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Decision Tool for Growers to Evaluate Economic Impact of Grafting Technology Adoption: An Application to Open-field Conventional Tomato Production

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SUMMARY. **Grafting could potentially become an important part of integrated pest management programs in vegetable crops in the United States due to increased pathogen densities, reliance on pathogen susceptible varieties, increased use of organic and high tunnel production systems, limited land or input resources, value-added benefits, and the loss of, or regulatory restrictions on, soil fumigants. Adoption of this technology imposes additional costs on growers due to significantly higher grafted transplant prices, but associated yield improvements are potentially more than sufficient to offset the higher transplant costs. Therefore, the economic impact of the technology adoption depends highly on the specific circumstances of each grower. In this study, we propose a decision tool for growers to facilitate grafting technology adoption. We demonstrate an application of the proposed tool to a scenario based on real-life data for the open-field production of tomato (*Solanum lycopersicum*). The results show that based on a 30% loss in marketable yields due to disease pressure in nongrafted systems, yield improvements in the grafted system with resistant rootstock were sufficient to offset higher transplant and harvesting costs and resulted in higher net revenues. Net revenue estimates were $7126/acre in the nongrafted system and $8374/acre in the grafted system. The sensitivity analysis resulted in positive net revenues in the grafted system ranging from $108 to $12,328 per acre. Estimated marketable yield required in the grafted system to breakeven with the nongrafted system was 73,880 or 19,980 lb/acre more than marketable yield in the nongrafted system.**

Grafting of fruiting vegetables was recorded as early as fifth century (Lee and Oda, 2003) and again introduced in the early 1900s (Lee et al., 2010). The method has been extensively adapted in Japan and Korea in the last 30 years and more recently in Western countries (Kubota et al., 2008; Lee et al., 2010). Vegetable grafting is now widespread in Asia and Europe and in protected culture systems in North America. Worldwide, commonly grafted vegetables include watermelon (*Citrullus lanatus*), tomato, eggplant (*Solanum melongena*), cucumber (*Cucumis sativus*), and pepper (*Capsicum* sp.). Grafting is still rare in U.S. field production systems due to the high cost of grafted transplants, lack of reliable information regarding benefits and limited access to large number of grafted transplants (Barrett et al., 2012; King at al., 2010; Kubota et al., 2008; Taylor et al., 2008).

Currently, large-scale propagators of grafted transplants catering to commercial growers in the United States are located mainly in Canada and focus on plants for protected culture (Kubota et al., 2008). The current capacity to produce large quantities of grafted plants is low in the United States, and many organic and small-acreage growers with greenhouse operations do their own grafting because there is no local propagator available (Kubota et al., 2008). However, the number and size of commercial vegetable transplant producers is growing in the United States as a result of greater demand for grafted transplants of high quality and better performance (Lee et al., 2010). This growth is complemented by investments of multinational seed companies to develop and distribute seeds for grafting. Current trends include breeding very specific superior rootstock for vegetables grown under specific conditions and environments (Lee et al., 2010), and growers prefer to purchase grafted seedlings from commercial nurseries rather than produce their own.

Producers rely on using specific rootstocks primarily to manage various soilborne pathogens in successive cropping systems (King et al., 2010; Kubota et al., 2008; McAvoy et al., 2012; Rivard and Louws, 2008; Rivard et al., 2010a). Currently, there are commercially available rootstocks

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.4536	lb	kg	2.2046
1.1209	lb/acre	$kg \cdot ha^{-1}$	0.8922

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that exhibit various degrees of resistance or tolerance to a number of bacterial and fungal pathogens and nematodes. Selected rootstock used for vegetable grafting may also be associated with greater vigor and improved absorption of water and nutrients, and as a result, improved yields even in the absence of measurable disease pressure (Djidonou et al., 2013b; Lee et al., 2010; Rivard and Louws, 2008). In addition, grafting may provide a tool to manage abiotic stress, reduce the use of agricultural chemicals, and enhance fruit quality (Lee et al., 2010).

Grafting could potentially become an important part of integrated pest management in vegetable crops in the United States in the near future due to increased pathogen densities, reliance on pathogen susceptible varieties to meet specific market demands, global movement of pathogens, increased use of organic and high tunnel production systems, limited resources, and the loss of, or regulatory restrictions on, soil fumigants (Barrett et al., 2012; King et al., 2010; Lee et al., 2010; Louws et al., 2010). In addition, improved grafting methods, efficiency of transplant nurseries and transportation systems, and resulting economic efficiency of grafted plant use could facilitate the further adoption of grafting (Lee et al., 2010).

Tomato is the major crop currently grafted in North America (Kubota et al., 2008). Improved vigor and extended harvest season are the primary reasons for grafting tomatoes in greenhouse production systems, whereas disease resistance is typically the primary advantage conferred by rootstocks in other production systems such as nonheated greenhouses where plants are grown in soil, in open-field production, as well as in the production of heirloom tomatoes, organic production systems, or both (Barrett et al., 2012; King et al., 2010; Rivard and Louws, 2008).

One of the challenges associated with tomato grafting is that rootstock selection for disease management, and therefore associated production and economic benefits of grafting, are specific to the site and depend on presence, population structure, and dynamics of the pathogens, as well as edaphic, environmental, and anthropogenic factors (Barrett et al., 2012; Buller et al., 2013; Louws et al., 2010). For example, ecological diversity of the three distinct regions of the southeastern United States (Coastal Plain, Piedmont, and Mountain region) impacts the spectrum of soilborne pathogens and other growing conditions (Louws et al., 2010). As a result, it is difficult to generate reliable universal scientific evidence that would allow growers to assess economic benefits of grafting for technology adoption (Kubota et al., 2008; Rivard and Louws, 2008).

Because high cost of grafted transplants have been indicated as barriers to adoption of grafted technology (Rivard et al., 2010b), it is necessary to develop information that would allow growers to determine whether the extra costs of transplants could be justified by increased output (Barrett et al., 2012). Most previous studies looking at the costs and returns associated with the use of grafted transplants in the United States had a very specific focus predetermined by location, crop, and production system of the experiment. For example, Barrett et al. (2012) investigated whether grafting with resistant rootstock could be cost effective to overcome root-knot nematodes (*Meloidogyne* sp.) in the production of organic heirloom tomatoes in Florida's sandy soils. They found that at the high levels of infestation, grafted plants demonstrated great potential for maintaining fruit yields and reducing economic losses. At the same time, grafting was not economically feasible when used in fields with low nematode pressure, in which case there was no significant yield improvement as a result of grafting. Taylor et al. (2008) arrived at a similar conclusion: it is not economically feasible for farmers growing seedless watermelons to use grafted transplants if *Fusarium* wilt caused by *Fusarium oxysporum* f.sp. *niveum* is not an issue. Djidonou et al. (2013a) compared the costs and returns of grafted and nongrafted fresh-market tomato production under common management practices in northern Florida in fumigated fields that allowed for the evaluation of the impact of grafting on yields beyond disease control. They showed that grafting increased production costs considerably compared with the nongrafted system. However, they did find that the net returns were also higher in the grafted system due to yield improvements, but varied considerably depending on seasonal yields and market prices. McAvoy et al. (2012) found in open-field tomato rootstock studies in Florida and Virginia that even though grafting required higher initial investment, it significantly reduced disease incidence and increased marketable yield, potentially offsetting any additional expenses. In their study, grafted plants performed well in nonfumigated soil, so elimination of fumigation could also make the use of grafted plants more economical.

Based on this evidence, it is clear that any decision to adopt grafting technology should be based on the assessment of very specific local transplant market conditions, availability of a suitable market for harvested fruit, agronomic situations, and presence of indigenous plant pathogens. The objective of this article is to demonstrate a tool that can be used by growers to assess economic viability of grafting based on their specific circumstances. Sensitivity analysis is used to evaluate the impact of potential deviations from assumed scenarios on economic returns of grafted systems. In addition, a formula is derived to calculate breakeven marketable yields in grafted systems. The proposed approach is demonstrated based on real-life data for conventional open-field tomato production under conditions where there was a 30% marketable yield loss assumed due to soilborne disease pressure (in this case, bacterial wilt caused by the soilborne bacteria *Ralstonia solanacearum* race 1).

Materials and methods

Assessment of economic viability of grafting and sensitivity analysis. The use of grafted transplants results in an increase in productions costs early in the production season as grafted transplants are typically more expensive compared with nongrafted plants (Rivard et al., 2010b). Other nontransplant production costs as well as yields could also be affected (Buller et al., 2013; Djidonou et al., 2013b; Kubota et al., 2008; Louws et al., 2010). The approach demonstrated in Table 1 could be used by growers to identify any cost or revenue-related items that could be affected by grafting technology adoption and is

Table 1. A summary of production costs and revenues for conventional field tomato production systems using nongrafted and grafted transplants.

	Nongrafted system[z]	Grafted system[z]
Annual production costs ($/acre)[y]	7,270	7,270
Number of transplants (plant/acre)[x]	5,800	5,800
Price of transplants ($/plant)	0.12	1.02
Cost of transplants ($/acre)	696	5,916
Expected marketable yield		
lb/acre	53,900	77,000
25-lb (11.3 kg) box/acre	2,156	3,080
Harvest costs ($/acre)[w]	6,468	9,240
Sale price ($/25-lb box)	10.00	10.00
Gross revenue ($/acre)	21,560	30,800
Net revenue ($/acre)	7,126	8,374

[z] $1.00/acre = $2.4711/ha, 1 plant/acre = 2.4711 plants/ha, 1 lb/acre = 1.1209 $\text{kg}\cdot\text{ha}^{-1}$, 1 box/acre = 28.0213 $\text{kg}\cdot\text{ha}^{-1}$, $1.00/box = $0.0882/kg.

[y] Production cost estimates do not include transplant, harvest, and marketing expenses.

[x] The number of transplants includes an additional 2% required to replant. It is calculated assuming 5 ft (1.5 m) between rows and 1.5 ft (0.46 m) within row plant spacing.

[w] Harvest cost was estimated assuming $3 per 25-lb box harvest labor rates.

proposed here as a tool to facilitate grafting technology adoption decisions. The table lists all important points of comparison for the two systems. The approach is flexible as selected points of comparison could be adjusted to reflect any specific grower circumstances and preferences. The number of alternatives to be compared could also be adjusted (e.g., when different spacing for grafted plants is considered).

The data presented in Table 1 is based on an updated commercial nongrafted farm budget developed for one-acre conventional open-field production of tomatoes (Sydorovych et al., 2012). The two alternatives in the option set are using nongrafted and grafted transplants for production. Preliminary work is underway to modify the level of various inputs (e.g., water, nitrogen) or management practices (e.g., plant spacing, pruning needs, training systems) in the open-field tomato production systems that use grafted plants, but final results have not yet emerged, and will be components of future analysis. Therefore, annual production costs were assumed equal for the two systems, including fumigation and disease management costs, with the exception of transplant prices and harvest costs.

Annual variable production costs needed to grow staked tomatoes conventionally in the field were estimated based on customary management practices recommended by North Carolina State University extension and research horticultural specialists, and practiced by growers (Ivors, 2010; Sydorovych et al., 2012) (Table 2). In the production cost model, we assumed that machinery and equipment costs reflect machinery components that could be used for other farming enterprises in addition to growing tomatoes. Current input prices were obtained from local growers and their suppliers. Because land rental rates vary, a land charge was not included. Wage rates of $9.59/h for hired labor and $15.77/h for the owner/operator were used to calculate labor costs [U.S. Department of Agriculture (USDA), 2013a], and account for workers' compensation, unemployment insurance, FICA taxes at current rates in addition to the base wage rate and assuming 40-h work week, 52-week year, 6-d holiday, and 5-d paid vacation.

The number of plants used in the calculations was 5800 based on 5 ft between rows and 1.5 ft within row plant spacing for both alternatives. This estimate includes additional transplants required for replanting (2%).

Prices of grafted tomato transplants vary from one propagator to another. The higher cost of rootstock seeds, rather than labor costs of the grafting operation, is one of the main contributors to higher grafted transplant prices (Djidonou et al., 2013a; Rivard et al., 2010b). Based on the information from several propagators and farmers who have experience with grafted plants as well as a literature review, grafted tomato transplants could cost anywhere from $0.59 (when produced on-site without commercial markup) to over $2.00 including $0.25 to $0.34 for seeds, whereas nongrafted tomato transplants cost anywhere from $0.12 to $0.76 including $0.04 to $0.07 for seeds (Barrett et al., 2012; Djidonou et al., 2013a; Rivard et al., 2010b). For our example, we assumed that nongrafted transplants cost $0.12 and grafted transplants cost $1.02 with seed costs included. These estimates were based on our conversations with growers and extension scientists who are familiar with grafted transplant markets.

The level of marketable yield in the grafted system (Table 1) represents potential performance of grafted plants under optimal management, and a 30% loss due to disease pressure was assumed in the nongrafted system. It was assumed that tomatoes were packed into 25-lb boxes and picking labor was paid $3/box (Sydorovych et al., 2012). Sale prices were obtained from USDA (2013b). The values used represent a USDA calculated average, but prices vary from year to year and within a year depending on market conditions. Gross revenue less annual production, transplant prices, and harvest costs were the net revenue estimates for each system.

Because some values associated with each alternative (e.g., expected yields) can only be estimated, as growers are not able to exactly predict future growing conditions and generally do not have much experience with grafted transplants, sensitivity analysis is also used. Sensitivity analysis seeks to measure the economic impact of selecting alternative when the values of some impact variables are uncertain (Safley et al., 2004). In our application, the decision to adopt grafting technology is based on expected net revenues, and grafted transplant prices and expected yield, major variable components used to estimate net revenue, are assessed at certain deviations from the originally assumed values.

BREAKEVEN YIELD IN GRAFTED SYSTEM. Calculating breakeven marketable yield required in the grafted system to make it as profitable as the nongrafted system is another way that could help farmers make informed decisions on the adoption of grafted technology. Eq. [1] represents the equality of net revenues in the two systems:

Table 2. Estimated annual variable costs to produce conventional tomatoes in the field (costs of transplants, harvest, and marketing are not included).

Production operation	Labor ($/acre)[z]	Machinery ($/acre)	Materials ($/acre)	Total ($/acre)
March				
Plow	12.66	20.60	0.00	33.26
Disk	6.33	11.48	0.00	17.81
Subsoil	17.27	23.75	0.00	41.02
Total March	36.26	55.83	0.00	92.09
April				
Apply preplant fertilizer	8.63	12.64	127.50	148.77
Assemble irrigation system	95.93	21.85	0.00	117.78
Bedding and fumigation	34.53	280.59	990.00	1,305.13
Total April	139.10	315.08	1,117.50	1,571.68
May				
Transplant plugs and replant (2%)	55.64	62.05	0.00	117.68
Drip irrigation	594.75	315.38	210.60	1,120.73
Install stakes	52.50	0.00	550.00	602.50
String	34.80	0.00	9.90	44.70
Prune	47.85	0.00	0.00	47.85
Weekly sprays	25.32	50.68	266.43	342.44
Postemergent herbicide	6.33	9.15	13.78	29.26
Total May	817.20	437.49	1,050.71	2,305.16
June				
Drip irrigation	575.57	305.20	210.60	1,091.37
Weekly sprays	25.32	50.68	312.05	388.06
Postemergent herbicide	6.33	9.15	17.75	33.23
Total June	607.22	365.04	540.40	1,512.66
July				
Drip irrigation	594.75	315.38	210.60	1,120.73
Weekly sprays	25.32	50.68	150.55	226.55
Total July	620.08	366.06	361.15	1,347.28
October				
Remove and dispose plastic	184.18	73.17	0.00	257.35
Disk	11.51	20.87	0.00	32.39
Apply lime	0.00	0.00	55.00	55.00
Plant cover crop	11.51	22.07	17.00	50.58
Total October	207.20	116.12	72.00	395.32
Total production costs (transplants and harvest not included)	2,473.10	1,655.39	3,141.75	7,270.24

[z] $1.00/acre = $2.4711/ha.

$$Y_g \times P - C_g - T_g - Y_g \times H = Y_{ng} \times P - C_{ng} - T_{ng} - Y_{ng} \times H \qquad [1]$$

where subscript g refers to the grafted system and subscript ng to the nongrafted system and where it was assumed that the cost to harvest one pound of tomatoes remains constant. In this equation, Y is marketable yield (pounds per acre), P is sales price (dollars per pound), C is annual production costs excluding transplant and harvesting costs (dollars per acre), T is transplant costs (dollars per acre), and H is harvesting cost (dollars per pound). Solving Eq. [1] for Y_g will give the level of marketable yield in the grafted system required to breakeven with the nongrafted system:

$$Y_g = \frac{Y_{ng} \times (P - H) + (C_g - C_{ng}) + (T_g - T_{ng})}{P - H} \qquad [2]$$

Alternatively, we can use Eq. [1] to express additional yield required in the grafted system to break even with the nongrafted system. Additional yield required in the grafted system to breakeven with the nongrafted system can be expressed as:

$$\Delta Y = \frac{(C_g - C_{ng}) + (T_g - T_{ng})}{P - k} \qquad [3]$$

where $\Delta Y = Y_g - Y_{ng}$.

Results

Annual production costs (transplant, harvest, and marketing excluded) required to grow conventional tomatoes on 1-acre field plot were estimated to be $7270/acre (Tables 1 and 2) in both nongrafted and grafted systems. The costs were separated by the different months of the growing season (Table 2). Operations in May were the most expensive, costing an estimated $2305/acre. Over the growing season, materials (excluding transplants) accounted for $3142/acre, labor costs (excluding harvest labor) were $2473/acre, and the costs linked to owning and operating the equipment were $1655/acre (Table 2). Transplant costs were estimated to be $696/acre in nongrafted and $5916/acre in grafted systems, while harvest costs which are based on expected yields were estimated to be $6468/acre in nongrafted and $9240/acre in grafted systems (Table 1).

Gross revenues were obtained by multiplying marketable yield estimates by sales price per pound. It was assumed that the yield in grafted system under optimal management is 77,000 lb/acre and 30% loss due to disease pressure was assumed in the nongrafted system resulting in yield estimate of 53,900 lb/acre. Net revenue estimates accounted for annual production, transplant prices, and harvesting costs in both systems and were $7126/acre in nongrafted and $8374/acre in grafted systems (Table 1). These results generally indicate positive net returns in both systems, but do not reflect marketing costs, land rental rates, property taxes, or any other fixed costs as these may vary depending on the grower's situation. Even though the grafted system had much higher transplant and harvesting costs, yield increase due to the use of disease-resistant grafted transplants was significant enough to offset these higher costs and result in higher net returns compared with the nongrafted system based on our assumptions.

SENSITIVITY ANALYSIS. As mentioned earlier, current grafted transplant prices vary considerably. Expected marketable yields in the grafted systems can also be variable as they depend on many factors such as rootstock used, weather, disease pressure, management, etc. Therefore, sensitivity analysis of net revenue to the deviations from the originally assumed values in transplant prices and expected yields was conducted for the grafted system and reported in Table 3. Net revenue was reported for 15% and 30% increases and reductions in the base grafted transplant price ($1.02) and 15% and 30% reductions and 5% and 10% increases in base yield in the grafted system (77,000 lb/acre). Smaller percentage increases in yield were selected to reflect realistic possible yield levels. Thirty percent reduction in base yield in the grafted system is a scenario where yield is equal to the nongrafted system with disease pressure (there are no yield improvements from using grafted transplants). Reported net revenue values are all positive and range from $108 to $12,328 per acre. Comparing these values with base net revenue in the nongrafted system ($7126/acre) allows us to identify combinations of marketable yield levels and grafted transplant prices in the grafted system, which may result in net revenue improvements. Net revenues were also reported for various marketable yield levels assuming the transplant cost of $0.12/plant. These values demonstrate net returns in the nongrafted system at various levels of disease pressure ranging from $7126 to $15,750 per acre.

Table 3. Sensitivity of net revenues to changes in expected marketable yield and transplant prices in conventional field tomato production system using grafted transplants with assumed 77,000 lb/acre (86,301 kg·ha^{-1}) baseline yield and $1.02/plant grafted transplant price.

	Marketable yield (lb/acre)[y]				
Transplant price[z]	**53,900**	**64,450**	**77,000**	**80,850**	**84,700**
$1.33/plant	108	3,062	**6,576**	7,654	8,732
$1.17/plant	1,036	3,990	**7,504**	8,582	9,660
$1.02/plant	**1,906**	**4,860**	**8,374**	**9,452**	**10,530**
$0.87/plant	2,776	5,730	**8,664**	10,322	11,400
$0.71/plant	3,704	6,658	**10,172**	11,250	12,328
$0.12/plant	7,126	10,080	**13,594**	14,672	15,750

[z] Transplant prices $1.33 and $1.17 per plant represent 30% and 15% increases from the $1.02/plant baseline transplant price level, correspondingly. Transplant price $0.71 and $0.87 per plant represent 30% and 15% decreases from the $1.02/plant baseline grafted transplant price level, correspondingly; $0.12 is the assumed nongrafted transplant price.

[y] Marketable yield levels 53,900 and 64,450 lb/acre represent 30% and 15% decreases from the 77,000 lb/acre baseline marketable yield level, correspondingly. Marketable yield levels 84,700 and 80,850 lb/acre represent 10% and 5% increases from the 77,000 lb/acre baseline marketable yield level, correspondingly; 1 lb/acre = 1.1209 kg·ha^{-1}.

BREAKEVEN YIELD IN GRAFTED SYSTEM. Assumed yield in the nongrafted system is 53,900 lb/acre. Based on Eq. [2] and the values presented in Table 1, the marketable yield required in the grafted system to breakeven with the nongrafted system is 72,542 or 18,643 lb/acre more than marketable yield in the nongrafted system. Considering the number of plants (5684/acre, excluding 2% of replants), the marketable yield required in the grafted system to breakeven with the nongrafted system is 12.76 or 3.28 lb/plant more than in the nongrafted system.

Table 4 explores the issue of required additional breakeven yields further. It presents additional marketable yields required in grafted field production systems to compensate for higher costs of grafted transplants at various sale price levels. It is an application of Eq. [3] where it was assumed that annual variable production costs (C) are the same in nongrafted and grafted systems, $C_{\mathrm{g}} - C_{\mathrm{ng}} = 0$. It was also assumed that the number of transplants is the same in both systems, and therefore additional yields could be expressed on a per plant rather than per acre basis. After these manipulations, data presented in the table are applicable to all systems regardless of plant density, nongrafted yields, and transplant prices.

Table 4 rows represent various possible price premiums for grafted transplants as compared with nongrafted on per plant basis ($t_{\mathrm{g}} - t_{\mathrm{ng}}$). The columns represent different sale prices per pound of marketable yield. The values in the table are additional marketable yields per plant needed to compensate for higher grafted transplant prices at certain tomato sale price levels and account for additional harvesting costs associated with an increase in yields. These values are selected to demonstrate the range of their variability for a comprehensive analysis, but the specific intermediate values based on system scenarios summarized in Table 1 can be calculated based on Eq. [3].

Discussion

Previously, high cost of grafted plants have been identified as a barrier to adoption of grafting technology (Rivard et al., 2010b), but this technology is economically viable under

Table 4. Additional yield per plant required in the grafted system to compensate for various grafted transplant price premiums at various sale price levels presented on a per plant basis.

Grafted transplant price premium ($/plant)^{z}	Tomato sale price ($/lb)^{y}						
	0.40	0.80	1.20	1.60	2.00	2.4	2.8
0.50	1.79	0.74	0.46	0.34	0.27	0.22	0.19
0.75	2.68	1.10	0.69	0.51	0.40	0.33	0.28
1.00	3.57	1.47	0.93	0.68	0.53	0.44	0.37
1.25	4.46	1.84	1.16	0.84	0.66	0.55	0.47
1.50	5.36	2.21	1.39	1.01	0.80	0.66	0.56
1.75	6.25	2.57	1.62	1.18	0.93	0.77	0.65
2.00	7.14	2.94	1.85	1.35	1.06	0.88	0.75
2.25	8.04	3.31	2.08	1.52	1.20	0.99	0.84
2.50	8.93	3.68	2.31	1.69	1.33	1.10	0.93

^{z}Grafted transplant price premiums represent differences between expected price of grafted transplants and expected price of nongrafted transplants ($t_{g} - t_{ng}$).

^{y}\$1.00/lb = \$2.2046/kg.

certain circumstances. Therefore, it is necessary to help growers determine whether the extra costs of transplants could be justified by increased net returns in their specific case. In this study, we proposed an approach that could be used to facilitate growers' decisions to adopt grafting technology. We demonstrate the proposed approach using real-life data for conventional open-field tomato production and disease pressure due to bacterial wilt.

Our specific demonstration was based on the scenario where grafting was used as a disease management tool to avoid yield loses, but a similar approach could also be used for a broad set of possible scenarios for assessment of economic viability of grafting. When applied to the problem of grafting technology adoption, our approach is very flexible and adaptable to specific scenarios. For example, it could be used to assess economic viability of grafting when used for disease management, enhancement of water and fertilizer use efficiency, and yield improvements. The set of alternatives could consist of two options (nongrafted and grafted production systems) or it could be expanded to include other production alternatives such as varied spacing of grafted plants, rootstock/scion combinations, or both. The number of impact variables could also be adjusted to reflect many specific circumstances and grower preferences.

In our application of the approach, we show that the use of disease-resistant grafted transplants is economically viable in a system where 30% of marketable yield in the nongrafted system is lost due to disease pressure. The information on annual production costs, yields, and tomato transplant and sale prices was collected and summarized for both nongrafted and grafted systems. Annual production costs were assumed equal for the two systems, including fumigation and disease management costs, with the exception of transplant prices and harvest costs. Even though grafted transplants were much more expensive compared with nongrafted (\$1.02 and \$0.12 per plant for grafted and nongrafted, correspondingly), yield improvements in the grafted system were significant enough to recover these extra costs and to result in greater net returns (\$8374 and \$7126 per acre in grafted and nongrafted systems, correspondingly).

The price of grafted transplants is an extremely important factor to farmers as considerable additional investment is required early in the production season, thus increasing early season risk. The high costs of grafted transplants are the result of the high cost of rootstock seeds, intensive labor requirement in the propagation process, longer transplant production cycle, and potentially higher transportation costs due to the lack of local propagation facilities (Kubota et al., 2008; Rivard et al., 2010b), and may discourage potential users (Barrett et al., 2012). With further developments in rootstock breeding, grafting techniques, and automation, future reductions in transplant prices are possible. Alternatively, advances in rootstock genetics and use may reliably increase crop yield or decrease inputs and thereby improve net returns. These benefits would be desirable for tomato growers as they would improve economic viability of grafted systems as demonstrated by our sensitivity analysis (Table 3).

At the same time, the results of sensitivity analysis imply that net returns are much more sensitive to the impacts grafted transplants have on yields. For example, a 30% reduction in grafted transplant price (from \$1.02 to \$0.71 per plant) increases net returns from \$8374 to \$10,172 per acre at 77,000 lb/acre expected yield level (the difference of \$1798/acre or 21.5% improvement in net returns). At the same time, a 30% increase in expected yield (from 53,900 lb/acre to 77,000 lb/acre) increases net returns from \$1906 to \$8374 per acre at \$1.02 transplant price level (the difference of \$6468/acre or 339.4% increase). In part, these results are based on our original assumptions, but generally it is evident that if a farmer expects a significant yield improvement from adoption of grafted technology, transplant prices at current levels should be less relevant for the adoption decision as overall impact of grafting on net returns would be positive.

The results presented in Table 4 demonstrate additional yields per plant are required in the grafted system to compensate for higher transplant prices and to breakeven with the nongrafted system. These data are very informative in terms of interaction of different factors, including fruit selling price, affecting the economic impact of grafting technology in tomato production. Presented data show that at high fruit selling prices, for example, possible with organic heirloom tomato varieties or with direct marketing, growers can afford to pay premium prices for grafted transplants because only very modest yield improvements per plant are required to compensate for the higher cost of grafted transplants. For example, at \$2.00/lb selling price, a grower needs only 1.33 lb/plant more fruit to compensate for a \$2.50 price increase for each transplant. Also, the range of values presented in the columns decreases considerably as selling price increases, implying that variations in transplant prices will have less impact on net returns as tomato selling prices increase. At the same time, at lower fruit selling prices typical for wholesale conventional field tomatoes, yield improvements need to be significant even if grafted plants are acquired at only a moderate price premium. For example, a transplant price increase of only $0.75/plant should result in at least 2.68 lb/plant of additional yield at $0.40/lb selling price to compensate. Also, any additional incremental increase in the grafted transplant price premium results in considerable changes in required yield needed to compensate for such an increase.

This analysis assumed that the use of grafting technology has no impact on production beyond transplant prices and harvesting costs associated with changes in yields. This might not apply in all real-world circumstances. Grafted systems may differ in terms of nutrient requirements, pest management practices, the number of transplants needed due to different spacing or use of more vigorous rootstock, etc. If this is the case, annual production costs assumed constant in this analysis would be affected. Potential impact of all changes possible in production costs is beyond the scope of this analysis and could be a fruitful area for future research.

While our results indicated that it may be economically viable to use grafted transplants to avoid yield losses due to disease, actual costs and returns will vary from grower to grower due to a number of factors such as market situation, weather conditions, managerial skills, disease pressure, etc. Since every situation is different, the decision facilitating approach combined with the sensitivity analysis provides a useful tool for growers to carefully assess their individual situation.

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