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Review

Sustainable Management of Plant Quarantine Pests: The Case of Olive Quick Decline Syndrome

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Abstract: The disease outbreak of *Xylella fastidiosa* subsp. *pauca* strain CoDiRO (*Complesso del Disseccamento Rapido dell'Olivo*) in Salento (Apulia, South Italy) associated with severe cases of olive quick decline syndrome may represent not just a new disease paradigm, but a challenge for policy formulation and science communication in plant pathology. Plant health management can be achieved by applying a technocratic model, in which objective science is thought to directly inform policy-making, or via decisionistic or inclusive models, in which scientific considerations drive risk assessment. Each could be applied to *X. fastidiosa* and CoDiRO strain management, thanks to consistent literature related to pathogen/host interactions, hosts, vectors, and diagnostic tools, reviewed here. However, consensus among stakeholders seems to be necessary in order to avoid plant health management failures or gridlocks, due to environmental, economic, and social implications in the *X. fastidiosa* threat. Here we discuss the role of consensus in building scientific opinion, reporting different approaches of governance after severe disease outbreaks in Europe. These case studies, and the available risk analysis for *Xylella* strains, should drive policy formulations towards more cooperative networks.

Keywords: *Xylella fastidiosa*; science communication; plant health monitoring; disease outbreaks; CoDiRO

1. Olive Quick Decline Syndrome, an Agroecosystem Threat

The impact of *Xylella fastidiosa* subsp. *pauca* strain CoDiRO (*Complesso del Disseccamento Rapido dell'Olivo*, or olive quick decline syndrome—OQDS) [1,2] in Europe was unprecedented due to the specific characteristic of the host, the olive tree of Salento (Apulia region, Italy). A phylogenetic study has shown that the olive strain was likely introduced via infected plant material [3], but *X. fastidiosa* is not the first plant pest to cause dramatic effects in European agriculture. *Phytophthora infestans*—the cause of potato late blight, and probably the first frightening plant disease in Europe—is unrivaled, due to the following Irish Great Famine in the 1840s [4]. Populations in third-world countries may be exposed to similar threats, but human communities are less dependent on (few) local foods as in the 19th century; thus, it is quite improbable that a plant disease can directly represent a threat to human lives. *X. fastidiosa* is a devastating factor for oil production in an Italian region (Apulia) in which it represents a major agricultural activity and income. Moreover, this economic threat could interest the whole Mediterranean area [5,6], in which the olive tree is among the predominant cultivated species. However, *X. fastidiosa* is not only a production-related menace, as is the case with *P. infestans* or many other pathogens. As Almeida reported [7], while the European Community aims to address the threats of *X. fastidiosa* as a plant pathogen, the Apulian background requires a different approach, because the death of olive trees can cause many social effects. Furthermore, the best management outcomes for limiting the impact of this pest to Apulia and Europe may be the result of discussing scientific and technical opinions according to policy [7]. Thus, *X. fastidiosa* may also be considered like other forestry-related pathogens, such as *P. ramorum* or *Ophiostoma ulmi*, due to the devastating impact on the environment and citizens' feelings [8]. Furthermore, *X. fastidiosa* is known to have a broad host range, affecting many weedy hosts and non-cultivated crops [9], which may seriously impact Apulian biodiversity and the native landscape, as was reported for *O. ulmi* in Europe [10].

2. Established and Emerging *X. fastidiosa*

2.1. Research on X. fastidiosa

X. fastidiosa has been one of the most studied plant pathogen microorganisms in recent years, because it is the causal agent of devastating diseases such as Pierce's disease (PD) of grapevine (subsp. *fastidiosa*), citrus variegated chlorosis (CVC), or citrus X disease (subsp. *pauca*), phony peach disease in peach, and a number of so-called leaf scorch diseases in *Prunus* spp. (subsp. *multiplex*, *pauca*) [11,12]. Recently, the CoDiRO strain found in infected Apulian olive tree was assigned to subsp. *pauca* [13], while olive leaf scorch was observed in the USA (subsp. *multiplex*) [14], Argentina (subsp. *pauca*) [15], and Brazil (subsp. *pauca*) [16]. Many research papers have been published since its description in 1987. With regard to the last decade, a classification of main topics of articles (retrieved from the Scopus database, last accession 18 January 2017; main keywords used were *Xylella*, Pierce's disease, citrus variegated chlorosis, CoDiRO, olive decline, and OQDS) can lead to some consideration about trends in research and difficulties in control strategies. European Food Safety Authority (EFSA) reports were also included in the literature review. Studies related to vectors (behavior, biology, and insect/pathogen interaction), plant/host interaction (with particular regard to biofilm formation in xylem vessels), and pathogen characterization (mainly genomic and transcriptomic studies) are equally represented topics (22–26%) in both five-year periods considered in the literature survey. Altogether, they represent about 70% of research articles published. Control strategies (i.e., antimicrobial tests) or the evaluation of putative tolerant/resistant species and cultivars represents the fourth topic in research in both periods, but an increase was observed in 2011–2016 compared to the previous period (+56% of papers). Thus, the lack of effective control tools against *X. fastidiosa* led research towards pathogen- or host-related studies to investigate molecular or physiological mechanisms of disease with the aim of knowledge about pathogenesis, and in turn, to feed future control-related research. Similarly, insects are a common target of research, in order to investigate epidemiologic relationships to contrast the spread of the disease. The comparison between the two periods—even if small quantitative differences were observed, graphically shown as a research output in 2006–2010—did not alter the behavior of research groups in the following period. By literature analysis, a consistent share of research was carried out by the same five research groups in both periods. The United States Department of Agriculture (USDA)—the US federal executive department for farming, agriculture, forestry, and food—was the most productive affiliation in research concerning in *X. fastidiosa* in both periods considered (23% and 18% of published original papers in 2006–2010 and 2011–2015, respectively). The recurrent research contributions in the last ten years are probably influenced by the status of the quarantine pest *X. fastidiosa* in most countries, and its restrictions in management. This limit may be underlined by countries interested by research: more than 60% of published papers referred to US researchers in both periods, while a significant number of papers belong to Brazilian affiliations (38% and 27% in 2006–2010 and 2011–2015, respectively). Fewer than 3% of papers involve researchers belonging to other countries in 2006–2010, while about 5% of papers belong to Italian affiliations in 2011–2015.

2.2. Pathogen/Host Interaction

PD represents the most studied system to understand the biology of this pest [11], while knowledge in olive tree infections is rapidly growing. The cause of symptoms represents a challenging task for research; in grapevine, it seems clear that the plant response is due to extensive bacterial colonization [17,18], and bacterial cells seem able to move passively within the length of a grapevine [19]. Moreover, symptoms are related to the proportion of vessels that harbor large *X. fastidiosa* cell aggregates and not simply to the number of vessels that are colonized [20]. Data about the colonization behavior of bacteria within olive xylem were not yet available, even if differences in the population size in different olive cultivars were observed, suggesting a correlation between the amounts of bacteria and the severity of symptoms [21]. Even if no correlation was detected between the pathogen quantity and the disease severity in well-studied hosts such as grapevine, suggesting the existence of among-cultivar variation in plant response to infection [22], the search for resistant or tolerant cultivars in olive trees may represent an important task.

The complete genome sequence for several *X. fastidiosa* strains (e.g., causal agents of PD or CVC) showed the absence of genes encoding conserved Type III secretion system machinery or secretion effectors [23,24], whose main role is to suppress the host plant defense responses. Conversely, mutation of TolC (a component of Type I secretion systems) in *X. fastidiosa* causes a severe loss of virulence in grape, indicating its critical role to the survival of this pathogen in the xylem [25]. Those genome studies also indicate that virulence factors such as adhesins, Type IV pili, and extracellular cell wall-degrading enzymes, were regulated by a small diffusible signal molecule [23,24,26]. Cell-to-cell signaling mediated by a fatty acid diffusible signaling factor (DSF) may also show different chemical structure according to strain [27–29]. Regulation of pathogenicity factors (rpf) cluster [27,30–32] as well as DSF and cyclic di-guanosine monophosphate [33,34] were also critical for biofilm formation, plant virulence, and insect transmission. The complete genome of the CoDiRO strain is not currently available, while assessment of the genome diversity of CoDiRO isolates has been carried out [35–37]. However, the EFSA stated that currently available scientific evidence does not support the notion of the existence of heterogeneous populations of *X. fastidiosa* in Apulia [38]. The belonging of the strain to subsp. *pauca* [13] was also controversial, because the sequence type profile (ST53) clustered in one clade close to the subspecies *pauca*, but was nevertheless distinct from them [35]. Mang et al. [37] also suggest how it should be possible that in the near future the CoDiRO strain will be classified as a new subspecies. However, since subsp. *pauca* is a frequently reported subspecies (as well as *sandyi*, *tashke*, or *morus*), only *fastidiosa* and *multiplex* are so far considered valid names by the International Society of Plant Pathology Committee on the Taxonomy of Plant Pathogenic Bacteria (ISPP-CTPPB) [39], and a revision was recently proposed [40].

Studies also involve the patterns of gene expression in *X. fastidiosa*-infected grape in order to evaluate host responses to infection [41], but it is still unclear if changes in gene expression are the primary responses to localized water stress due to the blockage of vessels or if they are evidence of other host defenses to the pathogen. However, in olive trees, *X. fastidiosa* elicits a different transcriptome response among cultivars, which determines a lower pathogen concentration in putative tolerant, compared to sensitive cultivar, indicating potential genetic constituents or regulatory elements able to contrast pest infection [21].

3. Environmental Impact of OQDS

3.1. Plant Hosts of CoDiRO Strain

While *X. fastidiosa* seems able to infect more than 350 plant species, 22 of them were found to be infected by the CoDiRO strain [9]. The Apulian strain was found in three other woody plants besides olive trees (*Laurus nobilis*, *Prunus avium*, *P. dulcis*) and 18 shrubs (*Acacia saligna*, *Asparagus acutifolius*, *Catharanthus roseus*, *Cistus creticus*, *Dodonaea viscosa purpurea*, *Euphorbia terracina*, *Grevillea juniperina*, *Lavandula angustifolia*, *Myoporum insulare*, *Myrtus communis*, *Nerium oleander*, *Polygala myrtifolia*, *Rhamnus alaternus*, *Rosmarinus officinalis*, *Spartium junceum*, *Vinca minor*, *Westringia fruticosa*, and *W. glabra*) [1,42]. However, the CoDiRO strain was not found in *Citrus* spp. (i.e., lemon, mandarin, and sweet orange), which are common hosts of subsp. *pauca* [2]. Monocots, dicots, conifers, palms, and succulent plants were also not found to be infected by the CoDiRO strain [43,44]. Since subsp. *pauca* was not yet considered a pest for grape (which is commonly infected by subsp. *fastidiosa* [12] or rarely by *sandyi* [35]), serious concerns were raised due to the great importance of viticulture in Apulia. Up to now, grapevine was not found naturally infected by the CoDiRO strain, regardless of the proximity of cultivation with infected olive trees [45]. However, difficulties in providing evidence about this hitherto unknown pathogen/vector/host interaction and the notice of recovery of *X. fastidiosa* DNA in inoculated grapevine plants with the CoDiRO strain even 12 months after inoculation did not exclude *Vitis* spp. infection without further experimental trials [45].

3.2. The Role of Salento Agroecosystem in Plant Health Management

Disquisition about the limited number of olive tree genotypes in Salento have been available since the late 18th century [46], in order to contrast the olive leaf scorch ("brusca"), which was particularly severe on cultivar "Ogliarola di Lecce", the olive cultivar most widely grown in the area. Thus, a top-graft with a less sensitive cultivar was suggested as a remedy. From chronicles of the 19th century, it seems that this disease was almost confined to Salento, affecting the most widespread cultivar, even if no more than other two or three cultivars were available.

Conway's vision significantly influenced agricultural thinking in the last decades [47]. One of the main ecological principles is based on the assumption of maintaining and, wherever possible, enhancing, diversity. More diverse agroecosystems tend to be more sustainable and, often, more productive than systems which are otherwise comparable [47]. Even if not frequently cited in original research about plant pathology, Conway's assumption of enhancing diversity in agroecosystems is widely accepted. As reported by Vercesi and Cravedi [48], agricultural practice based on the cultivation of several genetically uniform, very similar crops in contiguous fields often provides ideal conditions for severe outbreaks of diseases/infestations due to pathogens and insects able to attack the host plant grown in the area. These assumptions may be retrieved from legal disposal too, as reported in European Community rules for applying integrated protection management measures to all cultivated crops since 2014 [49].

Some plant pathology consideration may originate from debate derived by Wood's criticism [50]—in particular due to the application of this assumption to natural ecological systems, where diversity may not always be the answer to sustainability. Conway's response to Wood's criticism [51], limiting its concern about diversity to agro-ecosystems (fields, farms, villages, etc.), stated that "it is not diversity in itself that is important, but the nature and interrelationships of the individual components of the system". However, the simpler the system, the less likely is the presence of functional elements that can counter stresses and shocks. Conway encourages the return of the natural enemies of pests, and in the process, rebuilding the diversity of the system [51]. This last statement is a well-established vision among plant pathologists, but an interesting observation derived from Wood's statement about *Phytophthora cinnamomi*. The fungi are one of the most dangerous invasive plant pathogens which destroyed whole plant communities, such as species-diverse Australian forests [52]. Wood's assumption [50] is that a problem of any diversity-stability hypothesis is that species-diverse communities may not be stable, reporting Dover and Talbot's [53] considerations about the fragility of some of the most species-rich communities, such as tropical rainforests and coral reefs. Anyway, both Dover and Talbot's example and the case of *P. cinnamomi* are characterized by human-related instability factors. Thus, while Conway's promotion of diversity should be considered a very reasonable approach to plant defense in usual agricultural systems, this approach may be useless in contrasting some plant pathogen outbreaks due to the introduction of quarantine pests that make the community unstable. Is it the case of Salento's agricultural systems? Surely, as the area was cultivated with the "Mediterranean Trio" of wheat, olives, and vines (species that have sustained Mediterranean farming cultures from the Bronze Age onwards [47]), but many annual species were cultivated in olive tree orchards. Thus, mixed cropping—or, more frequently, inter-cropping—were common practices in Salento until a few decades ago. Recently, the low economic sustainability of olive oil production (mainly due to very old plants that produce low quantities of extra virgin olive oil and difficulties in plant management) led to reduced farmers' inputs in orchard maintenance, and further crop cultivations were widely abandoned in Salento, whereas good orchard maintenance obviously helps in rapid recognition of a disease outbreak.

The low diversity in genotypes of olive trees in Salento (five main cultivars, with a great predominance of two of them) did not permit the evaluation of the existence of resistant cultivars, even if some evidence of tolerance was observed [21], while in other species (e.g., grapevine), studies about the response of different genotypes were carried out [54,55]. However, due to the low input practices that are recurrent in olive tree cultivation in Salento, the eventual low diversity of cultured species was counter-balanced by high diversity in wild species, as well as other biota communities. In fact, thanks to its geographical position, Salento is one of the most interesting floristic areas from a phytogeographical point of view, and for the richness of species (1400 between species and subspecies, belonging to 560 genera and 115 families) [56]. However, woody plants (not necessarily cultivated) such as *L. nobilis* and *P. dulcis*, or many shrubs are host to the CoDiRO strain [1,42], and their infection could significantly impact Salento's landscape, as well as olive trees. Conversely, some wild hosts which are widely distributed in Apulia (e.g., *A. acutifolius*, *E. terracina*, *M. insulare*, *R. alaternus*, *V. minor*, and *W. glabra*) seem to be asymptomatic, and should be resistant to disease outbreaks. Woody wild or ornamental plants belonging to families Araucariaceae, Arecaceae, Cupressaceae, Cycadaceae, Musaceae, Pinaceae, or succulent plants belonging to Agavaceae, Aizoaceae, Aloeaceae, Cactaceae, Crassulaceae, or Xanthorrhoeaceae have not yet been found infected by the CoDiRO strain [44], suggesting that forestry or gardens should be less affected by a disease outbreak. However, olive trees and other wild hosts are widely and homogenously distributed in the infected area; thus, the eventual presence of vast segments of territory covered by non-host species that should restrain the pathogen spread throughout the region seems to be unrealistic.

4. Pest Management Policy

4.1. Disease Monitoring and Widespread Distribution of Pathogens

Diagnostic protocols represent the first tool for disease monitoring. Standards for diagnostic protocols for *X. fastidiosa* were recently revised [57]. The concentration of the pest in tissue depends upon environmental factors, *X. fastidiosa* strains, and the host plant species. However, sampling should be performed during the period of active growth of the plants, usually from late spring to autumn in Europe [57]. For the CoDiRO strain, symptoms associated with bacterial infections are more strongly expressed in summer, although persistent during the entire year, while petioles and midribs recovered from leaf samples [58] are also the best source for diagnosis in olive trees. Vectors should preferably be collected with sweeping nets or aspirators, while only the head of the insect should be used for DNA extraction [59]. For *P. spumarius*, up to five insects can be pooled, and removing eyes was recommended [57].

Several diagnostic protocols were tested for the CoDiRO strain, such as ELISA [60], PCR [60–62], direct tissue blot immunoassay [63], or Loop-mediated isothermal amplification (LAMP) [64,65]. Two real-time PCR protocols are also available [64,66]. The CoDiRO strain was successfully isolated [67] following Almeida and Purcell's [68] protocol, using Periwinkle wilt-modified (PWG) solid medium and D3 growth media [69].

As is the case for CVC or PD disease strains, the role of vectors of the CoDiRO strain is critical for epidemiology and control strategies. In addition to studies on the ecology of *X. fastidiosa* sharpshooter leafhopper (Hemiptera, Cicadellidae) and spittlebug (Hemiptera, Cercopidae) vectors [70–72], bacterial colonization of insect body has raised interest in defined sites in the vector. Meanwhile, traits such as adhesins seem to be critical in colonization [73,74]. Recently, a new paradigm of a non-persistent *X. fastidiosa* transmission mechanism was proposed, suggesting an egestion-salivation mechanism of pathogen inoculation [75]. In OQDS outbreaks, *Philaenus spumarius* (Hemiptera, Aphrophoridae) was rapidly identified as the most important vector for CoDiRO strain transmission [76,77]. The CoDiRO strain was also detected in other insects, such as *Neophilaenus campestris* (Aphrophoridae) and *Euscelis lineolatus* (Cicadellidae) [78,79], while sharpshooters may transmit subspp. *multiplex* and *fastidiosa* to olive at low efficiency [14]. Predictive models of *X. fastidiosa* distribution in the Mediterranean basin were also proposed, suggesting that the pest may spread up to Central Italy [5] and overcome the current boundaries outside Italy [6].

4.2. Risk Analysis and Policy Formulations for X. fastidiosa Management

The CVC strain of *X. fastidiosa* is listed as a regulated biological agent under the US Agricultural Bioterrorism Protection Act of 2002 [80]. As reported in the legal disposal, "the possession, use, and transfer of biological agents and toxins that have been determined to have the potential to pose a severe threat to public health and safety, to animal health, to plant health, or to animal or plant products. This action is necessary to protect animal and plant health, and animal and plant products". The reason for the inclusion of the CVC strain may be related to the importance of *Citrus* spp. In the US, compared to other *X. fastidiosa* hosts, because it is a microorganism with the potential to devastate the US citrus industry—an important sector of the domestic agricultural economy [80]. Theoretically, this approach to pathogen classification should increase the restriction in bacteria management for research studies, generating administrative obstacles: about 24% of original research papers concerning CVC published in 2003–2015 involved US affiliations.

The US classification of the strain also leads to a risk analysis relative to the likelihood of the introduction and consequence of the introduction (Table 1). The risk analysis rates as two out of three (the likelihood of intentional introduction of CVC in the US), whereas the high rates are assigned to epidemiologic assessment (establishment and spread potential) more than economic damage. In addition to political and religious ideological motivations that may lead to economic-based bioterrorism attacks, further motivation is related to genetically-modified (GM) organisms [81] and the possibility that activists will turn to diseases as weapons to attack GMOs [82]. Similarly, revenge against research and development of pathogens for killing or reducing yields of opium poppy, coca, and cannabis should be considered [83]. However, inclusion of *X. fastidiosa* in the Agricultural Bioterrorism Protection Act seems to be mainly precautionary, more dependent on the intrinsic negative potential of the pathogen than the intention of third parties to deliberately damage the US citrus industry and economy. Citrus-growing regions in the US match the climatic regions where CVC is already a problem, while a very high latent period was defined. Thus, the probability of spread was considered very likely. Due to these conditions, it is highly likely that, once established, the CVC strain will spread sufficiently to become a permanent resident of citrus-producing regions. Environmental impact (i.e., due to novel patterns in the use of insecticides, fertilizers, and irrigation, and the direct destruction of expansive acreages of infected trees that could lead to new crop and production patterns) and damage potential of the CVC strain was highly rated (2.5/3 out of 3) [80].

Regarding the CoDiRO strain, entry of the pathogen into EU territory by the movement of plants for planting is considered to be the most important pathway [84] (Table 1). In seven EU Member States between 2000 and 2007, more than 150 million individual plants belonging to genera listed as host plants for *X. fastidiosa* were imported from countries where *X. fastidiosa* is known to occur [84]. Thus, there is a high risk of introduction of the pathogen, especially with asymptomatic plants. The central role of the movement of plants for planting or infective vector transported on plant consignments has also been indicated by the EFSA since their first report [3]. Moreover, the introduction of *X. fastidiosa* subsp. *multiplex* in France on coffee plants imported for breeding purposes indicates the possibility of introduction through such a pathway. The uncertainty is also considered to be high, as the rate of unofficial introduction is largely unknown and is difficult to monitor [84]. MacLeod et al. [85] indicated inconsistencies in the EU's Plant Health Directive and weaknesses in the plant passporting system, allowing that the movement of plants across the EU and between very different biogeographical regions was provided with relatively minimal biosecurity standards. Further concerns may arise from phytosanitary certificates that are often issued on the basis of only cursory visual inspections [86].

Conclusions of the probability of pest entry in the EU lead to a high rank, mainly due to the "very likely" ranking for plants for planting. The EU seems to be a less sensitive target to agricultural bioterrorism than the US due to the lower impact of the agricultural industry in gross domestic product (GDP), whereas GM production is very limited in Europe, almost excluding this motivation. Other motivations, such as financial gain from the judicious use of plant diseases to manipulate markets or commodity prices [82], seem difficult to estimate.

Table 1. Risk analysis for *Xylella fastidiosa* subsp. *pauca* strain CVC (citrus variegated chlorosis) and subsp. *pauca* strain CoDiRO (*Complesso del Disseccamento Rapido dell'Olivo*, olive quick decline syndrome—OQDS).

	Likelihood of Introduction	**Rating**
	Pathogen Acquisition	
CVC	Only 2% of cargo and baggage entering the US is examined by USDA and APHIS; the introduction of contaminated plant material or vectors could be successfully achieved by several means.	1.5
CoDiRO	Plants and their packaging are examined on an official basis, either in their entirety or by representative sample (European Council Directive 2000/29/EC). The number of visual checks has to be defined in proportion to the existing risk identified by the Member State (European Commission, Guidelines for the survey of *Xylella fastidiosa* in the Union territory). While data about interception was published by EFSA, no data was retrieved about the number of tests of imported materials. More than 150 million individual plants potentially infected by *X. fastidiosa* were imported in 2000–2007 in seven EU countries [84].	Very likely for plants for planting; moderately likely for vectors.
	Intentional Introduction	
CVC	Given the requirements of a successful acquisition and introduction of *X. fastidiosa* CVC strain, there is a moderate degree of risk that this pathogen could be intentionally introduced with the intent of harming the US citrus industry.	2.0
CoDiRO	No data available	No data available from EFSA.
	Establishment Potential	
CVC	Citrus growing regions in the US match the climatic regions where CVC is already a problem. The likelihood of successful establishment by *X. fastidiosa* would also depend on the amount of initial inoculum present in a given region.	3.0
CoDiRO	Plant/host combination is unprecedented outside Europe. Olive-growing regions in Europe match the climatic regions where the CoDiRO strain is already a problem (South Italy). The amount of inoculum in Italy is remarkable.	Very likely
	Consequence of Introduction	
	Spread Potential	
CVC	Climatic conditions and native populations of *Oncometopia nigricans* and *Homalodisca coagulate* within the range of citrus production in the US are abundant and conducive to the establishment of CVC. The latent period—the period between infection and appearance of symptoms—will likely provide ample time for the pathogen to spread beyond the initial point of introduction into a nursery or orchard before it is detected.	3.0
CoDiRO	Climatic conditions and native populations of *Philaenus spumarius* within the range of olive production in the EU are abundant and conducive to the establishment of CoDiRO. A latent period was also supposed in olive tree infections, especially in older plants	Very likely
	Environmental Damage Potential	
CVC	The need to change crop and production patterns that might result from a serious epidemic could also temporarily disrupt the balanced environment in regions of large-scale production. In citrus, significant changes in disease management would include patterns in the use of insecticides, fertilizers, and irrigation and the direct destruction of expansive acreages of infected trees.	2.5
CoDiRO	Novel patterns in the use of insecticides, fertilizers, and irrigation and the direct destruction of expansive acreages of infected trees were carried out in Apulia.	Major
	Economic damage potential	
CVC	Annual crop loss due to diseases and pests is around 36%, regardless of whether pest controls are used. Prices would rise to cope with the cost of controlling the spread of the disease. The Brazilian citrus industry annual losses measured about US$100 million a year	3.0
CoDiRO	In addition to loss due to disease (not yet specifically estimated for CoDiRO), olive trees are an essential part of the Mediterranean landscape and culture, and may lead to detrimental effects on tourism.	Major

Data relative to CVC is retrieved from Ancona et al. [80] (rating: 1 = low; 2 = medium; 3 = high). Data relative to CoDiRO is retrieved from EFSA [84] (rating: very likely/major; moderately likely; low). USDA = United States Department of Agriculture (USDA); APHIS = Animal and Plant Health Inspection Service; GDP = gross domestic product; EFSA = European Food Safety Authority.

Many olive tree growth regions in Europe (i.e., other South Italian regions, Spain, Greece) match the climatic condition of Apulia, where CoDiRO is already a problem. Moreover, due to the spread of infected plants by CoDiRO in Apulia and by subsp. *multiplex* in France, the pathogen inoculum in Europe seems to be remarkable, suggesting that the establishment potential is very high. The spread of *Philaenus spumarius* and the latent period—the period between infection and the appearance of symptoms—will likely provide ample time for the pathogen to spread far away from the initial point of introduction before it is detected. Thus, the probability of spread was considered as "very likely" in the EU [84]. Due to these conditions, it is highly likely that, once established, the CoDiRO strain could spread sufficiently to become a permanent resident of the olive-producing areas. In fact, EFSA indicates the probability of such establishment as "very likely" [84].

CoDiRO in Apulia is impacting the environment (i.e., incremental use of insecticides or fertilizers, uprooting of infected trees that could change production patterns) and indirectly impacts tourism, which represents about 10% of the GDP in Italy. In fact, olive trees are an essential part of the Mediterranean landscape and culture; thus, their decline or death may cause further relevant economic loss. Finally, olive oil is a basic ingredient of the Mediterranean diet: significant reduction of European-produced olive oil may also increase food costs or degrade the concept of Mediterranean foods.

The EFSA rated the entry of the plant for planting pathway and spread as "medium" [84]. That is because the distribution of *X. fastidiosa* in the countries of origin are not fully known, knowledge of host plant susceptibility is only partial, only a few interceptions have been recorded, and it is difficult to detect asymptomatic infected plants. Moreover, there is a lack of data on how far the insect vector can fly or about how farming practices could possibly impact potential insect vectors and limit the spread of the disease [84].

As reported by Mills et al. [8], such technical assessments of disease risk must consider "intuitive and normative responses that act to balance conflicting interests between stakeholder organizations concerned with plant diseases within the managed and natural environments". Thus, plant health strategies need to shift from a technocratic or decisionistic model towards a transparent and inclusive governance model. Observing the decisionistic model applied to *P. ramorum* management in the UK, national consultative meetings were organized, as well as regional ones in most infected areas, and communication between government and stakeholder groups was seen as a critical step for the successful implementation of policy outcomes [8]. The result of meetings and debates was that ministers concluded that more needed to be done to contain and eradicate *P. ramorum*. Formal consultations were also launched in the UK for *Dickeya solani*, involving key national organizations with high interest and influence in the potato industry. Trade conferences, web comments, and online interviews involved thousands of potato growers, leading to the acceptance by the potato industry of a "zero tolerance" approach against the pest [8].

The first stage of the *Xylella* outbreak in Salento could be considered as a technocratic model approach, mainly due to the mandatory application of the European Council Directive 2002/89/EC in October 2013 immediately after the detection of the pathogen. Rapidly, the transition toward a decisionistic model was observed, formally involving research institutions and organizations representing professionals, and developing guidelines for disease management in July 2014. A further step towards a broader involvement of plant health professionals and researchers was the establishment of a task force in late 2015, while public debates at national, regional, and local levels were countless since the disease outbreak, even if not always formally organized. However, the case of *P. ramorum* in the UK underlines how the value of consultation and meeting depended on the diversity of organizations attending, because debates were not always able to attract key organizations or influencing groups that would lead to a broader and effective discussion with significant outcomes [8]. In Apulia, outcomes of consultations were numerous, but as of September 2016, the plant health policy is substantially linked to the European Directive, and the perception of a technocratic approach seems difficult to eradicate from the grower community as a whole.

Furthermore, difficulties may even arise from non-technocratic models. Emerging plant pathogens can sometimes change their character in a shorter timeframe (mainly thanks to developing research) than that allowed for consulting stakeholders or applying decisions, such as changes in the regulatory status of the pathogen and relative management practices [8]. These difficulties emerged for *P. ramorum* [8], but the rapid widespread of *X. fastidiosa* subsp. *pauca* in Italy (Salento, in 2013) and subsp. *multiplex* in France (Corse and Provence-Alpes-Côte d'Azur, in 2015) [87] should also have raised a debate about classification in the A1 list of the European and Mediterranean Plant Protection Organization in late 2016.

4.3. Eradication

As previously reported, Italian protesters affirmed that *X. fastidiosa* cannot be eradicated. Indeed, reports about the eradication of *X. fastidiosa* after its recovery in agro-ecosystems are not available. However, is it pathogen-related or does it depend on other factors? Quarantine plant pathogens can sometimes be eradicated or controlled, and the US continues to represent an interesting case study for Europe. Citrus canker (*Xanthomonas azonopodis* pv. Citri) was detected in 1912 and eradicated in 1933 [88]; 53 years elapsed before it was detected again in 1986 [89]. Continued quarantine efforts to avoid spread of Sharka (Plum pox virus) have been carried out since 1999 [90]: control of aphid vectors, elimination of infected trees, and enforcement of domestic and international quarantine regulations seems effective in contrast to virus spread, even if eradication seems to be no more achievable. Conversely, in the case of huanglongbing outbreak in Florida in 2005 (a severe bacterial disease of citrus), a science panel concluded in the same year that eradication of the disease in Florida was no longer considered feasible because the epidemic was widespread [91], but the opposite in other US states continues. Thus, absence of vectors in the infected areas or the availability of control methods and circumscribed infected areas represent some requisites to achieve a feasible eradication of a pathogen.

The complexity of this topic for the CoDiRO strain is underlined by the fact that the effectiveness of the eradication of infected plants is rated high by the EFSA ("this measure would restore an area to its initial state of pest absence"), but at the same time, the uncertainty is also high because plants may be symptomless or infected too recently for detection, and because many species other than crops can host the bacterium, with or without symptoms [84]. The EFSA briefly reports literature in which links between success and very early intervention were stressed, but conclusions about *X. fastidiosa* seems open to various interpretations [84]. Even if the analysis of the situation in Salento is now dramatic and several conditions for successful eradication [92] are no more fulfilled (i.e., early detection and rapid initiation of eradication programs; host or habitat specificity), the EFSA states that in optimal situations, the multiple hosts and potential vectors of the bacterium would make total eradication of the disease improbable [84]. Thus, eradication is practically difficult because of the wide host range, including crop species, ornamentals, and weeds. Moreover, the significant role of asymptomatic infection and problems with low detection effectiveness in many hosts further contributes to the impracticality of eradication. Since the eradication of *X. fastidiosa* requires early diagnosis and a small infected area, Almeida [7] stated that it no longer seems feasible in Apulia.

The importance of prevention and a fast reply to pest establishment was underlined by the modeling works based on Dutch elm disease, in which a counterfactual scenario was suggested (with unlimited funds and manpower, enabled instant and indefinite sanitation felling following detection of diseased trees) [93]. However, longer-term simulations shown as management scenarios, and a no-intervention policy converges to a similar eventual outcome, regardless of the timing or extent of intervention during the course of the outbreak. The acute pathogenicity of *O. ulmi*, its relationship with the vector, the feedback between the presence of dead trees and the beetle population, and the very wide dispersal of the fungus suggest that effective control was very unlikely once the disease had become somehow established [93].

5. Economic Impact of *X. fastidiosa* and the CoDiRO Strain

The most detailed cost analysis due to *X. fastidiosa* was relative to PD in California. Since 1999, several programs have started to control the spread of PD’s vector and reduce losses due to PD in California. The Pierce's Disease Control Program is the most relevant, involving the California Department of Food and Agriculture and the USDA, among others. As reported by Tumber et al. [94], federal, state, and local governments or industry, together, spent nearly $544 million dollars in the 1999–2010 period. Most of expenditures were sustained by the federal government (74%), mainly allocated for the Animal Plant and Health Inspection Service. In 2009–2010, 6.2% of federal expenditure was allocated for research grant programs. The grapevine industry supported about 10% of direct funding in the 1999–2010 period, mainly allocated to research programs (56% in 2001–2010). Other costs are due to nurseries complying with the shipping protocol measures, such as inspections, pesticide sprays, and quarantines, which are estimated as 17% of the total cost in 1999–2010 [94]. Furthermore, farmers must sustain the cost of plant losses, estimated at $51.1 million each year. However, this expenditure did not include the costs of preventive measures taken by farmers. Finally, farmers’ costs may change significantly due to PD pressure, ranging from $14 to $165 million dollars per year. Thus, aggregating all costs, the estimated cost of PD in California is approximately $104.4 million per year [94]. However, compared with the potential costs of PD ($185 million dollars) the costs of Pierce’s disease programs can be considered affordable [94].

The wide spread of CVC in Brazil was impressive in the first years of 2000, with more than 120 million infected plants [95]. Loss of trees, production losses, and disease control costs due to CVC in Brazil were estimated at $110 million in 2000, with a disease incidence of 34% [96]. However, plant health management policies led to a better situation in recent years, with about 3% of infected plants in 2016 compared to 43.8% in 2004 [97].

Even if the prediction of economic costs is difficult without precise knowledge of the widespread dimension of the disease and the vector, an economic analysis of a potential *X. fastidiosa* outbreak was carried out in the region in which the pathogen was not yet present, such as South Australia [98]. In this case, even if the outbreak was controlled within five years, and limited damage occurred at the regional level, the economic loss was estimated at AUD$135 million. Moreover, indirect losses would consist of a job crisis, a reduction in tourism, and domestic and international shipping restrictions on potentially-infested goods [99].

Non-cultivation-related economic losses may be also related to the infection of ornamental plants. The California Department of Transportation maintains oleander in over 2100 miles of freeway medians, and a $52 million loss was estimated if oleanders are destroyed by *X. fastidiosa* [100].

Regarding CoDiRO infection, aside from the direct loss of income due to the death of the trees, changes in farming techniques due to mandatory protection practices increase management costs [101]. A cost of €111–€119 per dead plant was based on the income of olive oil production in the infected areas, while the increase in management costs was assessed at 31%. Landscape losses, relative to centenary trees, was estimated at €64 per plant, using an interview-based method in which people should establish a congruous tax to pay in order to sustain protection practices instead of tree eradication. Thus, the potential impact of CoDiRO in Salento is very large due to the approximately 11 million olive trees planted in the infected area.

6. Social Sustainability of Plant Health Management Policies

6.1. The Role of Consensus for Building Scientific Opinion

For the scientific community, the progress in knowledge about *X. fastidiosa* achieved by researchers worldwide is unquestionable, and much information is available on preventing or contrasting the pathogen spread, or which agricultural practices may be useful—or not—to defend plants. Obviously, as for many other plant pathogens, the search for knowledge is far from over because many biological and epidemiological factors need to be further investigated to effectively contrast the pathogens once detected in agro-ecosystems. However, is it enough to question research activities outside the scientific community? While the unavailability of a cure for plants due to in-progress research, or due to specific research limitations (i.e., legal disposals, environmental commitments, limited economic interest to adequately support the research, etc.) is a frequent scenario for plant pathology researchers (in virology and bacteriology, above all), that conditions may be difficult to accept by communities when a disease outbreak occurs. In particular, when infected plants are perceived as common goods (i.e., urban greening, forestry) and citizens are directly involved, it may be difficult to communicate that a plant cannot be cured in a society where many severe human diseases are efficiently contrasted. Agronomical practices to improve the vigor of the plants and their resilience caused by bacterial infections generated countless debates; they were also suggested by the EFSA, even if they did not represent a cure for decline [102]. Thus, scientific consensus—among governance, researchers, stakeholders, and communities—should be the starting point for discussions.

Brunsson [103] stated that knowledge is consensus-related. For something to become a fact, people must agree that it has been demonstrated. This implicates that truth depends on human perceptual capabilities and social processes. Science should be a legitimated source of authenticated knowledge, but scientists both produce knowledge and authenticate it, which biases the evidence. Starbuck [104] affirmed the never-ending ambiguity that research does not produce closure. This is because almost all studies point out deficiencies in their methodology, call for more research to answer the questions they have not answered, and most studies raise more questions than they answer. Other issues may derive from unlimited productivity, while significance tests allow researchers to label any difference "significant", including meaningless ones [104]. Anyway, it is very difficult to state baseline truths in plant pathology, above all when pathogen characteristics or behaviors are not fully described, or new hosts are identified, as in the case of *X. fastidiosa* in olive trees. The baseline truth "*X. fastidiosa* is a quarantine pest in European Union" was a statement never put in doubt before the disease outbreak in Italy, but it was rapidly contradicted after the uprooting of olive trees started. Containment measures agreed upon by the European Union in 2015 were blocked for more than a year by dismayed protesters [105]. An alarming political and legal impasse has stopped measures to contain the pathogen, which has invaded nearly 200,000 hectares of olive groves and is killing most olive trees in its wake, including beloved specimens that are more than 1000 years old. Aside from their economic importance, olive trees have a long historical and cultural connection with these regions, generating public resistance to uprooting infected trees. With local political support, protesters dismissed the evidence that OQDS was caused by *X. fastidiosa*, and that it cannot be cured or eradicated, took their case to a local administrative court, which referred it to the European Court of Justice, paralyzing further actions. Meanwhile, public prosecutors started investigations on possible roles in disease outbreaks [106], even if the gridlock shows some signs of easing thanks to verification of Koch's postulate that confirmed the role of *X. fastidiosa* as a causal agent of the disease [67,107].

6.2. The Role of a Cooperative Network in Plant Health Management

In addition to knowledge about *X. fastidiosa* and CoDiRO, olive trees continue to be infected and killed [105], and as reported by Almeida [7], the strategies to manage the disease of socially important-plants such as Salento olive trees have to include social, economic, political, and cultural components. Thus, the *X. fastidiosa* epidemic should represent a lesson to overcome future contrasts among stakeholders, building a more cooperative network [7]. Furthermore, cooperative networks should be supported by the digital management of data derived from plant health monitoring programs [108,109], enhancing trust-based relationships among stakeholders.

Achieving consensus [110] is an important step in plant health management [8]. While plant disease risk can be assessed by using analytical techniques which consider spatial and temporal disease factors, Mills et al. [8] indicate that this technical approach may not provide the best guidelines for policy formulation and decision-making. Starting from Renn's notion on risk governance [111], Mills et al. [8] showed that plant health policy is often a technocratic model, with policy decisions traditionally based predominantly on advice from scientific analysis of pest risk [112]. However, this approach relies on a single source of authoritative advice having been associated with significant failures, such as control of Dutch elm disease in UK [10].

O. ulmi, the fungal agent of Dutch elm disease, changed the European landscape in the 20th century [93]. Even if the disease was widespread and almost uncontrollable in the European mainland, in 1960 the Chief Pathologist of the Forestry Commission of the UK, Tom Peace, regarded the disease as an endemic but controllable plant disease that would periodically recur, while extensive and costly interventions were not justified [113]. Ten years later, about 4% of the trees were dead or dying, while almost 10% were diseased. In 1980, few mature elms remained in the UK, and more than 30 million trees were dead [93]. "Done too little, too late" was the recurrent phrase, indicating that a lack in coordination and fast response after the disease outbreak was behind the disaster [114]. The Forestry Commission was defined as under-resourced and abandoned too early, while the disease should be contained by restricting movements of diseased timber [114]. The technocratic approach emerged when the record of meetings and written exchanges between plant pathologists and the Forestry Commission indicated reluctance to abandon the previously communicated view of Dutch elm disease as a controllable one [93]. When the severity of the disease was obvious, a regional quarantine line across Southern England to prevent a further northward spread was dismissed due to high costs, while a control order to inspect trees was also ruled out. The order was re-invoked later by local authorities of disease-free areas, but no intervention was carried out, and since 1975, the epidemic was accepted as unavoidable. In later years, pathologists involved in the Forestry Commission affirmed that the difficulty was due to contrast from Peace's paradigm, because he was authoritative, besides being "a fine scientist and a tremendous observer" [86]. Tomlinson and Potter [93] indicate that the failure may be due to scientists drawing essentially observational assessments, and not orientated towards a systematic risk assessment for policy purposes; that the Forestry Commission was not given the resources and administrative authority by the government; and the ineffectiveness of legislative responses when these were not linked to any program for implementation.

Conversely from technocratic model, Renn's decisionistic model is based on a wider range of stakeholders and their deeper involvement, evaluating socio-economic and political considerations that go beyond procedures commonly applied for disease management [8], and so achieving a consensus cannot be ignored. In this vision, there is a differentiation between the risk assessment (which is strongly relayed in scientific opinion) and political and value aspects, leading to a risk evaluation and management.

7. Concluding Remarks

Nisbet and Scheufele [115] stated that the false premise that deficits in public knowledge are the central culprit driving societal conflict over science. Deficit model thinking assumes that facts speak for themselves and have to be interpreted by all citizens in similar ways, otherwise irrational public beliefs are invoked [116]. In the case of the CVC strain in the US, as well as many other plant pathogens worldwide, interpretation of "facts" by citizens—or, more appropriately, biological observation—were similar, generally accepting scientists' findings or international guidelines about plant protection. Obviously, uprooting of plants is never welcome by farmers, and opposition sometimes occurs, but conflicts were always solved. In the case of CoDiRO, while scientific opinions for *X. fastidiosa* can be built on solid scientific literature, its management policy was still not fully solved (in July 2016, the European Commission asked Italy to fully implement a decision to stop the progression of *X. fastidiosa*), and difficulties in science communication may have played a significant role. Without analyzing exceptional cases in which even journalists can fall victim to well-orchestrated and presented public relations efforts regardless of their scientific validity [117], communicating science is not an easy task, and errors or misunderstandings may occur, mainly because science communication cannot be improvised. College and doctoral students majoring in the sciences should be offered courses and training in communication, introducing new scientists to focus on the relationships between science, the media, and society, providing valuable professional know-how and skills [115]—something that is particularly uncommon. Communication between government and stakeholder groups was indicated as critical for the successful implementation of policy outcomes for *P. ramorum* management. Updates about scientific findings, reports of meetings, news, and published literature were distributed through a website that acted as an accumulating warehouse of public information and provided a one-stop site for stakeholders [8]. This approach was also followed for the CoDiRO strain, and the website was also used to deliver information about the progress of monitoring activities. The ability to communicate to the masses via social media may be critical to the distribution of scientific information amongst professionals in the field [118], but also to the general population. Even if some criticism of science communication is derived from publications that are not really communicating science to anyone but other scientists [119], some concerns may derive from the interpretation of scientific communications if they are delivered via untraditional (for science) media (i.e., the Internet, social media, TV, etc.), where concepts are commonly shortened and simplified. Conversely, concepts such as "tolerance" or "resistance" to pathogens—frequently desired by farmers—are not always fixed adjectives, and may be misinterpreted; Rashed et al. [22] underlined that "among study comparisons between cultivars, degrees of susceptibility might not provide fully comparable results, as 'susceptibility' (or 'resistance') is a relative term that depends on the subset of the cultivars being evaluated in a given study under a defined set of conditions". Plant pathology is not included in the basic education training of citizens; thus, ever-simple concepts are missing in the cultural background of the audience and filling the gap after a disease outbreak is difficult. Moreover, as previously cited, specific pest-infected plants' values go beyond agricultural products; thus, personal scientific background in other disciplines (i.e., ecology, economy, etc.) may interfere significantly with plant pathology evidence. Again, specific graduate training and new interdisciplinary degree programs [115] may avoid risks derived by the use of social media for science communication.

Communication is a key component of a plant health policy model that goes beyond technocratic and decisionistic models, creating a transparent and inclusive governance model where both assessment and management were evaluated and discussed by science, politics, economic actors, and civil society [111]. In this model, the pre-assessment (framing), which includes socio-economic and political considerations, is a relevant factor, besides being quite difficult to carry out in emerging plant diseases with epidemic behavior, when time is a key factor. Mills et al. [8] suggest an interesting model for plant pathology purposes, connecting policy-makers to those with the information to assess risks and impacts. While economists provide estimates of the values attached to decisions for policy options, pest risk analysts quantify the risk of emerging pests to plants and the environment. From literature surveys, this latter task seems to be achievable for CoDiRO strain management. Thus, this multi-dimensional plant health policy should be provided by effective communication of scientific opinion towards policy-makers (for risk analysis), economists (for prioritization), and the public (for risk perception). However, in this model, the prioritization of options can be achieved through discussion between multiple expert groups and the assessment of perceptions of non-specialist groups that constitute the interested public. As Mills et al. [8] demonstrate, the success of this approach strongly relies on the identification of relevant stakeholders, and that choice is central to timely and acceptable decision-making as perceived by the end-user community. The emphasis on the involvement of individuals or organizations that will engender trust among end-users should be preferred to the selection of representative stakeholder groups [8].

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