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REVIEW

Triple bottom-line consideration of sustainable plant disease management: From economic, sociological and ecological perspectives

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Abstract
Plant disease management plays an important role in achieving the sustainable development goals of the United Nations (UN) such as food security, human health, socio-economic improvement, resource conservation and ecological resilience. However, technologies available are often limited due to different interests between producers and society and lacks of proper understanding of economic thresholds and the complex interactions among ecology, productivity and profitability. A comprehensive synergy and conflict evaluation of economic, sociological and ecological effects with technologies, productions and evolutionary principles as main components should be used to guide sustainable disease management that aims to mitigate crop and economic losses in the short term while maintaining functional farm ecosystem in the long term. Consequently, there should be an increased emphasis on technology development, public education and information exchange among governments, researchers, producers and consumers to broaden the options for disease management in the future.

Keywords: plant disease management, agricultural sustainability, disease economics, food security, resource conservation

1. Introduction

Plant diseases pose serious threats to food security, economic development, social stability and ecological sustainability (Burdon *et al*. 2020). Starvation and malnutrition during the Irish potato famine (1840s) caused by the potato late blight pathogen and the Bengal famine (1943) caused by rice brown spot disease resulted in millions of deaths and uprooted family and social structures. Such potential dangers continue to be present such as the threat posed to food supplies by the Ug99 strain of wheat stem rust in many developing countries (Li *et al*. 2019), the 13_A2 strain of potato late blight in Europe (Li *et al*. 2012) and emerging and spread of rice blast (Zheng *et al*. 2020). In industrialized agricultural systems, high resource inputs, intensification, monoculture and globalization all increase the potential for plant disease epidemics on a large spatial

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scale (Zhan *et al*. 2014, 2015). Indeed, direct losses in production and the use of preventative measures associated with plant breeding and pesticide application in these systems create economic costs in the billions of dollars per year (Verger and Boobis 2013).

Beyond agricultural production, plant disease can also have devastating impacts on forest resources and entire ecosystems (e.g., outbreaks of Dutch elm disease (Abboud *et al*. 2018), chestnut blight (Clark *et al*. 2019), pine blister rust (Landguth *et al*. 2017), and *Phytophthora* die-back (Lee *et al*. 2019)) with consequent economic and sociological effects. Furthermore, while many previously important crop diseases are now better controlled, the management strategies involved currently often have also caused serious impact on ecological services and threatened human and wildlife health, particularly if pesticides are used inappropriately and overwhelmingly. With the rise of environmental conservation and ecological sustainability in the late 1980s, the paradigm for plant disease management has gradually shifted from solo function for primary production to multiple functions serving for societal and natural needs and agricultural producers are now faced with the dilemma of achieving effective and convenient disease control to ensure immediate economic returns, while simultaneously meeting societal expectations for plentiful, high quality and cheap food with minimal negative effects on broader environment providing for immediate and long-term ecological service for societal and natural sustainability.

The current plant disease management paradigm tends to emphasize the importance of short-term economic benefits and societal need while largely ignoring the long-term ecological and evolutionary impacts on environment and sustainability. In essence interaction model among ecology, agricultural productivity, profitability and management success in the established plant disease management philosophy is simply not sustainable in the long term (He *et al*. 2016). Addressing this dilemma requires answers to a number of outstanding questions through a multi-dimensional, comprehensive analysis of synergies and conflicts of plant disease management in economic, social and ecological contexts:

(1) How does plant disease management have multifaceted short- and long-term impacts on producer's income, food security, social development, resource conservation, pathogen evolution, and ecological integrity?

(2) What are the benefits and costs associated with externality of plant disease management and how should they be taken into consideration in the decision-making processes of plant disease management?

(3) Why are development and dissemination of plant disease management technologies that are effective, durable, resource saving and environment friendly urgently needed and how can these technical development and dissemination keep pace with change in natural resource, pathogen, environment and societal expectation? and,

(4) Why is the application of Darwinian principles important to ecological management of plant disease with a great sustainability and high efficiency?

2. Economic, sociological and ecological impacts of plant disease management

Food security is one of the major concerns globally. Total food supply alone does not fulfill the requirements of food security because human health and social stability are built upon the food that is safe, nutritious, accessible, affordable and available in different forms (Burdon *et al*. 2020). Plant disease management, primarily through the deployment of resistance gene and application of synthetic pesticides, plays an important role in food security, as well as in economic development and social stability by increasing crop productivity, reducing food contamination by microbial toxins, contributing to lower food prices, and facilitating the growth of diverse crops in marginal areas. In turn, improved consumer affordability and food supply increase societal expectations for safe and high quality foods. It has been estimated that the implementation of plant disease management has contributed about one-third of the increase in global food production seen in the last decades (Savary *et al*. 2019) and ensured the successful growth of crops in areas that were historically unsuitable due to biological threats. Furthermore, plant disease management reduces the risk of aesthetic and economic damage to the natural landscape (i) when infectious disease runs rampant (for example, Dutch elm disease and sudden oak death in Europe and the western United States respectively) and (ii) through its contribution to increased crop yields which may reduce pressures for incorporation of new land into agricultural production. With the continuing increase in the size of the human population and losses in arable land in the coming decades, the role of plant disease management in food security, economic development, social stability and landscape maintenance is expected to increase (Carroll *et al*. 2018).

However, plant disease management has, directly and indirectly, also caused unintended problems for human society. Though more multifaceted approaches resulting from scientific and technological advantages have been proposed and adapted, plant disease management still relies heavily on the use of major host resistance gene and the application of synthetic pesticides. Inappropriate use of resistance in the current disease management paradigm facilitates the evolution of pathogens to new infectivity (Burdon *et al*. 2014; Burdon and Thrall 2014) and greater aggressiveness (Papaïx *et al*. 2015), thereby reducing the lifespan and economic return of breeding for host resistance and facilitates the loss of natural resources (e.g., resistant genes). While it generally requires 5–10 years to incorporate a resistance gene into a commercial variety and the availability of naturally occurring major genes for resistance (R genes) is finite, major gene resistance can be overcome by pathogens within 3–5 years of continuous cultivation of individual cultivar.

In many developed countries, the production of crops involves many in-season applications of pesticides even though many of these applications are prophylactic and bring no production and/or economic benefits (Rosenheim *et al*. 2020). For example, up to 16 fungicide sprays are executed annually to control potato late blight (Li *et al*. 2012) and more than 20 fungicide sprays are applied to control rose mildew (Gullino and Baribaldi 2006). In North America, managing fungal diseases of red winter wheat with fungicide applications may generate positive net returns in one year but not in others (Thompson *et al*. 2014), and increasing yield by fungicide application may not be translated into economic benefits in some cases (Ficke *et al*. 2018). In developing countries, dependence on pesticide application is also increasing rapidly in recent years (Leong *et al*. 2020). For example, extensive pesticides have been used to control strawberry, chrysanthemum and other plant diseases in Vietnam (Houbraken *et al*. 2016). Extensive and inappropriate application of pesticides increases resource wastage and input costs in the short term, and impacts human health, environmental integrity and ecological function through pollution and biodiversity reductions in the long term (He *et al*. 2016). It is estimated that there are at least several million cases of pesticide poisoning in the world each year, with approximately 200 000 deaths though it is not clear what proportion of these poisonings are directly attributed to plant disease management (Eddleston *et al*. 2008). Pesticides that indiscriminately kill both target and non-target species have increasingly caused secondary outbreaks of previously minor pests (Yang *et al*. 2017). Pesticide residues in crop production and run-off into other environments such as other fields, grazing lands, human settlements, rivers and natural areas pose a considerable threat to human, livestock and wildlife health and contribute to the general pollution of the physical and biological environment (Sponsler *et al*. 2019). Consequently, there are increasing societal expectations for reduced pesticide or even free-pesticide agriculture in Europe and many other parts of the world.

3. Challenges of decision making in plant disease management

Individual agricultural producers select and execute plant disease management strategies and understandably choose approaches that are generally easy to apply and save labor. More importantly, because producers only incur the short-term, direct costs associated with plant disease management they tend to select strategies that produce the best disease control but usually discount or ignore potential negative impacts of these management strategies on resource sustainability and environmental conservation (He *et al*. 2016). As a consequence, some highly effective disease management strategies such as major gene resistance and the application of synthetic pesticides have been used without sufficient regard to their long-term consequences such as the quick "breakdown" of resistant cultivars (Li *et al*. 2019), the rise of resistance to pesticides (Varah *et al*. 2020) and damage to ecology (Tang *et al*. 2019). In contrast, other more traditional management approaches which may seem less effective due to their greater complexity, or accept the presence of low disease levels are largely ignored, particularly in developed countries, even though millennia of natural selection has shown these traditional farming practices are more resource and environment friendly, and hence, sustainable. For example, even though both empirical and theoretical studies have shown that host diversification benefits resilience and capability of production, reduce disease epidemiology and pathogen evolution and improves soil fertility (Zhan *et al*. 2002; Sommerhalder *et al*. 2011; Yang *et al*. 2019), this agricultural practice has not been accepted by most of farmers.

The lack of an appropriate understanding of the complex interactions occurring among natural, agricultural, societal and economic elements also discourages agricultural producers from adopting sustainable plant disease management strategies (He *et al*. 2016). Agricultural productivity, marketing behaviors, producer profitability and environment health are intertwined (Fig. 1). In the long term, a healthy environment resulting from sustainable disease management benefits agricultural producers substantially through its positive impact on land productivity (e.g., increased soil fertility, enhanced soil microbial diversity), crop quality (e.g., balanced nutrition, reduced pesticide residue), resource consumption (e.g., reduced mineral element leakage; extended R gene longevity), management inputs and marketing prices. It has been documented that reduced host heterogeneity in the 20th century has increased the leakage of mineral elements from agricultural fields into the wider environment (Hatfield *et al*. 2009) and

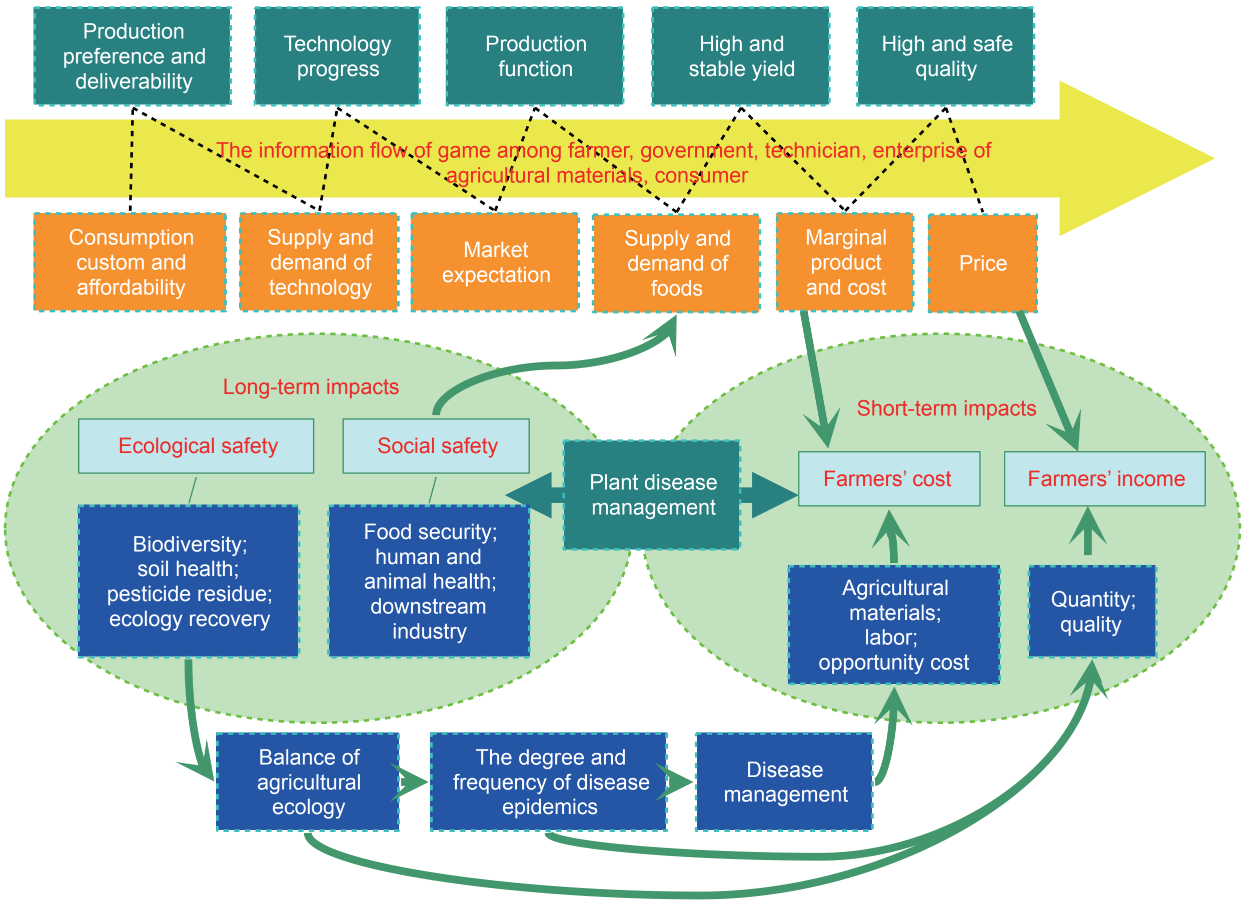

Fig. 1 Interaction among ecology, disease management efficiency, agricultural productivity and profitability. Each plant disease management action can have direct impacts on agricultural productivity and profitability in the short-term and indirect impacts on the environment and society in the long-term. Shifts in ecological properties such as biodiversity and soil fertility associated with the adoption of plant disease management strategies can affect the degree and frequency of disease epidemics, the efficiency of resource utilization, and the quantity and quality of agricultural production. In turn these influence the cost of plant disease management, the price of agricultural products and producer's profits. Sustainable plant disease management strategies such as diversification may result in lower productivity in the short-term due to their acceptance of non-zero levels of disease but in the long-term, these strategies may increase productivity and profitability as healthier environment for plants may generate sub-optimum conditions for disease development and pathogen evolution as well as the value for products with a 'clean, green' image.

facilitated evolutionary change in pathogens resulted from strong directional selection in a longer term (Zhan and McDonald 2013). In addition to other factors, high epidemic risk of plant diseases in reduced host heterogeneity systems may be caused by shrinking biodiversity in soil microbial community. Soil microbial communities that interact with the plant can act as an ecological defense against pathogen infection attributable to intensified resource competition with non-pathogenic microbes (Durán *et al*. 2018). Our recent results from multiple locations and years in the potato–late blight interaction indicate that increased host diversity achieved through cultivar mixtures increases potato yield and quality, production stability, soil fertility and microbial diversity, while simultaneously reducing the aggressiveness and evolutionary speed of *Phytopthora infestans* isolates (Yang *et al*. 2019).

Unpredictability of disease development and incomplete knowledge of the relationship among plant disease severity, production and economic impact, combined with a lack of policy support and asymmetric information flow among consumers, producers and researchers have also hindered the adoption of sustainable plant disease management strategies (He *et al*. 2016; Echodu *et al*. 2019; Burdon *et al*. 2020). The implementation, effectiveness and profitability of plant disease management are influenced by climatic, marketing and sociological conditions as well as host and pathogen traits (Sherman *et al*. 2019; Li *et al*. 2020), but producers often lack knowledge of real-time disease occurrences, critical control points, technology choices and consumer preferences (Mazigo *et al*. 2019). Taking organic farming as an example, plant disease management options in this cropping system are limited (Subhalakshmi

2019) but some newly developed and highly effective technologies have been largely ignored by producers. It has been documented experimentally that colonizing fields with atoxigenic *Aspergillus flavus* strain AF36 is very effective in controlling aflatoxin contamination in crops (Hruska *et al*. 2020). Surprisingly, this technology has been rarely used in commercial production systems, partially due to public concerns regarding its safety. On the other hand, there are no incentive polices promoting organic farming systems in many countries and consumers may be reluctant to buy organic foods if prices are too high either due to low purchasing power or if there is a lack of transparent information relating to the products (Massey *et al*. 2018; Ha *et al*. 2019).

4. Trade-offs of plant disease management strategies

4.1. Factors associated with the producer's balance of inputs and immediate returns in plant disease management

As with any marketing economy, agricultural producers tend to give top priority to short-term economic benefits. In applying plant disease management, they aim to reduce disease occurrence and severity to a minimum, thereby increasing agricultural productivity to a maximum. This philosophy of disease-free or near-free plant disease management assumes that less disease is always associated with higher productivity, and that the highest productivity always leads to the best economic return. However, it should be understood that the actual economic profit of a plant disease management strategy implemented on farm is determined not only by productivity and the cost associated with the disease management but also by other biological (e.g., the component of seed costs attributable to resistance breeding; pathogen type and frequency of occurrence) and marketing factors (e.g., demand–supply balance, quality of production). Hence, plant disease management strategies that routinely proactively aim for the highest in-crop productivity will not necessarily guarantee either the best immediate or long-term return to agricultural producers (Fig. 2).

In a biological context, as a result of mechanisms including compensation, tolerance and other genetic and physiological responses by the host (Mesa *et al*. 2017; Soares *et al*. 2017), disease severity is not always linearly correlated to crop productivity. When disease severity is reduced, the effectiveness of further control declines disproportionately while the costs involved are disproportionately higher (Fig. 2-A). In such a case, although final productivity per unit of land may increase, actual profit may be very low or even negative due to excessive application of resources. Furthermore, the short-term economic impacts of disease

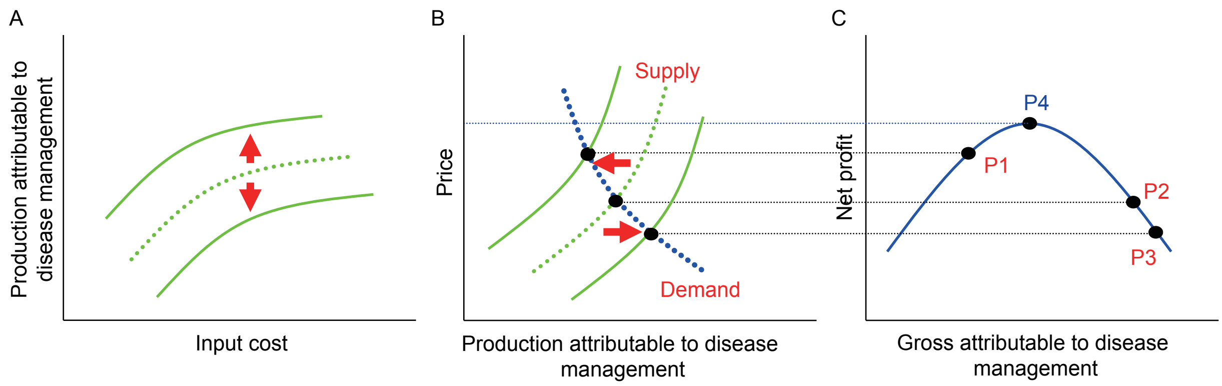

Fig. 2 Management cost, market price and economic profit as a function of total production attributable disease control (quantity) and the impacts of externalities on economic behaviors of plant disease management approach. A, the full cost to produce a unit of agricultural commodity increases nonlinearly as the disease-control related component of total production increases (dash line). This cost is under-estimated when the sunk cost of negative externalities is excluded from full economic evaluation of plant disease management (left solid line), encouraging agricultural producers to invest more in disease management resulting in over application of the management strategies that are most effective and that can generate immediate economic returns for the producers. On the other hand, exclusion of positive externalities (right solid line) from full economic evaluation results in an over-estimate of the actual cost of producing a unit of commodity, discouraging agricultural producers from adopting plant disease management strategies with positive ecological and societal impacts. B, if market demand (consumption) for a commodity is constant, increased total production leads to a reduction in price due to both increased supply and depressed market expectations. C, the producer's net profit resulting from plant disease management is P2 when externalities are not included in economic evaluations. When externalities are included, the net profit for agricultural producers is P1 and P3 for adoption of management strategies with positive and negative impacts to ecology and society, respectively. The goal of sustainable plant disease management is to achieve maximum profit (P4) by technology development, government regulation and public involvement.

can vary significantly among crops and pathogens.

In contrast to most field crop-pathogen interactions, quality may play a significantly greater role than quantity (productivity) in determining the market price of vegetable, fruit and ornamental crops. In these situations, even low levels of disease may be commercially unacceptable. For example, apples have a much lower value when they are produced for juice instead for fruit as a result of scab infections. Quality also becomes very important in field crops involving toxin-producing pathogens such as aflatoxins produced by *Aspergillus flavus* in maize (Rajasekaran *et al*. 2019) and deoxynivalenol produced by *Fusarium graminearum* in wheat and barley (Nogueira *et al*. 2018; Mandalà *et al*. 2019) where very low levels of infections can generate sufficient toxin to contaminate the entire harvest.

In a marketing context, though influenced by many factors including purchasing power, quality of products and preference of customers, the final price received by producers for their agricultural products is mainly determined by the balance of supply and demand. Severe disease outbreaks may lead to an increase in commodity prices due to a sudden shortage in supply and increasing productivity through disease management may have a counter-intuitive effect altering the demand-supply relationship, reducing expected profit (Fig. 2-B). Market expectations of oversupply due to good harvest may result in further reductions in price and hence the benefit (profit) attributable to effective plant disease management (Borsellino *et al*. 2020). However, this purely marketing performance does not imply that plant disease should not be controlled. For individual producers, inadequate control of plant diseases in a severe outbreak always leads to economic loss due to no or less harvest.

4.2. Externalities of plant disease management

More importantly, there are trade-offs between short-term, direct costs (benefits) of plant disease management to agricultural producers and long-term, indirect costs (benefits) to society. In coastal California, lettuce wilt caused by *Verticillium dahliae* is usually associated with growth of infested spinach seeds in the preceding crops. Planting spinach seeds with little or no *V*. *dahliae* in the preceding crops is an economic and efficient approach to prevent Verticillium wilt of lettuce but farmers are reluctant to do this because *V*. *dahliae* does infect spinach crops (Carroll *et al*. 2018). These trade-offs resulted from the impacts, positively or negatively, of plant disease management can affect environmental sustainability, natural resource conservation, landscape structure and biodiversity, etc. Given the central role of these factors to social development, agricultural productivity and human health and the significant costs and substantial time required to restore them after damage, some disease control strategies may have long-term, indirect benefits to both agricultural producers and society, reducing the actual costs of plant disease management. Oppositely other control strategies, though very effective, may lead to long-term, indirect damage to society, thereby increasing the total cost of plant disease management (Table 1). To date, these long-term, indirect benefits or costs (i.e., externalities) have not been taken into account in the economic analysis of plant disease management (Almeida *et al*. 2018).

Depending on how individual strategies impact on society and the environment, externalities associated with plant disease management can be divided into many categories (Table 2). Externalities emerge when the effect of plant disease management on other parties such as society and ecology is not reflected in the calculation of cost and profit (Zheng *et al*. 2019). Costs associated with the production of goods with chemical residue or treating workers affected by pesticides are negative, short-term externalities caused by plant disease management. Long-term negative externalities include environmental deterioration such as reduced soil health, water contamination, or loss of biodiversity, which in turn may generate negative impacts on the quality and productivity of crops, escalate of resource depletion of plants (e.g., resistance genes), or facilitate the evolution of pathogens. These negative externalities become a sunk cost, leading to an over-estimate of the economic benefits attributable to plant disease management (Table 1; Fig. 2-C).

Equally though, benefits that are not recognized lead to an under-estimate of the positive contribution of plant disease management. Positive externalities include impacts on the disease management of neighboring farms, on the evolutionary potential of pathogens (reduced), on the ecological resilience, and on social stability and development. For example, controlling plant diseases including the rational use of pesticides reduces pathogen population sizes, thereby also reducing their evolutionary potential to overcome resistance and pesticides (Gossmann *et al*. 2012). Similarly, application of plant disease management practices on one farm reduces epidemic pressure in nearby farmers' fields. For pathogens that produce toxins, positive externalities resulting from the implementation of management strategies can also include the reduced risk of poisoning livestock and humans, and consequent benefits in social development and food security.

5. Ways and opportunities to achieve multifunctional services of plant disease management

Sustainable plant disease management is multifaceted and

Table 1 Short- and long-term impacts of plant disease management strategies on convenience of application for agricultural producers, economic return, ecological integrity and pathogen evolution

Disease management strategy	Short-term impacts on producers				Long-term impacts on society		
	Convenience	Cost	Effectiveness	Profitability	Pathogen evolution	Agricultural resilience	Biodiversity in time/space
R gene sequential deployment	High	Low	High	High	High	Low	Low
R gene mixtures	Medium	Medium	Medium	High	Low	High	High
R gene recycle[1)]	Medium	Low	Low	Medium	High	Low	Medium
R gene rotation[2)]	Medium/Low	Medium	High	Medium/High	Low	Medium/High	High
R gene pyramid	High	Low	High	High	High	Medium	Medium
R gene regional deployment	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Quarantine	Low	High	High	Medium/High	Low	High	n/a
Hygiene	Low	High	Medium	Medium	Low	High	n/a
No-till cropping	High	Low	Medium/Low	Medium	Low	Medium	n/a
Crop rotation	Medium/High	Low	Medium/High	High	Low	High	High
Planting time	Medium	Low	Medium	Medium	Low	High	n/a
Pesticide	Medium	High	High	Medium	High	Low	Low
Bio-control	Medium	High	Medium/Low	Medium	Medium	High	n/a
Physical soil treatment	Low	High	Medium	Medium	Low	High	n/a

[1)] R gene variety is recycled after it has been 'defeated' by the evolution of pathogens.
[2)] R gene variety is replaced before it has been defeated by the evolution of pathogens.

expected to improve the short-term income of agricultural producers as well as to assist in maintaining land productivity, strengthening food security, preserving biodiversity, managing renewable natural resources and safeguarding social-economic viability (He *et al*. 2016). Over the last decades, attention in policy, planning and research in the agricultural sector has gradually shifted from a single goal of productivity to the provision of these multiple services and functions. Correspondingly, the philosophy in plant protection has been changed from integrated plant disease management focusing on pathogen eradication to ecological disease management emphasizing the creation of environments conducive to the growth and immunity development of hosts but suboptimum for the survival, reproduction, transmission and evolution of pathogens. To achieve these multiple goals, an integrative trade-off analysis and comprehensive economic consideration of plant disease management is required (Springmann *et al*. 2018). All costs and returns associated with a plant disease management including externalities related to long-term effects on the environment and society should be taken into account so that agricultural producers can formulate management schemes to maximize the total benefit. Including such externalities can have significant impacts on the benefit and choice of plant disease management strategies by agricultural producers (Fig. 2). Taking pesticide management of plant diseases as an example, total benefits (producer and society) are substantially reduced when externalities are included in economic analysis. Though it is well known that externalities are an important part of plant disease management, estimates can be rarely found in literature, possibly due to a lack of robust approaches to quantify them. For example, a few methods have been developed to score the externality effects of using pesticides to manage plant diseases but no agreement was found among the scores (Agost and Velázquez 2020).

Technological developments such as marker-assisted breeding (Ma *et al*. 2018), molecular diagnosis (Scala *et al*. 2018), digital agriculture (Basso and Antle 2020) and sophisticated in-field precision farming approaches (Rimbaud *et al*. 2019) coupled with increased public attention on environmental conservation, raise the real possibility of balancing the services of plant disease management to food security, social economic development and ecological sustainability. Recently, plant pathologists have increasingly highlighted the importance of applying evolutionary ecology principles for sustainable disease management strategies (Zhan *et al*. 2014, 2015; Burdon *et al*. 2020) and have stressed the potential of subjecting pathogens to disruptive selection by manipulating the spatiotemporal structure of hosts (Burdon *et al*. 2014; Burdon and Thrall 2014). For example, it was found that landscape structures that promoted smaller pathogen populations (smaller plot) on a wild host mitigated

Table 2 Types and examples of externalities associated with plant disease management

Type	Examples
Biotic	Biodiversity, pathogen evolution, resistance durability, genetic resource
Abiotic	Characterization of soil, water and air, climate change
Short-term	Human, wildlife and livestock poisoning, third party epidemics
Long-term	Pesticide residue, balance of pathogens, environment, wildlife, livestock and human health, ecosystem resource and downstream industry
Positive	Improving consumer welfare, maintaining natural landscape, ensuring social stability and safety, reduced pathogen population size, reduced third party epidemics, minimizing toxin production, etc.
Negative	Pollution, toxin, carcinogenesis, ecological degradation (biotic and abiotic), resource depletion, increased disease management costs and reduced disease management efficiency, etc.

the emergence of new pathotypes and reduced the potential of pathogens to adapt to the adjoining crop (Papaïx *et al*. 2015). However, while the use of varietal mixtures and multiline has been advocated repeatedly in the past (Wolfe *et al*. 1985; Mundt *et al*. 2002), there remains a reluctance among breeders and seed companies to adopt this disease management philosophy due to perceived problems associated with quality standards, variable maturity dates and consequent marketing issues. Yet, new approaches in plant breeding, coupled with molecular and genomic technologies (Mi *et al*. 2018), and the increasing availability of genomic information linked to functional understanding that facilitates the use of highly specific gene-editing techniques (Bak *et al*. 2018) makes the rapid production of truly isogenic lines differing for specific traits only eminently feasible. Adoption of these techniques will greatly increase opportunities to put the pathogen 'on the back foot' by deliberately pushing it into an environment of variable selection that will disrupt its ability to track host changes. This should lead to a significant increase in the durability of individual crop varieties with concomitant reductions in the use of fungicides. Associated with this, quick, accurate and timely diagnosis of plant diseases by the application of molecular technology will also enhance the cost efficiency of management (Paul *et al*. 2019).

Full economic evaluation of plant disease management involves multi-dimensional interactions across agricultural, economic, social and natural systems. Traditional models focusing on single dimensions such as an agricultural producer's income and simple elements such as productivity will not serve the purpose. With the advance of computation technology in recent years, particularly in the areas of modeling and simulation, such full estimates of short- and long-term economic costs and benefits associated with plant disease management strategies become possible. Through specialized algorithm and visualization software, modeling allows many factors in disease management networks to be evaluated simultaneously thereby assisting prediction of how best economic benefit can be achieved under different ecological, environmental, marketing and social scenarios. Furthermore, developments in mobile information exchange technologies are revolutionizing the financial sophistication of farm decision-making processes. Thus, in Australia top wheat producers are now routinely using a variety of 'apps' on hand-held computers to assess the impact of fertilizer application on likely yield at various stages in the season and determine whether the costs involved are supported by expected values on international wheat futures markets. Bringing the cost–benefit profile of disease management practices (including the willingness of consumers to pay for environmental benefits) into such approaches is essential and inevitable.

Government intervention aimed at balancing supply and demand in the food and technology sectors is also crucial to achieve sustainable plant disease management. When food supply and affordability are guaranteed, governments should incentivize the application of plant disease management strategies that have long-term ecological and environmental benefits even if these may lead to lower productivity by subsidizing agricultural producers (Zheng *et al*. 2019) who adopt sustainable approaches. In this case, regulatory policy associated with energy management can provide an example for how externalities could be transferred in plant disease management strategies. Such systems typically levy additional tax for the discharge of greenhouse gas from fossil fuels and financially subsidize clean energy generated from renewable resources. Governments can also play a role by: (i) increasing research and technology investments favoring the development of sustainable plant disease management strategies aimed at maximizing combined triple bottom-line benefits with social, ecological and economic perspectives (Fig. 2-C); (ii) insisting that this knowledge and technology be transferred to agricultural producers in a user-friendly form; and (iii) enhancing information exchange among agricultural producers, researchers, educators, consumers and the public as to the availability and genetic, societal and environmental consequences of management technologies. Social development and public awareness of the advantages and disadvantages of plant disease management are also extremely important. For example, genetic modifying techniques are highly controversy in publics (Napier *et al*. 2019) though they can be very useful in sustainable plant disease management by keeping plants in co-evolutionary advantage over pathogens through a quick integration of novel resistance genes from other species.

Changing societal expectations and increasing disposable incomes enahnce the ability and willingness of consumers to pay a premium for agricultural goods produced in a sustainable way and should encourage government's legislation ensuring such outcomes. Whether that includes financial incentives for agricultural producers to adopt sustainable plant disease management strategies at an international scale remains to be seen.

6. Conclusion and future research directions

Globally, plant disease management has performed remarkably well in the past in assisting in the process of delivering food at progressively lower prices despite rapid population growth. But this success has often been at the expense of depleted natural resources, polluted environments and deteriorating ecological systems. Tackling these long-term problems requires a multi-dimensional and integrative analysis of conflicts and synergies associated with plant disease management in-term of economic, ecological and sociological aspects. A lack of a broadly-based societal understanding of thresholds between inputs and outputs across the plethora of ways in which plant disease management strategies may affect the agricultural and natural environment, either positively and negatively, and the understandable economic focus of agricultural producers on short-term solutions, means that disease management approaches with less immediate effect but better environmental and societal impacts are reluctantly explored and adopted.

To ensure a balance of benefits flowing from plant disease management to food security, social economic development and ecological sustainability, future research should focus on: i) evaluating relationships among costs, productivity and economic benefits of various short-term and long-term plant disease management strategies; ii) determining the potential impacts of environmental and ecological health on soil fertility, efficiency of plant disease management and agricultural productivity; iii) developing new methodologies to quantify externalities; iv) investigating the effects of social economic factors such as consumer preference and government policy on the adoption of plant disease management strategies; and v) exploring the application of molecular, genomic and computation technologies to sustainable plant disease management in order to identify strategies with the lowest trade-off between short- and long-term benefits.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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