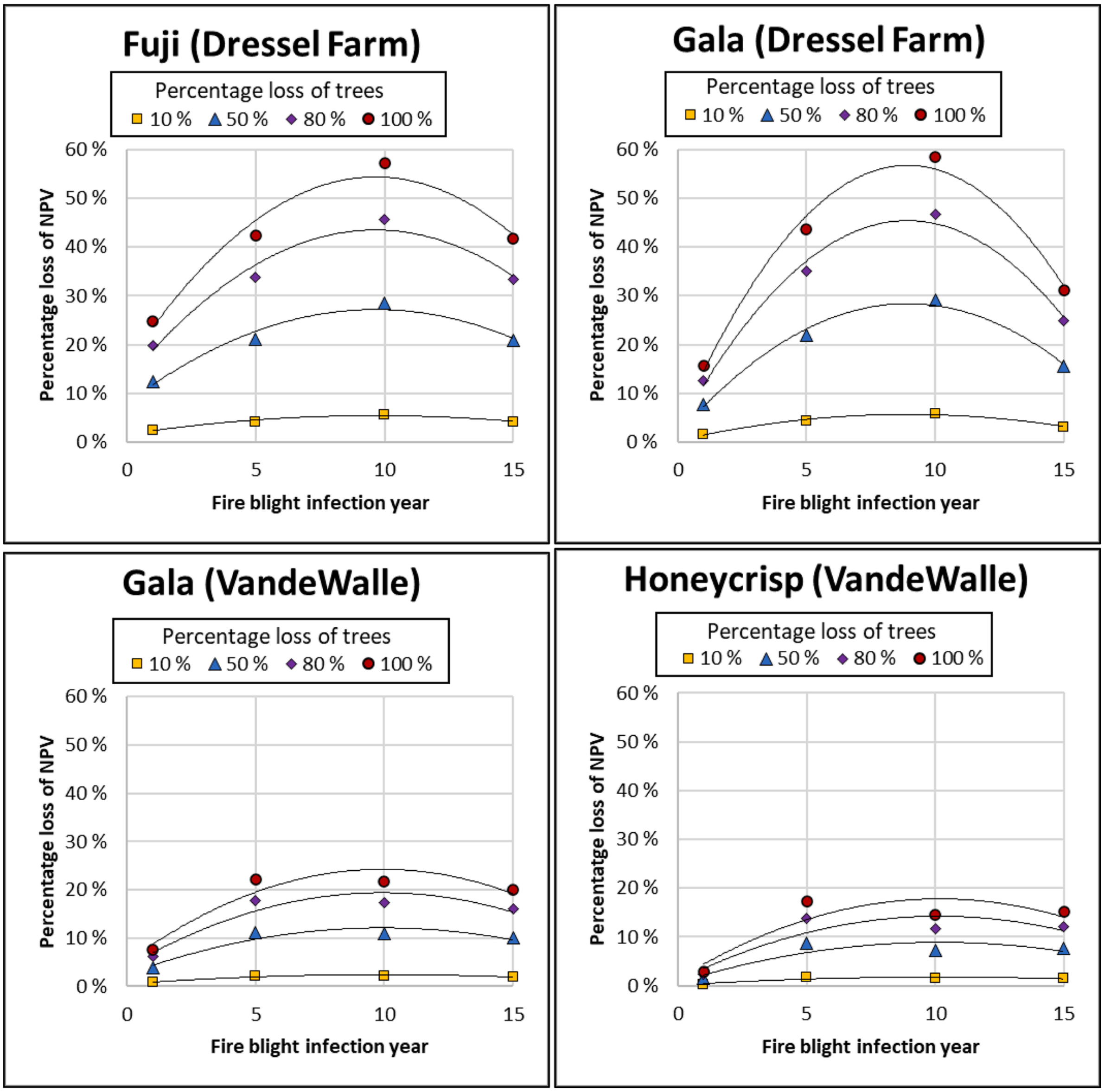

Fig. 1. Effect of cultivar on lifetime losses of NPV due to fire blight infection rates in different years of the orchard's life. Percentage loss trees in the legend represent fire blight infection rates.

that can help inform apple growers of the economic risks associated with this disease.

First, the use of fire blight resistant rootstocks had a very large impact on the level of loss in NPV associated with fire blight induced tree death. With susceptible rootstocks (M.9 and M.26), the reduction in NPV with high levels of tree infection was as high as 70 % which would render the planting not profitable while with resistant rootstocks the losses in NPV were much lower (<30 %) and would not render the planting unprofitable. Rickard et al. (2023) also reported significant improvement in lifetime NPV from the use of fire blight resistant rootstocks using hypothetical yield data.

Second, the smallest impact of fire blight induced losses on lifetime NPV occurred when the fire blight infection occurred in year 1. Although the early loss of trees due to fire blight would require replanting trees, the new trees would have sufficient time over the remaining 19 years of orchard life to mature and produce high yields resulting in only a small reduction in lifetime NPV. When fire blight infection occurred at year 5, losses in NPV were substantially greater than in year 1. This was due to the large investment in tree development over the first 5 years which would be negated by tree death and the need to replant trees to again go through the tree establishment phase vs. development years. The greatest degree of losses in NPV were found to be associated with tree losses in year 10 when the development years of a new orchard had passed but the income from the full production years 11–20 was severely reduced by fire blight and the need to replant trees. If fire blight infection did not occur until year 15 then enough of the full production years had already passed that tree losses at that point did not hurt lifetime NPV as much compared to similar tree losses in year 10.

Third, as expected our scenarios also show that the percentage of trees infected with fire blight was a major factor in the magnitude of the reduction in lifetime NPV. With a low percentage of tree infection with fire blight at any given year of the orchard life, the negative impact on lifetime NPV was low while at greater levels of infection, the reduction in lifetime NPV was much greater. This is similar to results reported by Rickard et al. (2023).

Other important findings were that high density systems like the Tall Spindle system had less sensitivity to fire blight induced losses than lower density systems. This was due to the much higher yield level of the Tall Spindle system compared to the lower density systems. Ho et al. (2024) reported that the higher NPV with the Tall Spindle system was

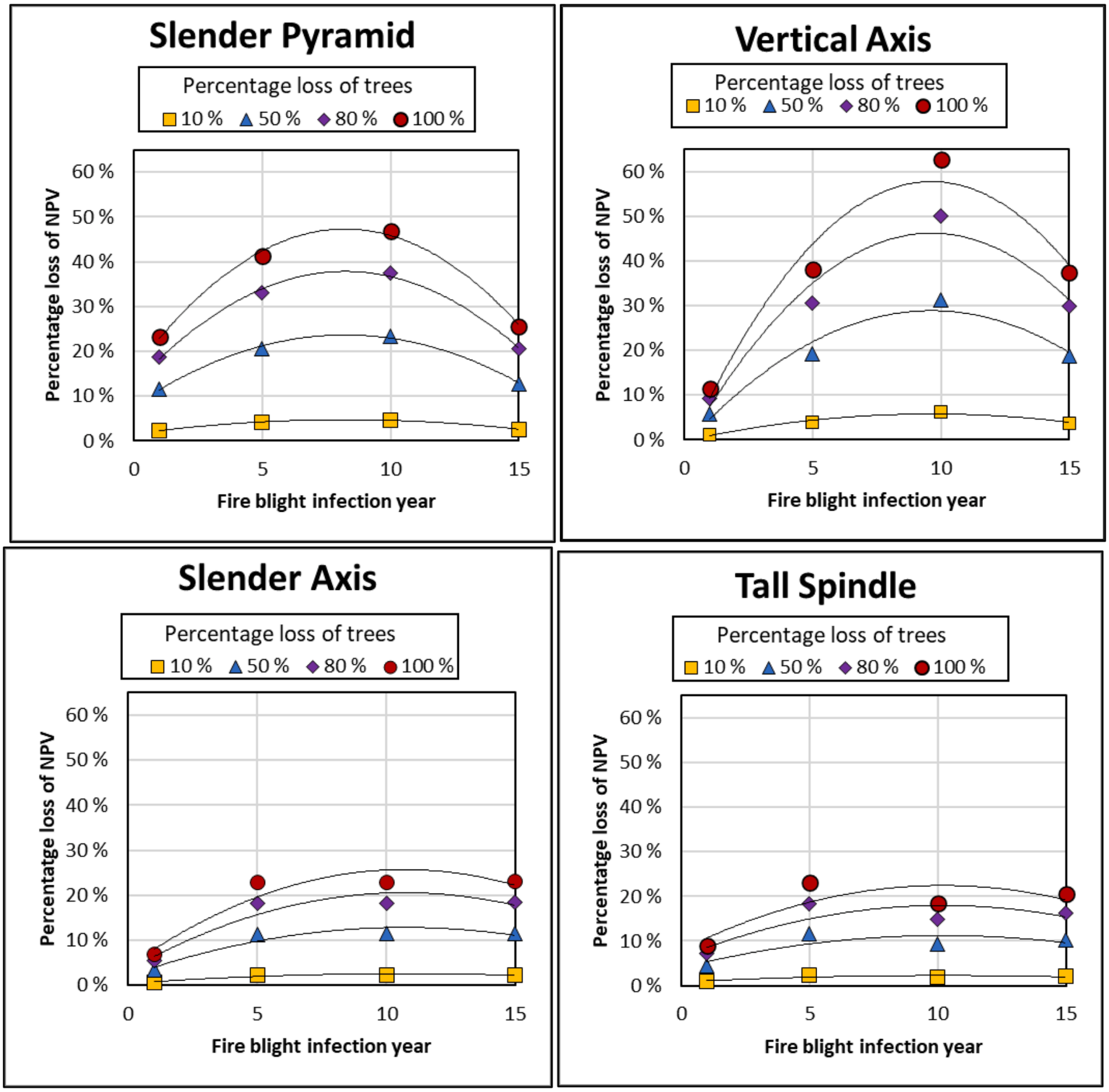

Fig. 2. Effect of planting system on lifetime losses of NPV due to fire blight infection rates in different years of the orchard's life. Percentage loss trees in the legend represent fire blight infection rates.

due to the high early yield and the higher mature yield compared to the lower density systems. Lordan et al. (2019) showed a curvilinear relationship between tree density and cumulative NPV with several apple cultivars. This positive effect of high tree density on yield and cumulative NPV also results in greater tolerance of fire blight infection and associated tree losses on NPV.

Lastly, we showed that cultivar had an important effect on the level of fire blight induced losses of NPV. With a high priced cultivar like 'Honeycrisp' the losses in NPV were less than the lower priced cultivars 'Fuji' and 'Gala'. This would be an even greater difference if the purported lesser sensitivity to fire blight of 'Honeycrisp' resulted in less tree death.

The use fire blight susceptible rootstocks in new high density apple plantings, results in high risk and requires stringent management protocols to manage the disease in young orchards (Breth, 2008). Even with the intensive management protocols implemented in new orchards, fire blight infections have resulted in large tree losses, in Washington from 2014 to 2019, in Michigan in multiple years since 2000 and NY State in 2020–2023, from the use of susceptible rootstocks (Milkovich, 2022; Robbins, 2019). The risk of fire blight tree deaths was not as severe in previous times with medium and low density plantings which generally used fire blight tolerant rootstocks such as M.7. Our results show that with M.7 rootstock the losses in NPV with fire blight infections are relatively low compared to M.9 and M.26, which are used in high density plantings. However, yields and NPV with M.7 are low compared to dwarfing rootstocks in high density plantings (Reig et al., 2019).

5. Conclusions

When an apple producer, in a region with risk of fire blight, makes the decision of which rootstock to use in a new high density planting the decision should consider the fire blight susceptibility of rootstocks. Rootstocks that are susceptible to fire blight introduce significant risk to the investment if fire blight infection occurs and causes tree death. Meanwhile resistant rootstocks impart significant risk mitigation to the new orchard and the value of this reduced risk depends on whether actual fire blight infections occur. Recent tree losses from high intensity fire blight infections in both the eastern, central and western production regions of the United States indicate that the use of resistant rootstocks is a wise economic decision. In our study the greatest cumulative NPV was

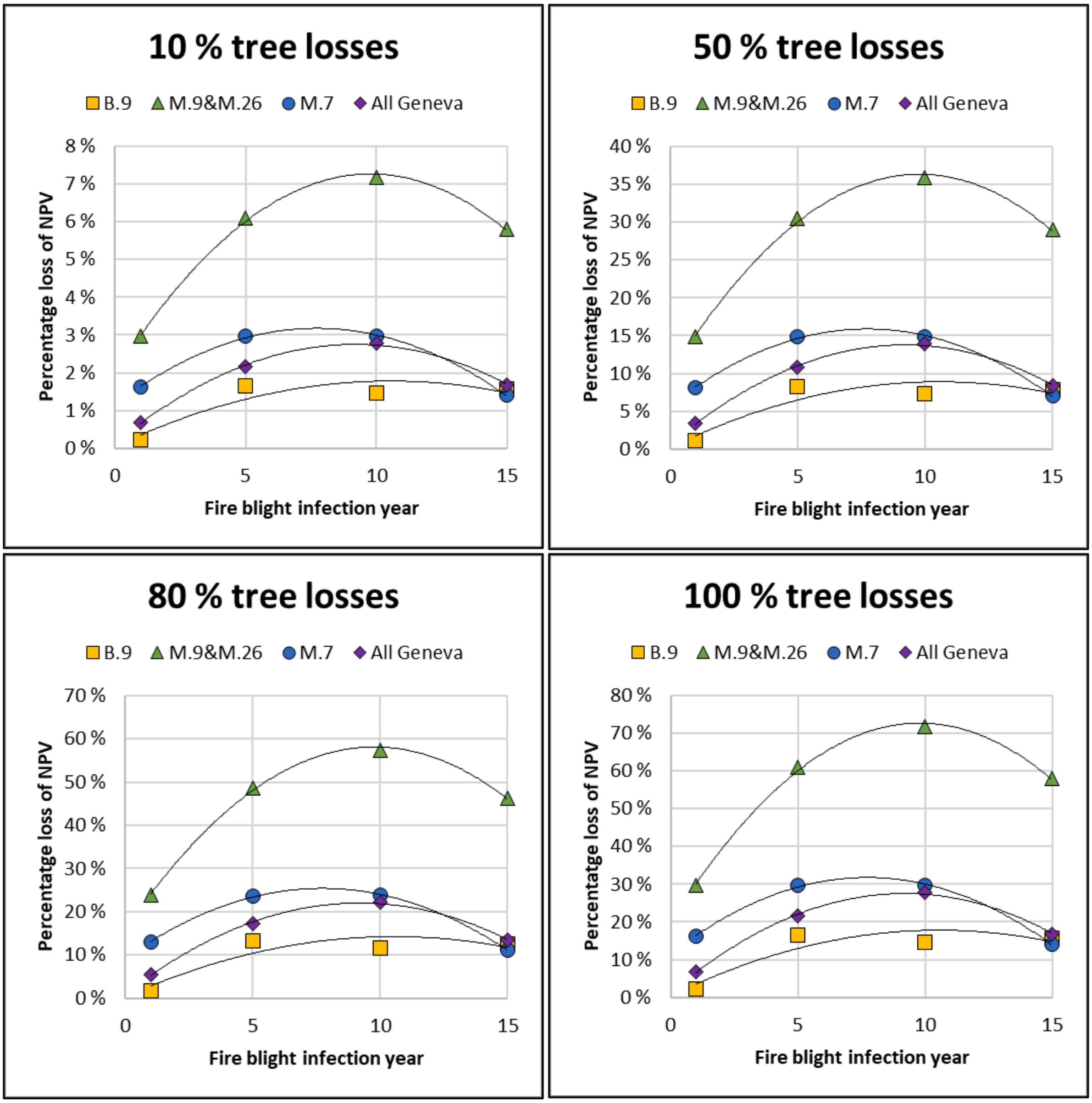

Fig. 3. Effect of rootstock on lifetime losses of NPV due to fire blight infection rates in different years of the orchard's life. (M.9 and M.26 grouped together as susceptible East Malling rootstocks to fire blight while all Geneva (grouping all Geneva rootstocks together), M.7 and B.9 are resistant to fire blight).

obtained by the adoption of fire blight resistant rootstocks, planted in the high-density tall spindle system and using high priced cultivars.

CRediT authorship contribution statement

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

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 was provided by Cornell AgriTech. Luis Gonzalez Nieto reports a relationship with Cornell AgriTech that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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