WP 2019-12
2019

Working Paper

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A Review of Economic Studies on Pathogen-Tested Plant Materials and Clean Plant Programs for Specialty Crops

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A Review of Economic Studies on Pathogen-Tested Plant Materials and Clean Plant Programs for Specialty Crops

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Acknowledgements

This work was supported by a grant from the National Clean Plant Network (cooperative agreement #AP18PPQ58-T00C065). We would like to thank the participants attending the workshop, "Economic Studies: An assessment of past and current efforts, an evaluation of needs, and a roadmap for future actions" who advocated for this literature review and all the people who reviewed prior versions of this paper. Most especially, we would like to acknowledge the important work performed by those reviewed here.

Introduction

Graft-transmissible plant pathogens such as viruses, viroids, and bacteria are disseminated through infected propagation material and can cause diseases of substantial economic relevance due to lower yields, decreased product quality, and higher management costs. They are one of producers' major concerns in specialty crop production. Some of these pathogens require expensive treatment and management programs, while others may be untreatable once infections are established in the field (Gergerich et al., 2015). Regardless of how feasible it is to control a disease after it is established in a field, pathogen-tested, foundation plant materials free of deleterious pathogens are vital to disease management and profitable production of specialty crops. The National Clean Plant Network (NCPN)1 was established in 2008 in the U.S. to promote and provide pathogen-free, clean, propagation materials for selected specialty crops. Clean plant centers of the NCPN are responsible for screening plants for selected pathogens and maintaining and distributing pathogen-tested plant materials (Gergerich et al., 2015). Currently, the crops covered by NCPN centers include fruit trees, grapes, berries, citrus, hops, sweetpotatoes, and roses.

Cembali et al. (2003) suggested that a program that tests for viruses in plant materials can

[1] National Clean Plant Network

provide benefits to each of the three sectors of the specialty crop supply chain – nurseries, growers, and consumers,. Nurseries and growers could benefit from the reduced risk of facing yield and/or quality losses, while consumers could benefit from the abundant supply of high-quality products derived from pathogen-tested stocks and from the resulting lower production costs. Continued research that shows the economic benefits of using clean plants along with educational efforts to promote the adoption of pathogen-tested plant materials in crop production is needed. Thus, it is important to understand the current status of economic research of pathogen-tested plant materials.

We conducted a review of the literature that addresses the economic impacts of selected plant diseases and the economic value of using pathogen-tested plant materials. Although we focus primarily on the specialty crops covered within the scope of NCPN, we also include relevant studies related to economic impacts of diseases of crops outside of the scope of NCPN and their management. First we review the impacts of selected plant diseases on their industries, which provides a broad insight into the economic influences diseases may have on their industries. Second, we summarize the set of studies which included economic evaluation of farm management strategies when facing a certain disease. Third, we review studies that used economic approaches to evaluate either the adoption of pathogen-tested planting materials or the establishment of a pathogen-testing program. In each section, we categorize the studies by crop focus. This study ends with a discussion on the current state of literature and the future direction.

1. Economic impacts of selected plant diseases on their industries

To understand the economic impacts of plant diseases, economists in most cases have used data inputs from field experiments, farm surveys, crop budgets, and market prices to estimate the average economic impacts. The effects that diseases have on crop production can vary significantly depending on a number of factors, such as the geography, region, cultivar, and management practices. Thus, to estimate the economic impacts of any particular disease, some studies use scenarios to allow for variations in disease impacts, geography, yield loss or management practices. Appendix Table 1 summarizes studies which assessed the economic impacts of selected plant diseases.

1.1 Sweetpotatoes

Previous studies have documented the impacts of sweet potato feathery mottle virus and other potyviruses in terms of yield and quality of sweetpotato production (Bryan et al., 2003a, 2003b; Carroll et al., 2004; Clark and Hoy, 2006). Most of these studies conducted field trials or experiments for their analyses on production impact, but none has documented disease impacts in terms of economic losses to the industry.

1.2 Citrus

Citrus greening disease or huanglongbing (HLB) is associated with three nonculturable species of α-proteobacteria of the genus *Liberibacter; Candidatus Liberibacter asiaticus (CLas), Ca. L. africanus (CLaf)*, and *Ca. L. americanus (CLam)* with *CLas* being the most pervasive. HLB constitutes the most economically devastating disease of citrus, posing a major global risk for the citrus industry (Bové 2006). HLB reduces the quantity and quality of citrus fruits, eventually rendering infected trees useless. A severely affected tree produces fruit that is unsuitable for sale as fresh fruit or for juice.

This disease has been studied extensively in the U.S. since becoming endemic in Florida in 2005. In Florida, citrus bearing acres have decreased from 679,000 in 2003– 04 to 402,000 in 2017–18, while the number of citrus operations decreased from 7,389 in 2002 to 2,775 in 2017 (USDA-NASS). The number of orange trees in Florida has declined from about 80 million down to approximately 60 million trees currently. Grapefruit has experienced an even greater drop, declining from a peak of about 14 million trees to approximately 5 million trees currently. New tree plantings are at historically low levels and only about 50% of orange trees that are lost to HLB are being replaced. The disease affects not only growers, but other levels of the industry. The number of juice-processing facilities decreased from 41 in 2003–04 to 14 in 2016–17 while the number of packinghouses in Florida decreased from 79 to 26 during the same period (Florida Department of Agriculture and Consumer Services).

Hodges and Spreen (2012) used an Input-Output framework to estimate the direct, indirect, and induced impacts of HLB on orange juice production in Florida. Their results showed substantial losses in production, value-added, employment, and labor income. They estimated that the value of total output was reduced by $4.541 billion, or an annual average of $908 million, from 2006-2007 through 2010-2011 crop years. Court et al. (2017) updated the work by Hodges and Spreen (2012) and estimated the economic impact of HLB in Florida at a loss of $4.393 billion in cumulative industry output over the 4-year period 2012-13 through 2015-16, or an annual average of $1,098 million. The total value added and employment contributions decreased by an average of $658 million and 7,945 full-time and part-time jobs respectively over this same period. Moss et al. (2015) conservatively estimated a reduction of $18 million in producer surplus and $154 million in consumer surplus in the Florida orange industry per year due to HLB.

In California, the citrus industry contributes $7.117 billion to the economy according to a new study commissioned by the Citrus Research Board (CRB). The CRB study looked at the possible impact a 20 percent reduction in California citrus acreage or yield or a combination of the two would have from increased costs associated with meeting government regulations, combating the Asian citrus psyllid (ACP) and warding off the invasion of HLB. Such a reduction could cause a loss of 7,350 jobs and could reduce California’s GDP by $501 million in direct, indirect, and induced impacts. The CRB currently is devoting most of its resources to battling HLB and its vector ACP and to help ensure the sustainability of California citrus.

1.3 Grapes

The impacts of grapevine virus diseases are relatively well-studied, especially the grapevine leafroll disease (GLRD). Most of the studies addressed the economic impacts of GLRD using several scenarios, such as disease prevalence, yield reduction, and quality price penalties. For the case of New York state, Gómez et al. (2010) and Atallah et al. (2012) estimated economic impacts of GLRD of approximately $25,000 (assuming a 30% yield reduction and no grape quality penalty) to $40,000 (assuming a 50% yield reduction and a 10% penalty for poor fruit quality) per hectare in the absence of any control management.

Ricketts et al. (2015) estimated economic losses due to the GLRD in the three major winegrape producing regions of California, i.e., Northern San Joaquin Valley, Sonoma County, and Napa County. Loss calculations varied due to differences in price premiums and inputs, such as land and labor costs. Economic losses over the lifetime of a 1-ha vineyard of Cabernet Sauvignon was estimated to range from $29,902 in Northern San Joaquin Valley (assuming 5% initial infection, 25% yield reduction, and no quality penalty), to over $226,405 (assuming 40% infection, 40% reduction in yield, and a 10% price penalty for reduced quality) in Napa County. In addition, Fuller et al. (2019) published estimates of impacts by GLRD on California's North Coast vineyards. Among the scenarios considered, losses were greatest when growers established vineyards with unscreened vines and then did not replant. Under this scenario, growers would lose an average $2,643/ha/yr, with a net present value of $66,063 over the vineyard's 25-year lifetime.

Aside from GLRD, Ricketts et al. (2017) estimated similar losses as a result of grapevine red blotch disease (GRBD) in four wine grape growing regions across the U.S. These ranged from $2,213/ha in eastern Washington (assuming 5% initial disease rate with a 25% price penalty), to $68,548/ha in Napa County (assuming initial 60% disease prevalence level and a 100% price penalty for the proportion of infected grapes). Furthermore, Alston et al. (2013) measured the economic impact of Pierce's Disease caused by the bacterium *Xylella fastidiosa* on the California winegrape industry. On top of the estimated $92 million costs incurred by Pierce's Disease at the time, they estimated that Pierce's Disease would cause an additional $185 million annually to the industry if the current, regional control program was ended.

1.4 Fruit trees

Welliver et al. (2014) documented the costs of detection and eradication of plum pox virus (PPV) in Pennsylvania from 1999-2009. PPV is the most serious viral disease of stone fruits globally and was detected in peaches in Adams County, Pennsylvania in 1999. Because this virus is regulated, an eradication program was implemented to control the disease. The cost of removal and destruction of stone fruit trees, along with associated payments to growers for other control operations, totaled $30 million over a ten-year period ($22 million from USDA, and $8 million from the Pennsylvania Department of Agriculture) (Welliver et al., 2014). The PPV program operations cost an additional $29 million. In 2009, Pennsylvania was declared PPV-free.

2. Economic effects of disease management strategies

In this section, we summarize studies with the objective of estimating farm management strategies for optimal economic performance (Appendix Table 2). We focus on the studies which evaluated the farm-level management strategies with economic assessment, this means that analyses with field experiments only are not included.

2.1 Citrus

Morris and Muraro (2008), Roka et al. (2009), and Salifu et al. (2012) analyzed ways to manage HLB using economic performance measures. These authors recommended using only plant materials that are certified free from the disease organism to restock groves along with other orchard management strategies. We note that none of the studies were able to evaluate the economic benefits of planting pathogen-tested stock versus stock that was not certified as virus free.

Specifically, Morris and Muraro (2008) calculated better economic returns for replacing infected trees with new trees. In addition, the best financial performance was for planting the highest density grove. It provided returns of 11.8% and 16.1% on the $6,533 investment in infrastructure at delivered-in prices of $1.25 and $1.50 per pound of solids, respectively. Using price and cost assumptions, Roka et al. (2009) provided a framework for analyzing high-density plantings to counter losses from HLB using net present value (NPV) analysis. A net present value analysis is able to compare the net returns of different experimental groups over time. The results suggested that the establishment costs of switching to the proposed production systems can only be recovered if the yield per acre was higher.

Salifu et al. (2012) compared the NPV of using no control methods for HLB to the standard disease control model which includes scouting, aggressive measures to control for the HLB psyllid vector, and symptomatic tree removal. The control method with the highest NPV varied depending on the age of the trees at disease detection and by disease incidence at first detection. This research indicated the existence of a multidimensional relationship between these factors. This study did not take into account the effect of leaving infected trees on the possibility of secondary spread of the disease over subsequent years.

Scientists currently recommend controlling the psyllid as the primary economic means to control the disease. Singerman et al. (2017) studied the effect of area-wide pest management, whereby multiple growers coordinate scouting and sprays as opposed to individual growers. They found evidence that higher yields were obtained when growers coordinated sprays in area-wide blocks.

2.2 Grapes

Gómez et al. (2010), Atallah et al. (2012, 2017) and Ricketts et al. (2015) evaluated management strategies that used rogueing infected vines and replanting with vines derived from pathogen-tested stocks to maximize NPV under different scenarios. Partial replanting with pathogen-tested vines was also the cost-minimizing strategy suggested in Ricketts et al. (2017) in the case of GRBD. Atallah et al. (2015, 2017) further considered the role of spatial-dynamic diffusion on optimal management and found that the spatially targeted rogueing strategies performed better than other control strategies for grapevine disease.

Kaplan et al. (2016, 2018) estimated the economic benefits of vine pruning against other management strategies to control grapevine trunk disease. Although this disease cannot be managed by using pathogen-tested vines, the studies provide analytical methods to consider in future economic studies. Ricketts et al. (2017) identified the best management options for GRBD under different scenarios. Their results suggested replanting with pathogen-tested vines only if the disease prevalence is low to moderate, generally below 30% of vines infected. If disease incidence is high (over 30% infected), then the manager should replace the full vineyard. These infection thresholds may vary by region and by economic factors.

3. The economic value of NCPN clean plant programs

In this section, we reviewed the studies which assessed the value of NCPN clean plant centers and other similar pathogen-testing programs (Appendix Table 3).

3.1 Sweetpotatoes

Fuglie et al. (1999) estimated the economic benefit of establishing a pathogen-testing program for sweetpotatoes. The study examined a program that distributed pathogen-tested sweetpotato roots and vines in 1994 in China. The program conducted surveys of sweetpotato growers and collected data on changes in yield program costs associated with research, extension, and plant propagation. An internal rate of return of 202% of the pathogen-tested seed distribution program was estimated (Fuglie et al. 1999). The study also indicated that the pathogen-testing program could provide a net benefit of $145 million annually once fully established. Bryan et al. (2003a) compared the profitability of sweetpotato seeds of various generations from the original pathogen-tested seed. Their results indicated that although the pathogen-tested seeds had greater productivity, it had overall lowest profitability due to the higher price of the pathogen-tested stock.

3.1b Potatoes

Although potatoes are not part of NCPN, we include papers examining research related to our subject. Frost et al. (2013) provided an overview of the Wisconsin Seed Potato Certification Program. These authors estimated that despite increased costs of other farm inputs, the real cost of certification per hundredweight of potato had remained nearly the same from 1992-2010, suggesting there had been no real cost increase based on fees paid to the certification program by seed growers. They posited that the certification fees had been cost-effective for controlling diseases, and an additional benefit of a program that provided pathogen-tested planting materials was having a mechanism to protect against future risks, such as new diseases, or outbreaks. Guenthner et al. (1991) determined that a 1981 Maine law requiring Maine potato growers to plant certified seed potato resulted in average increased profits of $14,700 per year for the average grower. A preliminary study by Fuller et al. (2017) suggested a large benefit of the Montana seed certification program, which they estimated at $7.3 million annual return to Idaho growers.

3.2 Citrus

Roistacher (1996), which reviewed the economic impacts of HLB in Thailand, suggested that establishing a certification program that provides pathogen-tested planting materials can be a critical component in controlling HLB. The study also suggested that the program should provide pathogen-tested stocks certified not only for HLB but also for all graft-transmissible pathogens of citrus.

3.3 Grapes

Benefits of pathogen-testing for grapes have been demonstrated by Gómez et al. (2010), Atallah et al. (2012), Fuller et al. (2013, 2019), Verteramo Chiu et al. (2016) and Troendle (2017). To mitigate the economic effects of GLRD, planting with pathogen-tested, clean plant material is advised. Atallah et al. (2012) considered a scenario where a vineyard is established with pathogen-tested vines and found that the negative economic impact under this scenario is limited to approximately $2,000/ha, assuming a 25% premium on pathogen-tested vines.

Gómez et al. (2010) and Atallah et al. (2012) conducted NPV analysis to compare farm-level control strategies and suggested that partial replanting with vines derived from pathogen-tested stock was the cost-minimizing strategy in some scenarios. Fuller et al. (2013, 2019) demonstrated the value of a pathogen-screening program to the winegrape growers in California North Coast region. These studies calculated a benefit to growers over 60 times the cost, even if growers pay a premium of $0.045 per pathogen-screened vine. Under the assumption of a 100% adoption rate of pathogen-screened vine in the region, the estimated economic benefit of the program will be $22.5 million annually, which was around 2.7% of the revenues for the region.

Troendle (2017) constructed a cost-benefit analysis of using pathogen-tested vines in California and New York. Cumulative benefits from using pathogen-tested material from the Foundation Plant Services program in Davis, California from 2009-2025 were estimated at $3.26 billion (in 2002 dollars) and cumulative costs were estimated at $26 million for a benefit-to-cost ratio of 117. Cumulative benefits for Cornell's NCPN-grape center at the New York State Agriculture Experiment Station in Geneva, New York were to reach $19.5 million by 2025 and NCPN funding to operate the grape center estimated to cost $2.7 million by 2025.

3.4 Fruit Trees

Cembali et al. (2003) analyzed the value of the NCPN fruit tree program, formerly known as

National Research Support Project 5 (NRSP-5), using the supply-demand model in economic theory. They ran scenarios with different probabilities associated with production losses and the spread of viruses to estimate the changes in welfare. Their results showed high benefits for growers (avoiding yield losses), nurseries (avoiding an increase in production costs), and consumers (avoiding an increase in prices) from the established NRSP-5 program. Total benefits for all three sectors were estimated at approximately $227.4 million annually or more than 420 times the cost of the NRSP-5 program. Furthermore, they concluded from the historical standpoint that the NRSP-5 program drastically reduced viruses in the domestic fruit-growing region at the time. They also suspected that if the program had not been established, it would be less likely that pathogen-tested fruit tree cultivars would be researched and introduced, reducing the competitiveness of the industry.

Seavert and Julian (2012) estimated the net present value of plant certification programs in the Pacific Northwest for the major fruit tree crops, including apples, pears, peaches and cherries. They estimated grower returns using the certification programs to be $2.6 billion (assuming an 8% discount rate over twenty years). Under five different production scenarios without plant certification programs, reductions in grower returns range from $828 million to $4.7 billion.

4. Discussion and conclusion

Economic studies can help companies, industries, and policy makers allocate limited resources to achieve their goals. The studies in this literature review help us answer such questions as, "What resources should policy makers allocate to NCPN centers," and "How does using pathogen-tested plant materials optimize grower resources and control or prevent economic losses due to diseases?"

This article reviewed studies that evaluated the economic impacts that diseases have on select specialty crops. We also reviewed studies that assessed the economic value of using pathogen-tested plant materials and of operating clean plant centers, and we reviewed studies that used economic analyses to evaluate disease management strategies.

Studies have shown clear economic benefits to using pathogen-tested plant materials. These benefits include increased production and product quality due to pathogen-tested seed for sweetpotatoes, as well as potatoes, and initial plantings of pathogen-tested plant materials for citrus, tree fruits, and grapes. Benefits have been found at the producer level that can also accrue to the industry and consumer levels. The benefits of having NCPN centers that test plant material for targeted viruses, perform pathogen-elimination therapy, and provide this high-quality propagation material to nurseries and growers have also been demonstrated.

Although a number of economic studies have been conducted, the need for more economic studies exists. Below, we outline several areas where additional studies would be beneficial.

4.1 Study crops limited

To date, studies that have analyzed the economic effects of plant diseases have focused on a limited number of crops. Of the seven crops that are tested and propagated in NCPN clean plant centers (sweetpotatoes, citrus, fruit trees, grapes, berries, hops, and roses), economic studies were found for only four, sweetpotatoes, citrus, fruit trees, and grapes. No studies that looked at the economic impact of disease or the use of pathogen-tested plant materials for berries, hops, or roses were found.

Most of the seven crops managed under the NCPN actually encompass multiple species. For example, fruit trees include apples, peaches, pears, cherries, plums, etc. Also, grapes include table, wine, juice and raisin grapes. In addition, new cultivars of each of the NCPN specialty crop species are being constantly developed by breeders. Economic studies have not been able to keep up with the new cultivar development, yet industries have been using cultivars that have not been studied for the disease impacts. Therefore, additional studies are needed to examine more crops as well as new cultivars.

4.2 Further studies needed

The effects of disease on crops can vary depending on a number of different factors, such as but not limited to, different management practices, growing regions and environments. Studies of winegrapes conducted in different growing regions have thoroughly considered regional differences in evaluating management practices using rogueing, plantings at various densities, and other management practices. Additional economic studies looking at these factors and the benefits of using pathogen-tested plant materials under varying factors would benefit growers.

To date, economic studies have examined benefits to crop industries, growers, and to a certain extent, society. However, other members along crop supply chains have largely been ignored, specifically nurseries. Plant materials tested, cleaned, maintained, and propagated by the NCPN centers are sold to nurseries or seed producers to further propagate and to sell to growers. This is a very important stage of the supply chain that benefits from the use of pathogen-tested plant materials. Anecdotally, nurseries have described greater production value from using pathogen-tested materials. Atallah et al. 2012 assumed a price premium of 25% for certified pathogen-tested stock paid by growers in calculating the economic value of rogueing as a disease management process and demonstrated positive returns.

Analyzing price premiums for clean stock that benefit nurseries and are affordable to growers would be valuable. Bryan, et al. 2003(a) estimated revenues from sweetpotato production using G1-G5 (first generation through fifth generation) cuttings from pathogen-tested stock, G1 representing pathogen-tested plant cuttings and G2-G5 the generations removed from the original pathogen-tested plants. Although production and quality were greatest from G1 plants, the G2 provided the greatest returns. However, the G1 plant price premium was 667% of the cost of using G2 plants ($0.20 per G1 plant versus $0.03 per G2 plant). These factors, freedom from reinfection and costs of production, as well as others are fluid, emphasizing the need for further studies using current infection rates and economic conditions.

4.3 Complex issues and complex methods

Additional economic studies are needed to examine the more complex questions about disease management using pathogen-tested plant materials. More complex studies will require more industry data and will increase in scope. Additional studies in the areas outlined above will also require the engagement of additional researchers. The current pool of production economists with expertise and time to evaluate complex interactions in production agriculture and disease management is somewhat limited.

Evaluating the economic benefits of using pathogen-tested plant materials for perennial crops has been more difficult and taken longer than sweetpotatoes, which is grown as an annual crop. In the case of citrus, winegrapes, and fruit trees, where orchards or vineyards are in production for many years, studies are more challenging and have required more extensive economic analytical methods and assumptions. A number of the studies reviewed have used net present value calculations encompassing the life of the orchard or vineyard as well as using multiple production and/or disease management scenarios. The net present value analysis can also assess the rate of returns and the associated time frame for existing or establishing a pathogen-testing program center.

4.4 Directions for future research

As reviewed, a few studies have examined the benefit-cost ratios of some of the NCPN centers and have found impressive returns. However, to ensure continued support and funding from industry and government, economic assessments of additional centers would be valuable.

Frost et al. (2013) indicated that valuing a pathogen screening center based merely on the production aspect (e.g. yield improvement) may ignore other benefits brought by the program, such as the “spillover” benefits of the program to other sectors along the supply chain. The improvement of production can provide consumers a steady supply of fresh produce and the price may decrease as a result (Cembali et al., 2003). Previous studies suggested that the distribution of benefits from screening programs to each related sector (e.g. growers, nurseries, consumers) depends on the elasticities of supply and demand. In the case of GLRD and California winegrape production, Fuller et al. (2019) indicated that growers face greater impacts than buyers due to the inelastic supply caused by the perennial nature of the crop and the lag between planting decision and harvest. They predicted that the majority of the benefits of adopting clean vines accrued to growers rather than buyers. Similarly, Troedle (2017) projected that growers capture more benefits of pathogen-tested vines than wineries.

Furthermore, the NCPN centers can provide other benefits that might be difficult to quantify, such as serving as a foundation for research if there are new invasive pests or pathogens outbreaks occur in the future. The NCPN centers also provide educational information and research to improve cultivars that can increase the competitiveness of the industry (Frost et al., 2013; Gergerich et al., 2015). In addition, work done by the centers on new cultivars can help reduce quarantine barriers to international trade.

Economic impacts of citrus greening have been researched, especially with a regional focus on impacts to the industry in Florida. The studies which estimated the economic impacts of HLB on the citrus industry in Florida illustrated that the losses have been drastic.

To date, California has identified and eradicated over 900 HLB positive trees in urban areas and ACP has spread to all citrus producing areas in the state. Although, no HLB in commercial citrus has been found yet, it is projected to occur in the future. California spent $40-45 million per year in the past 3 years in anti ACP-HLB programs.

The Texas citrus industry has a statewide economic impact of over $280 million. Despite efforts to control entry of the disease, detected sites with HLB has increased, reaching 26% and 40% of commercial groves and residential sites, respectively, by 2017 (Sétamou et al. 2019). Arizona remains infested with ACP but has not found HLB.

Industry adoption of pathogen-tested materials can be improved. To do so, economists need to better understand the incentives for adoption by growers and nurseries, and studies are needed that demonstrate positive results. For instance, studies have not emphasized enough the need for appropriate price premiums for clean plant material to motivate adoption and maintenance by nurseries that would in turn sustain activities at NCPN centers. The NCPN program is successfully supporting the production, maintenance and distribution of clean propagative material. Nonetheless, the impact of the program can be limited if nurseries do not extensively adopt clean propagative material or if certification programs in support of the release of clean plants are not active. Economic models assessing the value of clean plant material for nurseries and business models ensuring the availability of certified, clean plant materials for commercial production could address these limitations.

As diseases spread and migrate, policy makers, industry, researchers, and clean plant centers need to understand the economic impacts of the diseases. Given the large upfront costs of establishing, producing, and distributing pathogen-tested plant materials, it is important to identify the economic importance of the diseases so that appropriate and sufficient resources in time, money, expertise, etc. can be effectively allocated to mitigate their impacts. Secondly, if the economic impact of a disease is sufficient to warrant, researchers can evaluate the optimal management strategies to control the disease and evaluate whether pathogen-tested materials is an economically feasible option to employ. The economic impacts of diseases depend on infection rates, the cultivars(s) infected, crop management practices, the growing region, how well disease vectors are managed, and many other factors. For many pathogens that are relevant to a specialty crop industry, economic studies are scarce or non-existent. Therefore, more work is needed to understand the economic returns of pathogen-testing in specialty crop production.

Some specialty crop commodities have increased pressure on NCPN centers to add new cultivars to their foundation collections. This demand can eventually be greater than the capacities of the centers. Similarly, there is an increasing demand for new cultivars or new accessions of existing cultivars from foreign sources that are not yet available to the clean plant centers. These new accessions and cultivars are vital for producers to remain competitive. If clean plant centers do not have the capacity to address these new trends, there is a high possibility that industry will obtain the desired material, clean or not, wherever available, defeating the purpose of the NCPN program. This greatly increases the risk of contracting new diseases and outbreaks. For example, while NCPN has provided virus-tested materials for sweetpotatoes, black rot, a fungal disease re-emerged, and guava root-knot nematode invaded and both were increased and disseminated on non-clean seed.

Finally, most of the reviewed studies that evaluate farm-level management practices do not consider how disease management actions of neighboring growers might increase or decrease the incentive of growers to buy pathogen-tested material and control diseases in general. Exceptions being Atallah et al. 2017 and Singerman et al. 2017 who have started working in this area and suggested greater NCPN successes might rely on coordinated disease management actions.

Given the complexity of disease and crop production, a one-size-fits-all control tactic usually does not exist. Economic studies can shed light on best management practices by including multiple scenarios. We believe additional and more comprehensive information is needed about the production impacts of selected graft-transmissible plant pathogens in order to be able to analyze the cost benefits of pathogen-tested planting materials. Up-to-date and realistic crop enterprise budgets can be used as building blocks for data analysis as well as up-to-date and realistic market price data and sales. Additionally, as new specialty crop cultivars are being bred and new cultivars are imported, many of the past economic studies are becoming outdated and may not reflect the performance of currently adopted cultivars, stressing the need for additional economic studies.

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Appendix

TABLE 1. SUMMARY OF STUDIES WHICH ASSESS THE ECONOMIC IMPACTS AND IMPORTANCE OF RELATED DISEASES

STUDY	CROP/DISEASE	REGION	RESEARCH FOCUS	RELEVANT FINDINGS
ALSTON ET AL. (2013)	Grape Pierce's disease	California	Estimate the cost of disease on winegrape growers and consumer	The study estimated the annual costs of Pierce's disease at $92 million and projected an increase of $185 million without the disease control program at the time.
BABCOCK, BRUCE (2018)	Huanglongbing	California	Estimate of future economic impact	Examined the possible impact of 20% reduction of citrus acreage or yield or combination due to HLB. Resulting economic impact would be a loss of 7,350 jobs and $127 million in associated employment income and could reduce California's GDP by $501 million in direct, indirect and induced impacts.
BRYAN ET AL. (2003A, 2003B)	Sweetpotato feathery mottle virus and other potyviruses	North Carolina	Estimate the impacts of disease in terms of yield and storage root quality using field trials	While G1 plants generally produced higher yields for No. 1 quality than G2-G5 plants, potential net return was greatest for G2 plants due to the high costs for G1 plants.

STUDY	CROP/DISEASE	REGION	RESEARCH FOCUS	RELEVANT FINDINGS
CABALEIRO ET AL. (2013)	Grapevine leafroll disease (GLRD)	Spain	Estimate the economic impact of leafroll on white grape cultivars using NPV analysis	The economic impact of leafroll on white cultivars is as important as the red cultivars
COURT, CHRISTA D., ET AL. (2017)	Huanglongbing	Florida	Economic impact of HLB on contribution of citrus to Florida economy	Updated Hodges and Spreen (2015) Input-Output analysis through 2015-2016 season. Total impacts of HLB were estimated at an annual average of $1.098 billion.
FULLER ET AL. (2019)*	Grapevine leafroll disease (GLRD)	California	Estimate the costs and benefits of a pathogen-screening program for GLRD	Economic benefits from the GLRaV-3 testing, therapy, and distribution programs were in excess of $20 million/yr for the region and substantially outweighed the costs. Removing and replacing diseased vines showed potential benefits. Significant costs were associated with disease entering from infected vines on neighboring properties.
GÓMEZ ET AL. (2010) AND ATALLAH ET AL. (2012)*	Grapevine leafroll disease (GLRD)	New York	Analyze the impact of GLRD and identify the best management options under several scenarios	Results suggest that the economic cost of GLRD ranged from $25,000 to $40,000 per ha in New York.

STUDY	CROP/DISEASE	REGION	RESEARCH FOCUS	RELEVANT FINDINGS
HODGES AND SPREEN (2012)	Citrus greening (HLB)	Florida	Estimate the economic impact due to HLB	The estimated impacts from HLB in Florida is around $8.92 billion in revenue and $4.62 billion in gross domestic product between the 2006/2007 and 2010/2011 crop seasons
MOSS ET AL. (2015)	Citrus greening (HLB)	Florida	Estimate the economic impact due to HLB	The study estimated an economic loss of $18 million in producer surplus and $154 million in consumer surplus.
RICKETTS ET AL. (2015)*	Grapevine leafroll disease (GLRD)	California	Analyze the impact of GLRD and identify the best management options under several scenarios	Results suggest that the economic cost of GLRD ranged from $29,902 to $226,405 per ha in California.
RICKETTS ET AL. (2017)*	Grapevine red blotch disease (GRBD)	California, New York, and Washington	Analyze the impact of the disease and identify the best management options under several scenarios	The economic costs of GRBD from $2,213/ha to $68,548/ha depending on the location
ROISTACHER (1996)	Citrus greening (HLB)	Thailand	Estimate the economic impacts of HLB in Thailand	The study indicated the drastic impacts from HLB and suggested a program with a combination of methods to control HLB.

STUDY	CROP/DISEASE	REGION	RESEARCH FOCUS	RELEVANT FINDINGS
SÉTAMOU ET AL. (2019)	Huanglongbing	Texas	Estimate impact of HLB on Texas citrus industry.	HLB detection sites increased progressively reaching 26% and 40% of commercial groves and residential sites, respectively by 2017.
WELLIVER ET AL. (2014)	Plum Pox	Pennsylvania	Document the detection and eradication of the disease in Pennsylvania from 1999-2009	The estimated cost of removal and destruction is around $30 million over ten-year period, with an additional $29 million operation cost of the program.

Note: Studies with * are cross listed in the other tables

TABLE 2. SUMMARY OF STUDIES WITH ECONOMIC EVALUATION OF FARM MANAGEMENT STRATEGIES FOR RELATED DISEASE

STUDY	CROP/DISEASE	REGION	RESEARCH FOCUS	RELEVANT FINDINGS
ATALLAH ET AL. (2015)	Grapevine leafroll disease (GLRD)	Not region-specific	Estimate the spatial-dynamic diffusion of the disease to inform profit-maximizing control strategies	Spatial targeted strategies and age-structured strategies outperform the others
ATALLAH ET AL. (2017)	Grapevine disease	Not region-specific	A model that captures the spatial-dynamic externalities	The socially aggregated payoffs were affected by the difference in grape prices and the result suggested that the social cost depends on the spatial dynamics.
BRYAN ET AL. (2003A)*	Sweetpotato feathery mottle virus and other potyviruses	North Carolina	Estimate the impacts of disease in terms of yield and storage root quality using field trials	Estimated revenues from production using G1-G5 seeds from virus-tested stock
GÓMEZ ET AL. (2010) AND ATALLAH ET AL. (2012)*	Grapevine leafroll disease (GLRD)	New York	Analyze the impact of GLRD and identify the best management options under various scenarios	The study indicated that partial replanting with pathogen-tested stock was the cost-minimizing strategy in some scenarios.
KAPLAN ET AL. (2016, 2018)	Grapevine trunk disease	California	Analyze the best management practice for the disease	Adopting preventative practices combined with vine surgery outperforms other management strategies.
MORRIS AND MURARO (2008)	Citrus greening (HLB)	Florida	Evaluate the management strategies and control options	The results suggested resetting as the optimal strategies.

STUDY	CROP/DISEASE	REGION	RESEARCH FOCUS	RELEVANT FINDINGS
RICKETTS ET AL. (2015)*	Grapevine leafroll disease (GLRD)	California	Analyze the impact of GLRD and identify the best management options under various scenarios	The study suggested optimal management strategies based on the GLRD prevalence
RICKETTS ET AL. (2017)*	Grapevine red blotch disease (GRBD)	California, New York, and Washington	Analyze the impact of GRBD and identify the best management options under various scenarios	The study suggested replanting with pathogen-tested vines only if the disease prevalence is low. If disease incidence is high, then the manager should replace the full vineyard.
ROKA ET AL. (2009)	Citrus greening (HLB)	Florida	Evaluate the advanced production system and open hydroponic system for citrus production.	Need higher yield per acre to cover the establishment costs. The NPV analysis indicated that high planting density will generate higher future revenue.
SALIFU ET AL. (2012)	Citrus greening (HLB)	Florida	Evaluate the costs of different control strategies	Results indicated that the optimality among strategies depends on the age of trees and the initial rate of disease incidence at first detection.
SINGERMAN ET AL. (2017)	Citrus greening (HLB)	Florida	Evaluate the yields from area-wide blocks using coordinated sprays to psyllids with uncoordinated blocks	Yields in blocks using coordinated spraying were 28%, 73%, and 98% greater in 3 consecutive seasons compared with blocks with less participation in coordinated spraying.

Note: Studies with * are cross listed in the other tables

TABLE 3. SUMMARY OF STUDIES WITH ECONOMIC EVALUATION OF PATHOGEN-TESTING PROGRAMS AND/OR THE ADOPTION OF PATHOGEN-TESTED MATERIALS

STUDY	CROP	EVALUATED STRATEGY	ESTIMATION METHOD	RELEVANT FINDINGS
BRYAN ET AL. (2003A)*	Sweetpotato feathery mottle virus and other potyviruses	North Carolina	Numerical comparisons	Estimated revenues from production using G1-G5 seeds from virus-tested stock
CEMBALI ET AL. (2003)	Apple, sweet cherries, and Clingstone peaches	National Research Support Project 5 (NRSP-5)	Welfare analysis	Total benefits were estimated at $227.4 million a year, which is more than 420 times the cost of the program.
FROST ET AL. (2013)	Potato	Wisconsin Seed Potato Certification Program (WSPCP)	Statistical comparisons	The study suggested that cooperative programs to stabilize seed production and prices have aided in identifying the magnitude of each of these challenges and will also aid in management of these complex problems.
FUGLIE ET AL. (1999)	Sweetpotatoes	Distribution of pathogen-free propagating materials	Cost-benefit analysis	The internal rate of return was estimated at 202 percent.
FULLER ET AL. (2013, 2019)*	Grape	GLRaV-3 testing and distribution programs	Cost-benefit analysis, welfare analysis	The estimated economic benefits from the programs, $20 million per year for the region, were found to substantially outweighed the costs.

STUDY	CROP	EVALUATED STRATEGY	ESTIMATION METHOD	RELEVANT FINDINGS
FULLER ET AL. (2017)	Seed potato	Potato virus Y (PVY)-screened plants	Regression model, profit calculation.	The study suggested the importance of seed screening.
GUENTHNER ET AL. (1991)	Potato	Maine's mandatory seed law, implemented in 1981	Multiple linear regression	Results suggest that Maine potato yields increased, total acreage decreased, seed potato acreage increased, seed potato rejections from certification decreased, seed potato prices increased, and commercial potato prices decreased. Estimated an average increase in commercial potato grower farm profits of $14,700 per year.
SEAVERT AND JULIAN (2012)	Apple, cherry, pear, and peach	National Clean Plant Network (NCPN)	Cost-benefit analysis	Without plant certification programs, the study estimated a reduction in grower returns range from $828 million to $4.7 billion.
SINGERMAN, ET AL.	Citrus	vector control and area-wide pest management-Citrus Health Management areas	Random effects model and a pooled OLS model	Yields were greater with higher participation in Citrus Health Management Areas.

STUDY	CROP	EVALUATED STRATEGY	ESTIMATION METHOD	RELEVANT FINDINGS
TROENDLE (2017)	Grape	NCPN-grape centers	Welfare analysis	The analyses projected that the returns to public investments on pathogen-testing plants from 18 to 134 percent. The analysis also suggested that grape growers and nurseries capture most of the benefits as opposed to wineries.
VERTERAMO CHIU, ET AL. (2016)	Grape	NCPN-grape center in New York state.	Cost-benefit analysis	The study found that the NCPN-grape center provided positive net benefits.

Note: Studies with * are cross listed in the other tables

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