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Davide Spadaro[1,2], *Maria Lodovica Gullino*[1,2]

[1] Centro di competenza per l'Innovazione in campo agro-ambientale (AGROINNOVA), Università degli Studi di Torino, Largo P. Braccini 2, 10095 Grugliasco (TO), Italy. E-mail: davide.spadaro@unito.it

[2] DISAFA – Dipartimento di Scienze Agrarie, Forestali ed Alimentari, Università degli Studi di Torino, Largo P. Braccini 2, 10095 Grugliasco (TO), Italy. E-mail: marialodovica.gullino@unito.it

Abstract

The disease management strategy represents an important contribution to the sustainability of the farming systems. Plant disease management attempts to maintain disease levels below economic thresholds because complete elimination of disease is unnecessary and may result in unacceptable costs, labour and environmental impacts. Integrated disease management intends to manage plant diseases by assembling complementary approaches, depending on the pathosystem involved, the geographical location and the pedoclimatic conditions. The current chapter provides several examples of sustainable disease management, with particular reference to the control of soilborne diseases of vegetable and ornamentals crops. Healthy soils are fundamental to sustainable disease management. Most practices designed to improve soil health, such as organic matter supplementation also help to suppress the disease development. The use of healthy or treated propagation material is an effective tool to prevent native or alien pathogens. Chemical control with fumigants and fungicides should be considered when other approaches do not achieve the required pathogen control. Rapid and reliable diagnostic methods allow a rational and efficient choice of the management options. Decision support systems should be developed through forecasting models. The choice of the appropriate plant disease management strategy should not only integrate the impact on the soil and crop health, but also on the agricultural and non-agricultural environments, the natural resources, and human health. Economic, social, legislative and political issues should be considered together with regional, national and international regulations.

Keywords: biocontrol agents, chemical control, diagnostics, induced resistance, integrated disease management, plant pathogen, seed health, soilborne disease, soil health.

Introduction

An important goal of sustainable agriculture is the development of integrated farming systems with reduced use of natural resources (water, soil, energy), as well as of chemical fertilizers and pesticides. Sustainable farming systems should maintain and possibly enhance the quantity and quality of crop production, improve the farmer's income, and balance the economic, environmental and social consequences of human interventions. An important contribution to the sustainability of the farming systems is the choice of the disease management strategy. In fact, despite the use of pesticides, 20–30% of production is estimated to be lost due to plant diseases every year (Oerke 2006). Such figures would be even higher without any intervention for reducing losses causes by plant diseases (Esker et al. 2012). Crop losses due to plant diseases affect the potential production in industrialized countries, but in developing countries they are even costly in terms of food security, foreign exchange requirements for food imports, and income losses to farmers (Oerke et al., 1994).

Plant diseases result from complex interactions among host, pathogen and the environment. The disease triangle represents the main elements required for plant diseases: a susceptible host plant, a virulent pathogen able to cause disease, and a favourable environment. Moreover, time can influence a disease, so the disease triangle could become a tridimensional disease pyramid, by including this element. Other elements important for some disease could be vectors and human activities, which modify the interaction through agricultural practices, genetic resistance and fungicide application (Burdon et al. 2009).

Plant disease management

Plant disease management attempts to maintain disease levels below economic thresholds because complete elimination of disease is unnecessary and may result in unacceptable costs, labour and environmental impacts. Plant disease management faces significant challenges due to increasing demands for safe and diversified food (Flood 2010); reducing the production potential due to land competition in fertile areas; depletion of natural resources; reduction of biodiversity in the agro-ecosystems; and increased risk of disease epidemics due to agricultural intensification, monoculture, and climate change (Dun-chun et al. 2016). The pathogen spread is facilitated by human transportation, but there is an increasing evidence that global warming can drive pathogen movement towards the pole, by altering their latitudinal range (Bebber et al. 2013).

In the late 1960s and 1970s, the commercialization of a large number of broad-spectrum pesticides of novel structure and mostly with systemic activity marked an era characterized by intensified agricultural production. After some years of intensive chemical control, new pathogens became dominant once their competitors were eliminated and fungicide resistance developed (Delp and

Dekker, 1985). To address these problems, growers intensified the use of fungicides, which increased production costs and increased the risk of fungicide residues on crops (Oliver and Hewitt, 2014). Integrated disease management intends to manage plant diseases by assembling complementary approaches, depending on the pathosystem involved, the geographical location and the pedoclimatic conditions. As stated by the European Directive on the Sustainable Use of Pesticides, integrated pest management carefully considers all available plant protection methods and subsequent integration of appropriate measures that discourage the development of pathogen populations and keep the use of fungicides and other forms of intervention to economically and ecologically justified levels, by minimising the risks for human health and the environment. Plant pathogens are difficult to control partly due to their spatial-temporal dynamics and rapid evolution (Strange and Scott 2005), associated with high genetic diversity and short generation times that favour their ability to overcome effective disease control approaches. Integrated disease management emphasises the growth of a healthy crop with the least possible disruption of the agro-ecosystems and encourages natural disease control mechanisms.

Sustainable plant disease management

Sustainable management of plant diseases aims to create environments adverse for the pathogens and suitable for healthy plants, by ensuring high yield through the efficient use of natural resources (Zhan et al. 2015). An agroecological approach should be used for the management of diseases, leading to solutions serving the public good by simultaneously fostering agrifood system productivity and resilience, reducing energy consumption and supporting bioenergy production, as well as conserving water resources (Kremen and Miles 2012). Agroecology is the science of applying ecological concepts and principles to the design and management of sustainable food systems (Gliessman 2014). In addition, economic and societal impacts should be evaluated for each plant disease management scheme. An agroecological system approach to plant disease management consists of four pillars: (i) prevention of pathogen introduction and spread in the cropping system; (ii) reduction of pathogen populations to levels which can be controlled through natural mechanisms; (iii) introduction of practices into the cropping system designed to promote beneficial microbiota; and (iv) reduction of fungicide use through the adoption of integrated disease management (Chellemi et al. 2016). To achieve the goal of sustainable plant disease management, multidisciplinary collaboration between disciplines, such as plant pathology, plant breeding, agronomy, horticulture, agricultural entomology, soil science, environmental science, economics and social sciences is needed. Agroecology, besides being multidisciplinary, is also transdisciplinary, as it incorporates elements of practice and collective action, which enable the scaling of agricultural practices from individual farms to larger landscape-level (DeLonge and Basche 2017).

The current chapter provides several examples of sustainable disease management, with particular reference to the control of soilborne diseases of vegetable and ornamentals crops. Soilborne pathogens can cause heavy losses in vegetable production, by affecting both yield and quality. Soilborne pathogens can occur from the initial nursey stage, to the harvest. In vegetable production, crop rotations are minimal and soilborne pathogen propagules may accumulate in the soil, which is the primary inoculum. Soilborne pathogens are particularly favoured in vegetables, which are an intensive and dynamic system, characterized by a wide range of crop species and varieties, a continuous introduction of innovative technologies and the use of intensive cultivation techniques. For the above-mentioned reasons, the management of soilborne diseases in vegetable production represents a very interesting case study, both in terms of phytopathological issues and innovative strategies adopted for their control (Colla et al. 2012).

MAINTAINING HEALTHY SOILS

Healthy soils are fundamental to sustainable disease management, as they affect the density of pathogens, particularly of the soilborne ones (Janvier et al. 2007), the structure of beneficial microbiota, and the availability of organic and inorganic nutrition for plants (Larkin 2015; van Bruggen et al. 2016). Agricultural management strategies can have a major impact on soil quality with consequent effects on disease incidence. Soil organic matter, one of the primary indicators of soil health, is fundamental to the long-term sustainability of agroecosystems. Managing soil health is a matter of maintaining a suitable habitat for the soil (micro)-organisms. The aim of the practices adopted is to achieve the resilience (the capacity to self-organize into desirable steady states) and homeostasis (the maintenance of desirable steady states) of the soil microbiota. In most cases, regular additions of organic matter are necessary to replenish soil resources and improve soil health.

Suppressive soils

Suppressive soils are those where the disease development is naturally controlled, even in the presence of a virulent pathogen, a susceptible plant host, and with environmental conditions conducive for the development of the disease. Soil suppressiveness is a complex system of biotic and abiotic factors, such as soil structure, nutrient and water availability, microbiota (including pathogens and symbionts), and plant genotype. Natural soils have a general disease suppression compared to the same pasteurised soils, and it is directly related to the microbial activity (Schlatter et al. 2017). In cropping systems, a specific suppression is present when a group of microorganisms, selected for their antagonistic activity, is directly responsible for disease suppression. Soil bacteria and fungi, as *Pseudomonas* spp. and *Alcaligene*s spp. in the USA (Kloepper et al. 1980; Yuen et al. 1985) and *Fusarium* spp. in France and Italy (Janvier et al. 2007; Garibaldi et al. 1987), have been shown to be involved in Fusarium wilt suppression. Antagonistic *Fusarium* spp., isolated from the rhizosphere of carnation grown in suppressive soils, showed high rhizosphere competence. When applied to soil and substrates they controlled Fusarium wilts on different crops, such as tomato, basil, carnation, cyclamen, and bulb crops (Gullino and Garibaldi 2007). Soils suppressive to *Rhizoctonia solani* are correlated with the presence of large amounts of *Trichoderma* spp. (Chet 1987).

Soil management for disease suppression

Organic matter can be added through agronomic practices, such as crop residues, rotations, and cover crops.

Crop rotations are one of the most interesting agronomic practices, as they are able to combine the optimal use of nutrients with the reduction of soilborne pathogens. The evolution of agriculture has led to the abandonment of rotations in favour of monoculture, with consequent negative plant disease profile. Monoculture, in fact, leads to the progressive soil accumulation of propagules of plant pathogens to unacceptable levels, which force the adoption of disinfestation practices. Some pathogens (*Fusarium* spp., *Verticillium* spp., or *Rhizoctonia spp.*), which show high competitiveness at saprophytic level or differentiate survival structures, tend to accumulate in the soil. The mechanism underlying the beneficial effects of rotation is starving the pathogen when the susceptible host is not cultivated. This occurs in the case of organisms with narrow host spectrum, modest saprophyte capacity, and lack of survival structures. The level of specialization of the parasite is important: crop rotation has higher effect on species-specific pathogens (i.e. *formae speciales* of *Fusarium oxysporum*) than on the polyphagous ones (*Sclerotinia sclerotiorum*, *Verticillium dahliae*). Crop rotation can also include the alternation of cultivars of the same species with different levels of pathogen susceptibility.

Crop rotations are associated with increasing soil microbial activity and diversity, due to the cultivation of different plant species in the soil (Garbeva et al. 2004; Welbaum et al. 2004). Crop rotations that maximize diversity of plant and root systems (mixing legumes, cereals, solanaceous, cucurbits, brassica, etc.) may significantly modify soil microbiota and their disease suppression potential.

Cover crops are grown primarily to cover the soil, to protect it from erosion and nutrient losses when production crops are not present. Benefits of cover crops may include disease control (Larkin, 2015).

Green manuring is the incorporation of fresh plant material to enrich the soil organic matter. Green manuring results in higher organic matter inputs than traditional crop rotations or cover crops, producing improvements in soil fertility, structure, and microbiota, with an effect on disease suppression (Collins et al. 2006; Stark et al. 2007). Most practices designed to improve soil health, such as organic matter supplementation also help to suppress the disease development (Welbaum et al. 2004; Bonilla et al. 2012; Page et al. 2013).

Suppressive substrates

Suppressiveness has been found for several substrates used in horticulture. Sphagnum peat mixes can naturally suppress soilborne pathogens, but few weeks after potting, they become conducive to diseases (Hoitink and Boehm 1999). Peat mixes well tolerate the introduction of biocontrol agents or the addition of composts (Hoitink and Locke 2012).When hardwood bark is used, improved plant vigour and disease suppressiveness, from richer microbiota, are observed in potted plants (Hoitink and Boehm 1999).

Increasing the use of compost as a potting substrate would contribute to waste recycling and reduction of chemical fertilizers. Compost is interesting as a peat substitute, for the lower production cost and for the increasing concern about the environmental impact of peat extraction (Silva et al. 2007). Some composts, particularly those amended with composted bark, suppress most soilborne plant pathogens (Hoitink and Boehm 1999; Noble and Coventry 2005; Termorshuizen et al. 2006). Composts were demonstrated to be more suppressive than crop residues and peat (Bonanomi et al. 2007). Low amounts of compost in growing media avoid the lower growth and the phytotoxicity caused by high pH and electrical conductivity (Sullivan and Miller 2001). Composts originating from green wastes or municipal biowastes, blended with a peat substrate effectively reduced Fusarium wilt on basil, *Pythium ultimum* on cucumber, *Phytophthora nicotianae* on tomato and *Phytophthora capsici* on pepper (Pugliese et al., 2014). On the contrary, saline composts were reported to enhance *Pythium* and *Phytophthora* diseases, while high nitrogen composts could enhance *Fusarium* wilts (Hoitink et al. 2001). The efficacy of compost for disease control depends on the raw materials from which the compost was prepared, the composting process used, and the compost maturity and quality (Termorshuizen et al. 2006). Of particular interest is the use of disease suppressive composts, thanks to the introduction of selected antagonists: their use is particularly interesting in the case of nurseries (Garibaldi 1988; Hadar 2011; Hoitink and Fahy 1986). In other cases, composts have been identified as a potential source of antagonistic microorganisms (Pugliese et al. 2008). In some cases, it is interesting to combine the use of compost with that of resistant rootstocks (Pugliese et al. 2014).

Although interesting for field crops and vegetables, the use of organic amendments for disease control is still not widespread, due to many factors such as the lack of standardization, the inconsistency in their efficacy, and the complexity of their use.

Soilless media

Soilless cultivation is realized in inert or cation exchange capacity substrates (rock wool, perlite, peat), used as a mechanical support for the plant, replacing the soil. Soilless cultivation requires a continuous feeding of the plants with a complete nutrient solution. This technique offers numerous advantages, such as better control of soilborne pathogens and more effective planning of crop cycles. Soilless cultivation could permit the production cycle completely free of pathogens. It also permits eradication of the soilborne pathogens in the recirculating nutrient solutions (Van Os et al. 2012). Soilless cultivation allows excluding soilborne pathogens: the possibility of contact between the host and pathogen is avoided by growing the plant in a pathogen-free environment (Postma 2004, Garibaldi and Gullino 2010). Soilless systems, while they strongly limit some pathogens, they could favour pathogens that find favourable conditions for their diffusion in the nutrient solution. *Pythium* and *Phytophthora* are the most frequent pathogen genera in the root system of soilless vegetables and ornamentals. Many pathogens (*Pythium aphanidermatum, P. myriotylum, Phytophthora cryptogea, P. nicotianae*) found in hydroponics are the same present in normal soil conditions, while others affect plant hosts which are resistant when grown in soil. *Phytophthora cryptogea* in soilless systems becomes strongly virulent on lettuce. *Pythium dissotocum* becomes extremely virulent in soilless cultivation of spinach and lettuce. Other pathogens are specific for soilless crops, such as *Plasmopara radicis-lactucae*, reported on lettuce roots.

Among the potential sources of pathogen infection in soilless crops, there are the substrates; perlite, vermiculite, rock wool, polyurethane, and polystyrene are generally considered sterile, but organic materials, such as peat, coconut fibre or non-composted bark, represent the main source of infection of *Pythium* spp., *Fusarium* spp., *Olpidium* spp. and *Thielaviopsis* spp. (Van Os 2010). On the other hand, the cultivation substrate could show a natural suppressiveness, depending both on chemical and microbiological factors. By comparing different substrates, there are substantial differences in the microflora established, which generate a different degree of suppressiveness.

In closed systems, higher electrical conductivity of the nutrient solution, amendment with potassium silicate, and their combination were effective against powdery mildews, downy mildews, leaf spots, and Fusarium wilts (Gullino et al. 2015). Silicon provided partial control of powdery mildews on greenhouse crops and soilborne diseases on turfgrass (Bélanger et al. 1995; Brecht et al. 2004; Uriarte et al. 2004): in addition to the deposition of amorphous silica in the cell wall, there is an increased lignin production, which could limit the pathogen penetration in the plant cell (Gullino et al. 2015).

Soilless systems also permit microbial optimization, thanks to the application of microorganisms able to colonize the plant rhizosphere. Slow sand filtration combined with the application of different antagonistic strains of *Fusarium* spp. and *Trichoderma* spp. was effective against *Phytophthora cryptogea* in gerbera (Garibaldi et al. 2004a).

Pathogen diffusion in soilless cropping systems can be greatly reduced by adopting proper disinfection methods for the recirculating solution, such as slow sand filtration (Van Os, 2010). Moreover, preventative methods to increase the plant resistance to diseases and the use of diagnostic tools constitute an integrated approach for soilless systems (Van Os et al. 2012).

Organic amendments

Organic amendments include manure, crop residues, compost, and organic fertilisers. The application of organic amendments is commonly adopted in traditional agricultural systems to provide nutrients to the crop and to improve the soil fertility and structure (Bailey and Lazarovits 2003; Bonanomi et al. 2007; Bonilla et al. 2012). Suppressiveness has been found for organic amendments used in agriculture. Several chemical and physical changes in the soil are due to the incorporation of amendments and result in control of soilborne pathogens, with reduced application of chemicals (Pugliese et al. 2015).

A proper nutritional status makes plants more easily able to react to any kind of stress. High nitrogen fertilization, by favouring the vegetative growth of the host and the tissue turgidity, is conducive to the pathogen attack. Generally, adequate potassium fertilization makes the host resistant to several parasites.

Soil amendments can be useful to modify the soil pH. For example, pH values above 7 reduce the incidence of *Plasmodiophora brassicae* on cabbage (Webster and Dixon 1991), though at these pH values the occurrence of *Erwinia carotovora* increases (Bain et a.l 1996). Alkaline soils are conducive to the spread of the scab of potatoes, as *Streptomyces scabies* usually develops between pH 5.2 and 8.0 (Hooker 1981). It is, however, difficult to generalize and to choose a unique intervention practice. For example, on carnation, soil pH reduction reduces the attacks of *Phytophthora nicotianae* (Spencer and Benson 1981) and increases the wilts caused by *Fusarium oxysporum* (Jones et al. 1993).

When added to soil, amendments, such as cow or poultry manure and brassica residues, are subjected to microbial degradation that releases toxic and volatile compounds directly affecting soilborne pathogens or indirectly increasing microbial soil suppressiveness. Organic amendments can promote the re-establishment of a more balanced and suppressive microflora. Furthermore, the development of plant disease is reduced thanks to the extended root systems growing in a rich soil (Chellemi 2010). Composts and Brassica pellets are considered among the most promising organic amendments. A growing interest is directed to the use of isothiocyanate precursors, contained in selected brassicaceae (*Brassica juncea* and *B. carinata*), used as alternating species and then applied as green manure or as flour or pellets (Larkin and Griffin 2007). The use of Brassica species as green manure is a type of biofumigation that involves the release of volatile compounds able to control a wide array of soilborne pathogens (Larkin and Griffin 2007). Biofumigation, however, provides results that are not always univocal: promising efficacy was obtained against *Colletotrichum coccodes* on tomato, *Fusarium oxysporum* f. sp. on cucumber, *Verticillium dahliae* on eggplant grafted onto *Solanum torvum,* and Fusarium wilt of lettuce, rocket and basil (Garibaldi et al. 2010; Gilardi et al. 2014). Partial or negative results have been observed in other crops, such as *Brassica* spp., where the inoculum of soilborne pathogens could be favoured (Lu et al. 2010). The combination of green manure with soil solarisation is also very effective and reduces the period of soil mulching with plastic films.

Organic amendments for disease control are not yet widespread, due to lack of standardisation of production parameter, inconsistent efficacy and difficult application. Control of soilborne diseases with organic amendments must be considered a component of a system approach, where the impact of crop production practices on resident soil microflora is addressed.

Soil solarisation

Solarization is the soil covering with plastic film during the summer. The method has been widely exploited in warm and temperate countries (Katan and DeVay 1991). Farmers are generally sceptical about its adoption, as it requires soil free of cultivation for at least 4 weeks. An integration strategy, often adopted to increase soil solarization efficacy, is its combination with biocontrol agents, to reduce the solarisation period and to permit its use in marginal areas (Minuto et al. 2005). The combination of soil solarization and *Streptomyces griseoviridis* is effective against fusarium and verticillium wilts and corky root, and it increases the range of pathogens controlled with respect to the single treatments. Significant increases in yield and fruit weight were observed, confirming the potential additive effect caused by biocontrol agent and solarization in terms of yield increase.

PLANTING MATERIAL

Healthy propagation material

Considering the losses caused by most emerging pathogens, the first preventative strategy that should be considered by seed producers and farmers is the use of healthy seeds and propagation material. The use of healthy or treated propagation material is an effective tool to prevent native or alien pathogens from being introduced in the agricultural environment. It is estimated that almost 800 fungi, over 150 viruses, 100 bacteria and 20 phytopathogenic nematodes are transmitted through propagation material. To avoid this risk, programs have been activated for the most important crops aimed at certifying the health of the seed or propagation material. This requires specific phytosanitary assays, which consist in estimating the possible presence of the pathogen using different biological and molecular methods.

The control of propagation material is important for clonal species (carnation, geranium, strawberry) for which the use of uncontrolled material could facilitate disease outbreaks. The importance of the use of healthy or treated material is particularly evident in the case of pathogens (viruses, bacteria) with few or ineffective control strategies (Gullino and Munkvold 2014). On strawberry, the use of certified propagation material, obtained by thermotherapy, meristem cultivation and subsequent indexing is a consolidated practice.

Another important aspect is seed health. Stock seeds should be produced in locations with low disease risk, characterized by low humidity and dry summer climate, to reduce fungal or bacterial epidemics (Munkvold 2009). The choice of proper geographical areas, possibly isolating seed and seedling production from the environment, and the application of good agricultural practices are critical for producing high-quality, pathogen-free seed.

As it is unrealistic to pursue an absolute seed health of the seed, a certain tolerance is admitted. Very common is the diffusion of fungal and bacterial seedborne pathogens on vegetables (Koch and Roberts 2014). The production of virus-free seed must follow appropriate production and certification schemes, which involve the controlled cultivation of the mother plants and diagnostic tests both on the mother plants and the seed produced (Gullino and Bonants 2014).

To reduce the risks of fungal and bacterial seedborne diseases, it is recommended that stock seeds undergo precautionary chemical or physical treatments. Chemical seed treatments have successfully been applied to vegetable seeds and are in commercial use for a wide range of crops against different seedborne pathogens (Munkvold 2009). Several surface disinfectants (bleach, hydrogen peroxide, ethanol) can be applied to remove pathogen inoculum from seed coats (Mancini and Romanazzi 2014). Chemical treatments are effective but they can also negatively affect germination and cause phytotoxicity (Axelrood et al. 1995; du Toit 2004), besides having negative effects on human health and the environment (Lamichhane et al. 2016). Alternative strategies for the control of seedborne pathogens include physical seed treatments, treatments with natural compounds, antagonistic microorganisms, and resistance inducers. Physical strategies include mechanical (sorting and brushing), heat, ultrasonic, radiations (with microwaves resulting in elevated temperatures), UV-C light, and redox treatments (cold plasma and electrons (Spadaro et al. 2017). Thermal treatments with hot water, aerated steam or dry heat can be very effective, but they need to be optimised for the pathosystems, due to the different temperature and time required (Koch and Roberts 2014). Although alternative seed treatments have been intensively investigated, there are few examples of commercial application (Koch and Roberts 2014; Gullino et al. 2014).

Seed treatments can also be an effective means to increase seedling emergence, particularly when done on seeds of low vigour and when the seed coat has been damaged (Mancini and Romanazzi 2014). In general, the use of healthy or disinfected seed is a very useful practice for plant disease management.

Resistant varieties and grafting

Host resistance, which is the use of resistant and/or tolerant plant varieties, is one of the most effective strategies against pathogens. Varieties, which are resistant or at least tolerant to one or more pathogens, are available for many crops and the industry is investing on research in this field. Resistant cultivars of lettuce are able to control Fusarium wilt. Lettuce varieties that are resistant, or at least tolerant, to race 1 of Fusarium wilt are available (Garibaldi et al. 2004b; Gilardi et al. 2014), but their use is complicated by the presence of different races of the pathogen. Seed breeding companies are currently working hard in order to develop planting material resistant to the recently detected race 4 (Gilardi et al. 2017a).

Host resistance, and the integration of such varieties with other management strategies is fundamental within the framework of IPM, but few research focused on the integration of plant resistance with other IPM strategies (Stout and Davis 2009). Moreover, the breeding approach used to date to develop resistant and/or tolerant crop varieties should be revised, as most crop cultivars bred to date are based on a market-driven approach focused on high yield and remunerative crop varieties. This trend has facilitated the adoption of short rotations or monoculture practices and ignored the potential that minor side crops may have for IPM. The limited range of available minor crop varieties is one obstacle to crop diversification, thereby confining certain beneficial practices such as multiple cropping or intercropping. Sustainable disease management should develop crop breeding based on the competitiveness of crops and their adaptation to diversified cropping systems (Lamichhane et al. 2017).

Grafting is used to reduce susceptibility against pests, root rots and wilts, and to increase yield (Rouphael et al. 2010). In spite of disadvantages associated with grafting, including the additional cost and physiological disorders due to incompatibility between rootstocks and scions, the use of resistant rootstock strongly increased, mainly for vegetable crops. In spite of disadvantages associated with grafting, including the additional cost and physiological disorders due to incompatibility between rootstocks and scions, the use of resistant rootstock, despite its high cost, strongly increased. Grafting on resistant rootstock is becoming popular on pepper and some of the commercially available rootstock provide a good control of Phytophthora blight (Gilardi et al. 2013). In the case of *P. capsici* on bell pepper, due to the lack of commercial cultivars with resistance, growers are interested in grafting. Grafted plants are popular in the case of tomato, to control soilborne pests and pathogens and to increase yield (Chellemi 2002; Lee and Oda 2003; Gilardi et al. 2013). Grafting susceptible crops onto resistant rootstocks is interesting also for cucumber (*Cucurbita vicifolia* as rootstock resistant to Fusarium wilt) and melon (*Benincasa cerifera* resistant to Fusarium wilt) (King et al. 2008).

CHEMICAL AND BIOLOGICAL CONTROL METHODS

Chemical control: fumigants and fungicides

Chemical control with fumigants and fungicides is an inseparable component of plant disease management, and it should be considered when other approaches can not achieve the required level of pathogen population density reduction.

Soil disinfestation with fumigants is becoming very difficult due to the loss of registered fumigants due to recent regulation strongly limiting their availability (Colla et al. 2014). Among the fumigants available, dimethyl disulphide, metham sodium, and dazomet provide significant control of Fusarium wilt of lettuce (Gilardi et al. 2017b). Covering the soil with low-density polyethylene film (LPDE) permits the reduction of fumigant dosage, with interesting results, both under greenhouse conditions and in the open field. Combination of fumigants with alternative methods, notably solarization, are promising. The combination of solarisation for two weeks and fumigation with reduced dosage of fumigants was effective, and allowed a shortening of solarization, permitting a reduction in the non-cultivation period (Gullino et al. 2003).

Fungicides are not used to control soilborne pathogens in open field, , because of their relative high cost, but they could be used for seed dressing, in nursery to protect the plantlets from damping off and other soilborne diseases, and in potted plants.

Mechanisms of action and risk of pathogen resistance development should be considered, when selecting the active ingredient (Siegwart et al. 2015). Diversity of fungicides, concerning their chemistry and mode of action, is essential to ensure effective crop protection, to control new threats and to manage fungicide resistance (Leadbeater and Gisi, 2010). Overuse of many organic fungicides can result in resistant fungal populations, so it is important to use fungicides as part of an overall resistance management plan. In the case of Pythium damping off, control is mainly accomplished by treatments with fungicides, such as strobilurins and phenylamides. However, *Pythium* spp. can develop resistance to common fungicides, such as azoxystrobin or mefenoxam. This further suggests the necessity of using other fungicides and alternative means for damping off control, and an accurate identification of *Pythium* spp. before choosing the appropriate control strategy (Matic et al. 2018).

The use of fungicides in integrated disease management is not aimed at eradicating the disease but to reduce it at ecological and economical thresholds.

Induced resistance

Plants have constitutive and induces responses to defend themselves against pathogens. Two main types of induced resistance are known: systemic acquired resistance (SAR) and induced systemic resistance (ISR) (Vallad and Goodman, 2004). SAR elicits the death of one or a few cells, known as the hypersensitive response (HR) and the production of pathogenicity-related (PR) proteins, such as glucanases, chitinases and thaumatin-like proteins (Shoresh et al. 2010). New growth occurs following HR and salicylic acid plays a role in triggering the signal. SAR is often related to the induction via aerial plant parts and it usually takes a certain amount of time to be fully expressed in plants. ISR is often triggered by rhizosphere bacteria in the soil, it involves jasmonic acid and ethylene, but not salicylic acid and PR-proteins.

Induced resistance, mostly SAR, can be triggered by a variety of natural and chemical compounds (Walters et al., 2005). The increasing interest in their use depends on their broad spectrum of activity, and on the possibility of reducing the number of fungicide sprays (Walters et al. 2013).

Very interesting results have been observed against Fusarium wilt of lettuce and crown and root rot of zucchini, caused by *Phytophthora capsici*, using resistant inducers, based on either phosphites or acibenzolar-S-methyl, applied as pre-plant treatment in the nursery. Phosphite-based products also show a very positive effect on plant biomass (Gilardi et al. 2015; 2016). The benefits of preventive and repeated treatments with silicates to reduce the attacks of *P. aphanidermatum* (Heine et al. 2007) and *Fusarium oxysporum* f. sp. *radicis-lycopersici* on tomato (Huang et al. 2011) were demonstrated. Also commercial biocontrol agents (BCAs) were able to reduce Fusarium wilt of lettuce, particularly when their application starts at nursery (Gilardi et al. 2016) while they were not effective against crown and root rot on zucchini (Gilardi et al. 2015). BCAs can also be effectively applied, alone or combined with heat treatments, for seed dressing, in the case of seed-transmitted pathogens, such as *F. lactucae* (Lopez-Reyes et al. 2016). The efficacy of resistance inducers is seldom complete, as it is generally influenced by several factors (target pathogen, plant genotype, phenotype, environmental conditions, application timing, and formulation) (Walters et al. 2013).

Biocontrol agents

Many laboratories around the world have developed their own microorganisms and this allowed the collection of important contributions about the biology of pathogens and antagonists. Biocontrol agents may act in various ways but have specific modes of action, including antibiosis, competition, mycoparasitism and induced resistance.

Among the antagonists studied, saprophytic *Fusarium oxysporum*, often isolated from Fusarium suppressive soils, have been widely exploited for their activity against several Fusarium wilts (Garibaldi et al. 1994; Spadaro and Gullino 2005; Gullino et al. 2015).The good antagonistic attitude of strains belonging to *Trichoderma* spp. has been proved against Fusarium wilts in vegetables and ornamental crops (Harman 2006; Gilardi et al. 2016). Plant growth-promoting rhizobacteria, such as *Pseudomonas* spp. and *Bacillus* spp., can induce host systemic resistance against several diseases (Clematis et al. 2009; Lopez et al. 2014).

However, in spite of the initial great optimism and extensive research efforts, progress in achieving commercial, large-scale usage of biological control has been slow. When trials move towards the farm scale, many antagonists show inconsistent efficacy and lack reliability (Mathre et al. 1999).

Biofungicides still face significant constraints, but there are many possibilities for combining various biocontrol agents, with each other, or with agronomical, physical or chemical control methods (Spadaro and Gullino 2005). In particular, by combining different methods of control, the aim is to obtain a synergistic rather than additive effect. For that reason, a complete comprehension of the mechanism of control is needed. Combining a biocontrol agent with a fungicide improves the biofungicide efficacy and enables the reduction of the fungicide dosage. Moreover, the combination of control methods provides a wider spectrum of control, which is needed to replace fumigants.

ADDITIONAL TOOLS FOR SUSTAINABLE DISEASE MANAGEMENT

Diagnostics

Rapid and reliable diagnostic methods allow a rational and efficient choice of the management options. The easy spread of fungal spores, virus and bacteria combined with the intense trading globalization are key factors to allow the movement of pathogens around the world, which can become invasive in new areas and even cause the total destruction of the crop. Traditional detection methods based on visual assessment of plant symptoms, isolation, culturing in selective media, and direct microscopic observation of pathogens are frequently laborious, time-consuming and require extensive knowledge of classical taxonomy. For many diseases, the observation under microscope or stereoscopic microscope is used to determine the causal agent, taking into consideration pathogenicity tests and morphological features such as size and shape of the propagules and colony characteristics, such as colour. However, many microorganisms (including viruses) can produce the same symptoms in the plant, making difficult the correct identification of the causal agent. As many plant pathogens remain latent in the planting material, and may be present in very low numbers, high sensitivity, specificity, and reliability methods are required. The impossibility or difficulty of culturing some species *in vitro* and the inability for accurate quantification of the pathogen are other limitations. Early detection of pathogens in seeds and plant materials is of key importance to avoid further spreading and introduction of new pathogens into growing areas where they are not present yet. These limitations have led to the development of molecular approaches with improved accuracy and reliability. Molecular techniques are faster, more specific, sensitive, and accurate than traditional techniques and they can identify non-culturable microorganisms and facilitate early disease management decisions.

The combination of traditional and molecular techniques permits to characterize, detect, identify and quantify different pathogens. In the case of fungal pathogens, the Internal Transcribed Spacer region (rDNA ITS) has been selected by the Consortium for the Barcode of Life (CBOL) as the primary fungal barcode for species identification (Begerow et al. 2010). Other genomic regions are interesting for the fungal identification at species level, or even at subspecies level (Srinivasan et al., 2010). The 16S rRNA has been selected as universal barcode for bacteria identification (Weisburg et al. 1991).

An early pathogen detection represent the best preventative measure in several pathosystems, as in the case *formae speciales* and races of *Fusarium oxysporum* from seeds, plants and soil samples (Pasquali et al. 2007; Mbofung and Pryor 2010; Thomas et al. 2017; Gilardi et al. 2017a).

Loop-mediated isothermal amplification (LAMP) is a DNA amplification method that can be used to amplify nucleic acid in a target specific way without the need for thermal cycling (Notomi et al. 2000). LAMP is particularly promising for plant pathogen detection, as it is easier and quicker to perform than PCR, it can be performed on hand-held platforms, and it is well suited for in field use. The LAMP method has been demonstrated for the detection of bacteria (Hodgetts et al. 2015), fungi (Franco Ortega et al. 2018), phytoplasmas (Hodgetts et al. 2011) and viruses (Tomlinson et al. 2013). The limit of detection of pathogens, by comparing the molecular techniques, can reach nanograms of DNA for PCR, picograms of DNA for biosensors, and femtograms of DNA for qPCR and digital PCR. NGS technologies are having an enormous impact on biological sciences, allowing the determination of genome variation within a species or a population. Comparative analysis of the genome sequences allows the identification of highly conserved gene families, conserved regulatory elements, repeated elements, uncultured pathogens, new species, symbionts, etc., on which new markers could be designed. On the other side, the use of field techniques, such as LAMP and portable platforms, is a promising tool to early and quickly detect pests and a useful decision support system for appropriate pest and disease management. The choice of the diagnostic technique depends on the balance between the reliability and the cost per sample. Microbiological techniques are generally cheap, but time-consuming, while molecular technologies have a higher cost, which is counterbalanced by the higher performance. PCR, qPCR and LAMP have a progressively lower cost per sample in the order of 2-10 € sample, while NGS are more expensive and they are not yet used for routine analysis (Spadaro et al. 2018). The development of new instruments and platforms and the continuous increase of bioinformatics-data have allowed the use of bioinformatics-based techniques such as metagenomics, comparative genomics and genome sequencing as routine analysis tools. The dramatic decrease of the cost of the new sequencing technologies permits to foresee a higher adoption rate in diagnostic laboratories in the near future.

Forecasting models

Research tried to develop disease predictions models, also called forecasts or warnings, to help the farmers determine whether and when preventive management measures are needed. Plant disease models are simplifications of the relationships between pathogens, crops, and the environment that cause epidemics to develop over time and space. Plant disease models produce predictions about epidemics or single epidemic components that can be used as risk indicators. Such models also produce predictions about plant disease epidemics that allows growers to respond in timely and efficient ways by adjusting crop management practices. A prediction of low disease risk may result in reduced fungicide treatments with positive economic and environmental effects (Rossi et al., 2010). Disease prediction is most useful for economically important, sporadic diseases for which effective management measures are available. It is also important that growers or technicians be able to operate the prediction system themselves, or that there is a good communication tool between those who monitor and those who manage the disease.

Decision support systems

Decision support systems (DSS) should be developed through forecasting models, results of the early detection tools, as well as pathway, establishment and spread models. Data from various sources are interpolated using spatial statistics methods, making the DSS able to provide prediction data with high accuracy at field and site-specific scale. The DSS should have a user-friendly interface, having

Geographic Information System (GIS)/mapping functionalities to project the pathogen occurrence. They also could provide alerts when a new pathogen has been identified and could provide recommendations for treatment applications (ideal timing and dosage, optimal sprayer calibration, real-time indicator for tractor speed).

Recently developed DSSs are characterised by holistic treatment of crop management problems (including pests, diseases, fertilisation, canopy management and irrigation); conversion of complex decision processes into simple and easy-to-understand ‘decision supports’; easy and rapid access through the Internet; two-way communication between users and providers that make it possible to consider context-specific information (Rossi et al. 2012).

Conclusions

Attempts to control soilborne pathogen populations include the use of pesticides, genetic resistance, crop rotations and a variety of cultural practices, aimed at reducing plant infections. Since these measures not always provide adequate disease control, fumigants and fungicides are sometimes needed, as part of an integrated disease management (Ojiambo et al. 2017). Adopting preventative and combined methods of disease management has become the choice for the control of soilborne pathogens on economically important crops.

The management of soilborne pathogen represents a real challenge and it is a bright example of how complicated can be a sustainable approaches to plant disease management.

The implementation of the concepts of soil health and soil health management into agricultural production is essential for sustainable crop production and environmental quality (Larkin 2015). The choice of the appropriate plant disease management strategy should not only integrate the impact on the soil and crop health, but also on the agricultural and non-agricultural environments, the natural resources, and human health. Economic, social, legislative and political issues should be considered together with regional, national and international regulations.

New disease outbreaks emerge and will emerge, requiring continuous changes to the disease management system and reprioritization of goals and objectives. Globalization of trade, new consumption habits, shifts in diets, and climate change are among the factors influencing the occurrence, frequency and severity of new plant diseases, with an important impact on decision-making tools for the related disease management measures that should be adopted.

Effort for a continuous monitoring and disease surveillance is necessary. Strategies to produce healthy seeds and seed treatment methods need to be investigated and made available to seed companies and growers.

Plant disease management should be adapted to the geographical areas, to the crops and to the pathogens. Future plant disease management should continue to strengthen food security for a stable society, but also safeguard the health of associated ecosystems and reduce dependency on natural resources.

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