chapter nine

Invasive plant pathogens in Europe

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Contents

9.1 Introduction

In the second half of the nineteenth century, grapevine and potato crops in Europe were destroyed by diseases caused by invasive plant pathogens, such as the Oomycetes *Plasmopara viticola* and *Phytophthora infestans* (causing grapevine downy mildew and potato late blight, respectively) and the Ascomycete *Erysiphe necator* (causing grapevine powdery mildew). These “great invasions” by pathogens of non-European origin significantly contributed to the individualization of plant pathology as a science distinct from botany,[1] and the threat represented by the introduction of nonnative plant pathogens was quickly emphasized. In an international congress held at the Hague (the Netherlands) in 1891, the Danish plant pathologist Emil Rostrup advocated the setup of “measures for preventing the importation of living plants or seeds from contaminated areas.”[2] In a seminal book subsequently translated in several languages, the Swedish plant pathologist Jakob Eriksson stated that the increased prevalence and severity of plant diseases

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(in Europe) should be related to the recent emergence of new diseases and their spread worldwide.[2]

From the 1878 Phylloxera International Convention of Bern to the adoption in 1951 by the FAO Conference of the International Convention on Plant Protection (IPPC), a series of international conventions sought to relieve European agriculture from "foreign parasites."[3] The purpose of IPPC, revised in 1979 and 1997, is to secure at a global level a common and effective action against the introduction and spread of plant pests. This treaty also supplies a framework for phytosanitary measures to be taken against "invasive alien species," as defined by the Convention on Biological Diversity, as far as they are plant pests.[4] The revival of the European ideals following the trauma caused by the two World Wars triggered, as far as plant protection is concerned, the formation of the European Plant Protection Organization (EPPO) in 1951. EPPO was given the task to ensure cooperation between national plant protection organizations (e.g., official plant protection, plant health, or plant quarantine services) and to harmonize for plant health. EPPO grew from 15 founding members to a current membership of 50 European and Mediterranean countries (including countries from North Africa, the Middle East, and former Soviet Union Republics of Central Asia). The first objective of EPPO is "to develop an international strategy against the introduction and spread of pests that damage cultivated and wild plants in natural and agricultural ecosystems." In particular, the organization has tried to identify the main risks for Europe and made recommendations to its member countries, as to which pests should be regulated as quarantine pests (EPPO A1 and A2 Lists) and which phytosanitary measures could be taken. Another European particularity was the development of the European Union (EU), an economic and political union of 27 member states. Since 1993, lists of quarantine pests and phytosanitary measures have been harmonized in the EU Council Directive 2000/29/EC (revising Council Directive 77/93/EC). Today, approximately 300 pests have been identified as quarantine pests (largely on the basis of EPPO's recommendations), and many of them are invasive plant pathogens. Accordingly, the issue of invasive plant diseases is still a main concern in Europe, requiring significant effort in both research and management.

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In this chapter, we first summarize the results of recent inventories of invasive plant pathogens in Europe. Second, we present data on the economic impact of some of the worst invasive plant pathogens, considering both direct (market cost via yield and quality loss) and indirect (detection, control, eradication, and compensation) costs. Third, we discuss the methods used to assess the impact of invasive plant pathogens on ecological services. Last, we evaluate the threat represented by plant pathogens currently emerging in Europe or not detected yet.

9.2 *Recent inventories of invasive plant pathogens in Europe*

The International Union for Conservation of Nature (IUCN), mostly concerned with wild ecosystems, restricts the definition of invasive species to "species with a potential impact on biological diversity." Accordingly, IUCN lists only three plant pathogens among "100 of the World's Worst Invasive Alien Species"[5]: *Ophiostoma novo-ulmi*, causing Dutch elm disease; *Phytophthora cinnamomi*, causing dieback, crown, and root rot in some 900 species of perennial trees; and *Cryphonectria parasitica*, causing chestnut blight. In a European perspective, the Delivering Alien Invasive Species Inventories for Europe (DAISIE) consortium lists *O. novo-ulmi, P. cinnamomi,* and *Seiridium cardinale*, the cause of a lethal canker disease on cypress and related conifers, among the "100 of the Worst Invasive Alien Species."[6]

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Conversely, most fungal pathogens of crops would not be considered to be invasive according to IUCN definition, since they have no known impacts on biodiversity. Indeed, many crop plants are themselves exotic in the areas where they are grown, and the pathogen species that attack them followed them from their area of origin.[7] However, in several cases, pathogens were introduced in Europe decades or even centuries after the introduction of their host; such a "reencounter"[8] between a fungus and a plant that had escaped the pathogen challenge for centuries and progressively lost resistance factors is a main cause of "successful" invasions, as exemplified in the case of potato late blight. Rather than a consequence of invasion by pathogenic fungi, the dramatic narrowing of genetic diversity of most crop plants in the twentieth century is an inadvertent help to new fungal attacks. New pathogens usually emerge at the infraspecific level, as virulent pathotypes of pathogens already established, and are not taken into account in inventories of new species. Recent examples are the spread of the virulent strain Yr17 of yellow rust (*Puccinia striiformis*) all over Europe[9]; the emergence in Africa of the Ug99 strain of *P. graminis* f.sp. *tritici*, the stem rust fungus, a strain that potentially threatens wheat growing worldwide[10]; and the inadvertent introduction in Europe of the A2 mating type of *P. infestans*.[11] In a few cases, pathogenic fungi on cultivated species were shown to be able to infect wild species as well (for instance, *Ramularia collo-cygni* and *Sclerophthora macrospora* reported on grasses and cereals).

The first inventories of alien invasive species for Europe, including fungi, were recently issued by the DAISIE consortium.[12] The list of alien fungi is a compilation of available national lists and contains 688 species, among which plant pathogens represent 77%.[13] The highest numbers of alien species were found in the biggest European countries, France, the United Kingdom, Germany, and Italy. Rather than geographic characteristics, such as surface, latitude, longitude, and climate, the level of import of goods was the best predictor of the number of alien species in a given country. Most introductions of species at the European level are of North American and Asian origin. Most alien plant pathogenic fungi are assumed to have been inadvertently introduced with contaminated material, such as nursery stock (*Phytophthora ramorum*), log shipments (*O. novo-ulmi*), or even military equipment (*Ceratocystis platani*).

National inventories can provide more detailed insights into the characteristics of plant pathogen invaders. The French inventory includes 227 fungal species of presumably non-European origin recorded in France since 1800.[14] Plant pathogens are the most numerous ecological category, with 65% of all species, mycorrhizal and saprotrophic fungi representing 30% and 4%, respectively. Nearly half (46%) of the plant pathogen species have been recorded primarily on crop plants, while ornamental and forest pathogen species account for 31% and 22% of the records, respectively. More than 50% of plant pathogens attack woody plants (forest, fruit, and ornamental trees and shrubs). Three groups of diseases account for nearly 50% of the reported invasions, the downy mildews (Peronosporales), the powdery mildews (Erysiphales), and the rusts (Pucciniales), in respective proportions 2:1:1. The high multiplication rate of these pathogens; the extended dispersal potential of windborne powdery mildews, rusts, and some downy mildews; and the very visible damage they cause on plants might explain their apparent overrepresentation in the database.

The inventory of introduced, nonnative plant pathogens into Great Britain[15] was limited in time but addressed all taxonomic groups of pathogen species. The inventory includes 234 pathogens (fungi, bacteria, phytoplasma, and viruses) reported for the first time in Britain from 1970 to 2004, 79% of them being fungi. Some 60% of the fungal records were made on ornamental species, which is twice the proportion reported in France. Most of the ornamentals and a significant proportion of the horticultural crops on which new pathogens were detected grew in glasshouses or under polyethylene covers; accordingly, 50% of the new British records in the given period were found in protected environments. Here, again, transportation of contaminated plant material seems to be a main way of introduction of plant pathogens; from the limited evidence available on the origin of the infected plants, the Netherlands was pointed out as a main source of introduction. Evaluating the potential impact of the introduced species, panels of British specialists labeled 19% of the pathogens "important."

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9.3 *Economic impacts of invasive plant pathogens*

Detailed data on the economic impact of invasive plant pathogens in Europe are scarce. Pimentel et al.[16] estimated that damage associated with alien plant pathogens attacking British crop species could reach ~~$2~~ billion (€1.46 billion) per year; the estimation was the product of the estimated rate of alien plant pathogens in Britain (74%) and the economic loss associated with crop pathogens (~~$2.7~~ billion per year). No such figures are available at the European scale, for which the proportion of alien to native plant pathogens has not been assessed. We list ~~below~~ recently published assessments of economic loss due to some of the worst invasive plant pathogens; while most of the data are available at a specific country's level, we have attempted in some cases to extrapolate the economic cost of the pathogens to larger areas. Understandably, the economic impact of plant pathogens has mainly been assessed when host plants have an economic value, for example, for crop plants and trees with ornamental value.

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9.3.1 *Fungi and Oomycetes*

9.3.1.1 *Cultivated plants*

The downy mildew and the powdery mildew of grapevine, introduced from the United States in the nineteenth century, still threaten grapevine and therefore wine production in many European countries. Control of the disease using fungicides is mandatory to save grapevine yield and quality; in wet years, up to 90% of the fungicide sprays are targeted to these two diseases. According to a recent report on pesticide use in France,[17] fungicide cost in 2002 represented €287 per hectare for average quality wines, which account for 46% of the grapevine acreages; the cost increased to €398 per hectare for quality wines, which require a better protection against the mildews. Considering that grapevines cover slightly less than 600,000 ha, the total annual cost of chemical control of the downy mildews is more than €180 million. The French vineyards represent 12% of the European vineyard area, and the total cost for Europe can be extrapolated at €1.5 billion per year. However, the actual cost must be lower since most other European countries use less fungicide on vineyards than France.

Potato late blight has remained the main potato disease in Europe since its introduction in the nineteenth century. In 1991, ~~$223~~ million (€163 million) of fungicides were used worldwide against potato diseases, Europe accounting for 59% of this use. Diseases, including potato late blight, accounted for a yield loss of 15%, which could have reached 35% if no fungicide had been applied.[18]

Since then, the disease has increased in aggressivity and earliness in most European countries, a shift partially explained by the invasion of the continent by fungal populations with mating type A2.[19] In Finland, sales of fungicides used against late blight increased fourfold from the 1980s to 2002.[20] The total annual costs of the disease in Norway are about NOK 60 million (€7.4 million), including fungicide application, yield and quality loss, cost of inspection, research, advisory service, and warnings.[21] Annual losses in Ireland have been estimated at £8 million (€9.1 million) per year[22]; the value of the Irish potato pesticide market is approximately £3.5 million (ca. €4 million), of which 63% (£2.2 million, ca. €2.5 million) is spent on fungicides for the control of late blight.[23]

To control late blight, professional growers in Europe applied an average of 7.5 and 6.7 fungicide sprays in 2007 and 2008, respectively. For the four countries with the most intensive potato-growing system (the United Kingdom, Belgium, France, and the Netherlands), the average number of sprays was 12.8 and 14 in 2007 and 2008, respectively.[20] In Flanders (Belgium), the application of 10–14 sprays in most seasons costs between €200 and €400 per hectare for the fungicides depending on product choice.[24] In England, the cost of protection is £130–£200 per hectare (€148–€227),[25] whereas a cost of £167 per hectare (190) for 13 applications was considered "relatively low."[26] Using an average number of applications, derived from the 2007–2008 data of 10, 16, 14, and 16 for the United Kingdom, Belgium, the Netherlands, and France, respectively, with potato-growing areas of 140,000 ha, 68,000 ha, 157,000 ha, and 158,000 ha for the same countries, respectively, and an average cost of €18 per hectare for application, the cost of the protection against late blight in the European intensive production systems reaches €130 million per year.

9.3.1.2 Forest and amenity trees

In a detailed study of the impact of invasive alien species in Europe based on the DAISIE inventory, Kettunen et al.[27] listed 125 invasive species "with existing evidence of significant environmental, social, and economic impacts in Europe." Only four plant pathogens, all terrestrial fungi attacking trees, are included in the list: *Ophiostoma ulmi* (as "*Ceratocystis ulmi*"), *Ophiostoma novo-ulmi*, *Phytophthora cinnamomi*, and ~~*Seridium*~~ *cardinale*. Figures of economic costs were only given for the second Dutch elm disease epidemics caused by *O. novo-ulmi*; extrapolating the data available in Sweden (calculated costs) and Germany (estimated costs), the cost of the disease was estimated at €124 million per year in Europe. In the same report, the authors gave an "indicative estimate" of the economic impact of "unspecified plant pathogens" (fungi and others) as €1785 million per year. However, the estimation is indeed the figure given by Pimentel et al.[16] for damage by alien pathogens to crops in Great Britain, corrected by a 0.3% annual inflation rate, using 2007 as reference point.

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Canker stain of plane trees caused by the fungus *Ceratocystis fimbriata* f.sp. *platani*, was probably introduced in southern European harbors with American military equipment during the Second World War. The disease threatens city and road plantings; in the earliest foci of disease, nearly all trees were killed by the fungus. The Roads Agency of the Department of Bouches-du-Rhône (south of France, Marseilles area) conducted a detailed evaluation of the costs associated with the disease.[28] The removal of a diseased tree costs at least €1000; however, two neighboring trees have to be removed, too, for sanitation; therefore, the actual cost is €3000. Replanting in situ costs €1135 for a plane tree resistant to the disease, or €850 for a European hackberry immune to the disease. A brand new planting is a less-expensive option, with a cost of €450 for a resistant plane tree and €500 for a European hackberry.

For the whole of Bouches-du-Rhône, 170 infected plane trees were detected and removed in 2006. Prevention and detection cost €30,000, removal ~~cost~~ €170,000, while replanting, not completed, would have cost an average of €120,000 (€75,000–€193,000 depending on the retained technical options.) Accordingly, the fungus generates an economic impact of €1700 per tree. The cost of the disease for a private owner would be much higher. Moreover, reports of the spread of the fungus to natural forests in southern Italy[29] indicate that the impact of the fungus could increase in the future.

9.3.2 Bacteria and phytoplasma

Flavescence dorée is a quarantine disease of grapevine, caused by a phytoplasma transmitted by the insect *Scaphoideus titanus*. Steffek et al.[30] evaluated the cost of uprooting of a 800-ha vineyard in Serbia following the detection of the disease; the primary loss, due to lost investment, was €3.2 million, the income loss for the wine producers due to the decrease in grape production being assumed to be even greater.

Potato brown rot, caused by the bacterium *Ralstonia solanacearum* race 3 biovar 2, is another quarantine disease that has occasionally been found in European countries (including the Netherlands and the United Kingdom), but outbreaks are always submitted to eradication campaigns. Using a bioeconomic model simulating the spatiotemporal spread of the disease over a series of years, Breukers et al.[31] evaluated the cost of the disease to the Dutch potato industry. Analyzing the cost categories, they showed that reducing pathogen monitoring would half the structural costs but dramatically (nearly × 10) increase the export losses; accordingly, the overall cost would increase from €7.7 million to €12.5 million per year.

In the United Kingdom, trial programs have been set up to remove *Solanum dulcamara*, a common native plant from riverbanks that can be infected by the bacterium and acts as a source of inoculum; the cost of *S. dulcamara* removal was £1260 per km of river. The cost of a 4-year campaign on the River Trent was estimated at £2.06–£2.2 million (€2.3–€2.5 million), including removal of *S. dulcamara* and irrigation with disinfectant every year, as well as tuber testing before planting in the first year. Incidentally, the policy of removal of *S. dulcamara* was not implemented in the River Trent mostly because of its low benefit–cost ratio.[32]

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Fire blight of Pomaceae is caused by the bacterium *Erwinia amylovora*. The introduction of the disease into Europe during the twentieth century has led to severe losses in pome fruit tree orchards and nurseries, as well as in the ornamental sector. In Switzerland, where the disease was first observed in 1989, the financial burden of control measures (from quarantine to diagnostics), together with compensation payments for destroyed plants, were estimated as follows: €4.5 million in 1989/97, €26.5 million in 1998/02, and more than €4 million in 2003 (i.e., a total of €35 million over a 14-year period).[33] But even for a well-documented disease such as fire blight, there are no general estimates of economic impact given for the whole of Europe.

9.3.3 Viruses

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Sharka disease, caused by *Plum pox virus* (PPV), threatens the growth of *Prunus* worldwide. Cambra et al.[34] estimated the loss in European plum fruit production due to the disease at €5.4 million over the last 30 years. On peaches, PPV-M, an aggressive strain of the virus, caused a loss of €576 million over the last 20 years in Mediterranean countries. In Spain, mandatory and/or voluntary eradication programs have cost €63 million since 1989, including removal, compensation, and production loss. An extrapolation to Europe gave a cost of survey and eradication of PPV of €39 million since 1980. Worldwide cost during the same period, excluding indirect trade loss, is of €10 billion. Detected in Switzerland in 1967, sharka disease was subjected to an important program of eradication, and it was believed eradicated in 1973. Afterwards, the disease only occurred sporadically until 2004, when a new outbreak was detected and again submitted to eradication and containment measures. The total cost of the first eradication campaign (from 1967 to 1973) was evaluated at CHF 500 million (€340 million), including compensation payments and the costs of research on diagnosis and epidemiology. These eradication costs were estimated to be equivalent to an annual crop loss of 10% (assuming infection induced a 25% yield loss), and if no measures had been taken, Switzerland would have had an equivalent loss after a few more years.[35]

9.4 Ecological impacts of invasive plant pathogens

Traditionally, the estimation of the impacts of plant pathogens rely on the estimates of crop loss and control costs.[16] This approach will underestimate, however, the actual impact of pathogens on plants growing in wild environments, for instance, tree species. The second epidemic of Dutch elm disease, caused by *O. novo-ulmi*, caused the death in 1970–1990 of 28 million mature and 20 million young elms in the United Kingdom; comparable losses were also recorded in continental Europe, central Asia, and North America. Brasier[36] pointed out that economic formulae based mainly on visual and shade impacts, as applied at the landscape scale, could only provide a guide to estimate the actual loss.

Brasier[36] further argued that the cost of irreplaceable loss of a species, a part of the historical and cultural heritage of a country, cannot be evaluated. The economic assessment of biodiversity, especially of ecological services of ecosystems, is indeed a challenge that could prevent a comprehensive evaluation of the impact of invasive plant pathogens. In their review of the impacts of alien species on ecological services in Europe,[37] the DAISIE experts stressed that ecological and/or economic impacts were documented for only ca. 10% of the alien species recorded in the DAISIE inventory. Often evaluated separately, ecological and economic impacts are likely to be highly correlated and should be assessed together in impact studies. Unfortunately, the pathogenic fungi were not explicitly addressed in the review, which focused on the "worst" invading terrestrial plants, vertebrates, and invertebrates, as well as aquatic and marine fauna and flora. However, most conclusions of the review can be applied to plant pathogens. When assessing the impacts of alien species, such as invasive plant pathogens, on ecosystem services, most available data relate to provisioning impacts (food loss, threat to endangered native species) while data on cultural impacts (changes in recreational use, effects on ecotourism, changes in the perception of landscapes and aesthetics) are scarce.

The value of the ecosystemic services potentially impacted by invasive plan pathogens is also poorly documented. A recent report delivered to the French prime minister[38] proposed guidelines to improve the precision and accuracy of the assessment of the reference values of ecosystemic services. Accordingly, the reference value of different ecosystemic services of the French forest was evaluated at €970 per hectare per year on average (ranging from €500 to more than €2000), that is, €35,000 per hectare in total actualized value. Within this reference value, only a small part (€75 per hectare per year) was attributed to wood provision, while the most important parts related to carbon capture and storage and recreational services. This assessment can provide a basis to estimate the impacts of forest pathogens, especially of alien species, if one can estimate the part of "forest services" lost due to their action. We tentatively estimated this loss as follows. The rate of fungal diseases recorded in the systematic survey of crown status on 10,000 trees belonging to the International Cooperative Programme (ICP) forest European network[39] was 7% in 2005 and 2006 in France (see Département Santé des Forêts[40,41] for the last available years), which correspond to a significant, generally strong, impact of fungi on the crown status of examined trees. We estimated that 20% of the ecological services provided by those trees were lost (wood production, carbon storage, amenity value, etc.), leading to a low estimate of 1.4% loss in "forest value," that is, €208 million per year lost due to forest pathogenic fungi in France. However, only a few visible pathogen species are recorded in the systematic survey, which, for example, does not include root pathogens. In the database of the ~~French~~ Forest Health Service ~~(DSF)~~, the species recorded in the ICP network correspond to only 50% of all records. A more realistic estimate would therefore be over €400 million lost each year. This figure itself is probably an underestimation since even the ~~DSF~~ database only records disease symptoms and not growth loss per se. We therefore suggest an estimation of the impact of forest pathogens in France in the range of €400–€800 million per year. Because 37% of all diseases in the ~~DSF~~ database are attributed to alien fungi,[42] this would give an estimate of €148–€296 million per year for alien forest pathogenic fungi.

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In the aforementioned study on the impact of the canker stain of plane trees,[28] the amenity value of an average plane tree was evaluated at €4200. The infection of the tree by the fungus nullifies its amenity value. Accordingly, amenity loss due to the removal of the 170 infected trees in Marseilles area in 2006 can be estimated at €715,000.

9.5 *Foresight of impacts of invasive plant pathogens*

9.5.1 *Pest risk analysis and the assessment of economical impact of invasive pathogens (emerging or still absent in Europe)*

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Pest risk analysis (PRA) as defined by IPPC[43] is "The process of evaluating biological or other scientific and economic evidence to determine whether an organism is a pest, whether it should be regulated, and the strength of any phytosanitary measures to be taken against it." At the global level, guidance on how to perform PRA is given by the International Standard on Phytosanitary Measures (ISPM) no. 11.[44] At the European level, EPPO has elaborated a scheme to carry out PRAs[45] and also conduct PRAs itself by organizing expert working groups to assess the risks presented by specific pests. At the EU level, the European Food Safety Authority (EFSA) now also performs PRAs for the EU Commission. PRA can be used as a tool to predict the economic impact of invasive pathogens (whether they are regulated at the end of the process), but this remains a difficult task, as much economic data is lacking. The economic assessment is usually based mostly on expert judgment.[46,47] While representing a low-cost and efficient use of scientific knowledge, such an assessment lacks transparency and repeatability. Reliable economic data are rarely available to PRA assessors, especially when a potentially invasive pathogen is detected in a new area. However, attempts have been made to quantify the potential economic cost of the introduction of an invasive plant pathogen into Europe. The method used in these studies is the evaluation of direct economic consequences of an introduction by partial budgeting.[47]

The fungus *Tilletia indica*, which causes karnal bunt of wheat, is a quarantine pathogen in Europe (regulated in the EU Directive 2000/29, and included in the EPPO A1 List). A PRA funded under the EC 5th Framework concluded that the pathogen has the potential of establishing in the United Kingdom and many other European countries.[48,49] The economic impact of the introduction of karnal bunt of wheat was also evaluated in the PRA.[49] Assuming that a large disease outbreak (50,000 ha) would occur in the United Kingdom, the total costs at the European level would be ca. €34 million in the year of the outbreak; direct costs (yield and downgrading) would be insignificant (5% of total) compared with reaction costs (indirect quality losses, loss of exports related to its categorization as a quarantine pest in other countries, and seed industry costs; 43%) and control costs (52%). The main cost would be caused by downgrading (31% of total) or destruction (27%) of nonaffected crops due to mandatory measures. After 10 years, the cost supported by the United Kingdom would be €454 million.

Potato spindle tuber viroid (PSTVd), the cause of a destructive disease on potatoes worldwide, was placed on the A2 List by EPPO in the 1970s, as it was sporadically reported from a small number of European countries. However, the epidemiological situation of this disease needs to be further investigated because recent observations have showed that PSTVd could be detected in asymptomatic solanaceous ornamentals, which might act as reservoirs for the viroids. In particular, there is now epidemiological evidence that ornamental species (i.e., *Brugmansia* spp., *Solanum jasminoides*) can act as sources of PSTVd for tomato crops.[50] Soliman et al.[47] concluded that the introduction of PSTVd in the main potato-producing areas of the EU would have a direct impact of €685 million per year (control costs, €118 million; reduced revenues due to yield loss, €685 million). Further analyzing the indirect economic consequences of a PSTVd invasion by partial equilibrium modeling, Soliman et al.[47] found that the direct negative impacts would be transferred from producers (whose welfare would increase by 0.02%) to consumers (domestic prices would increase by 0.73%).

The complexity of assessing the economic impact of an invasive pathogen at a regional level is illustrated by the example of *Pepino mosaic virus* (PepMV). First described in Peru in 1974 (on *Solanum muricatum*), this virus emerged in Europe on glasshouse tomatoes in the 1990s. The virus is highly contagious (mechanically transmitted) and has the potential to damage tomato crops. The economic impact varies among European countries, as it seems to be particularly influenced by tomato fruit marketing systems. In the United Kingdom, only high-quality fruit is profitable, and there is no market for second-class fruit; therefore, any disease symptom will lead to downgrading and unacceptable economic losses for the growers.[51] In other European countries such as the Netherlands, a similar loss in fruit quality will not lead to unacceptable losses in terms of sale profits for Dutch growers. An EU research project (PEPEIRA) specifically dedicated to PepMV is currently underway, and one of its objectives is to assess the economic impact of PepMV on tomato crops and develop an economic model to determine the overall economic impact in EU member states, the ultimate goal being to provide an EU-wide PRA for PepMV.

To overcome the lack of sufficient data required to effectively carry out PRAs, an EU-funded project "PRATIQUE—Enhancements of Pest Risk Analysis Techniques" was launched in 2008. A particular objective of this project is to enhance techniques for assessing the economic, environmental, and social impacts[52] of quarantine pathogens.

9.5.2 Should we expect more invasive species in the future?

The globalization of trade and tourism and increased migrations of human populations for economic and political reasons, as well as global warming, have been highlighted as drivers of a potential increase in the rate of invasions by living organisms.[53–55]

At the British scale and over four decades, the number of pathogens introduced on the two most important plant groups, that is, ornamental and crop plants, has not significantly increased over 5-year period (11–28 species per period on ornamental plants, 4–15 species per period for crop plants). Considering the whole data set, the average rate of introduction of plant pathogens over 35 years of the survey is 6.7 species per year, including 5.3 fungal species per year.[15] For France, lower rates have been recorded, ranging from 0 to 36 per decade. However, many species labeled "alien" in Great Britain are considered to be indigenous in continental Europe. A significant result for the French inventory was the marked increase in introductions from 1800 onwards with less than 0.5 new species of fungi recorded per year until 1930, in spite of the effort of talented mycologists eager to record new species, to two new species per year in the last decades.[13] A significant exponential pattern in the rate of introductions from 1800 onwards was also observed at the whole European scale.[13]

9.5.3 Emerging invasive plant pathogens in Europe

Most of the aforementioned listed economic and ecological impacts on European agro-ecosystems are caused by invasive plant pathogens established in Europe for decades. We present here selected cases of invasive pathogens currently emerging in Europe.

Acidovorax avenae subsp. *citrulli*, a pathogen causing bacterial watermelon fruit blotch, is not yet invasive but shows potential for invasion (e.g., in the United States). That *A. avenae* subsp. *citrulli* is a seed-borne disease probably adds to the risk. Isolated findings have been made in Greece in 2005 and Israel in 2006 but have not been followed by the establishment of the disease in watermelon crops. Detected in July 2007 in Hungary, the pathogen seems to have been introduced on grafted watermelon transplants imported from Turkey, where the disease is present.[56]

Chalara fraxinea, a fungus causing the dieback of common ash, is an invasive pathogen currently increasing its distribution area. After its first finding in Poland in 2006,[57] the fungus has since been detected in many countries, covering most of the distribution range of *Fraxinus excelsior* (Kirisits, pers. comm.). The situation of *C. fraxinea* in Europe needs to be further investigated; in particular the relationships between the anamorph and teleomorph stages need to be clarified. The teleomorph of *C. fraxinea*, which has recently been identified (*Hymenoscyphus albidus*), is widespread, nonpathogenic, and native to Europe, while *C. fraxinea* apparently behaves like an "exotic" disease.[58]

The pine wood nematode, *Bursaphelenchus xylophilus,* is a major threat to European forests. *B. xylophilus*, an endemic species in North America, has caused serious economic damage in Japan, China, and Korea. This pest has been intercepted in packing material shipped into Europe from North America and Asia. More critical is an outbreak of the disease on maritime pine in Portugal, since 1999.[59] The European Commission has adopted emergency measures requiring the treatment of all nonmanufactured wood packing material from contaminated areas in order to prevent introduction of the nematode throughout Europe.

A stream of *Phytophthora* spp. with impacts on wild and horticultural plants has been introduced in Europe since the 1990s.[36] *P. ramorum*, the cause of sudden oak death in the United States, is spreading in commercial nurseries, woods, and gardens in Europe where it attacks several species (especially rhododendron), although forest tree infections are still limited.[60] In the United Kingdom, rhododendrons are attacked by *P. kernoviae*, which has been recently recorded on *Vaccinium* and therefore represents a major threat to the native heathland.[61] The highly aggressive species *P. alni* subsp. *alni*, spreading to riparian alders all over Europe, has been shown to be a hybrid between two less aggressive species, *P. alni* subsp. *uniformis* and *P. alni* subsp. *multiformis*.[62] *P. alni* subsp. *alni* easily transfers with nursery stocks and has the ability to jump from host to host and to hybridize; this *Phytophthora* species represents major threats to cultivated and wild plants in Europe. In a 6-year survey of Spanish nurseries, Moralejo et al.[63] detected 17 species from 37 host plants; several host–pathogen combinations were the first reports. Moreover, most of these species are of alien origin and could spread to natural environments.

Viruses transmitted by *Bemisia tabaci* have been a matter of increased concern since the emergence in the 1990s of many new species damaging vegetable crops (beans, capsicum, cucurbits, lettuce, and tomatoes). In a review, Polston and Anderson[64] stated that the number of new whitefly-transmitted viruses infecting tomatoes in Latin America increased from 3 in the 1970s to nearly 20 in the 1990s. More virus species have been described since then, and most of them still do not occur in Europe (e.g., tomato mottle virus, chino del tomate virus, and Sinaloa tomato leaf curl virus). But in Europe, outbreaks of yellow leaf curl diseases on tomato crops (caused by tomato yellow leaf curl virus and tomato yellow leaf curl Sardinia virus), only sporadic in the 1960s have now become a serious economic problem. In the eastern part of the Mediterranean Basin, tomato yellow leaf curl outbreaks sometimes result in total crop failures.[65,66] These disease emergences can be linked to the spread of their insect vector *B. tabaci*, which has recently increased its distribution area by moving northwards, possibly as a consequence of global warming, but certainly aided by the international transport of plant material.

9.5.4 Invasive plant pathogens still absent from Europe

The EPPO A1 List contains plant pathogens undetected yet in Europe, for which regulation as quarantine pests is recommended to its member countries. Information of worldwide disease distribution, biology, and risk analysis is available on the EPPO Web site.[67] We present below a short list of the pathogens from A1 List, which would most probably have the most severe impacts if introduced in Europe.

9.5.4.1 Fungi and Oomycetes

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EPPO considers *Ceratocystis fagacearum*, the cause of oak wilt, which occurs in the eastern and midwestern United States, to be a threat to oak trees in Europe: the fungus is pathogenic to European oaks[68] and could find a suitable insect vector. The main measure to prevent the entry of this pathogen in Europe is the prohibition of imported oak plants. Another means of introduction is the trade of oak wood infected with fungal mycelial mat or carrying bark beetles, but specific requirements are made by European countries in their phytosanitary regulations on wood and wood products to prevent this.

Sirococcus clavigignenti-juglandacearum, the cause of butternut canker, could present a high risk to Europe to kill large numbers of trees used for production of wood, nuts, and oil and threaten the walnut tree as an amenity species. *S. clavigignenti-juglandacearum* is even considered more aggressive than the fungi responsible for chestnut blight and Dutch elm disease. The introduction of infected host plants is the most probable means of entry of the fungus in Europe, and EPPO has recently added it to its A1 Lists of pest recommended for regulations.

Thecaphora solani, the cause of potato smut, indigenous in Central and South America, presents a significant risk to both seed and ware potato production in Europe. Mostly spread on infected tubers, the fungus is regulated as a quarantine pest in many European countries.

Cronartium spp. are various rust species, known in North America as "blister rusts" infecting conifer trees. While their aeciospores can travel over long distances, the trade of conifer plants from North America could be a pathway for introducing blister rusts. These pathogens among others are the reason why imports of conifer plants from North America into Europe are prohibited.

Diaporthe vaccini, the cause of blueberry twig blight, has been reported a few times in Europe but does not seem to have persisted yet. *D. vaccini* is probably imported from America on blueberry vines.

Gymnosporangium spp. are various rust species mostly of North American origin infecting fruit trees, especially apple trees. Infection of the telial host of the fungus, *Juniperus* spp. is systemic; accordingly, *Juniperus* branches could also be a source of entry of the fungus in Europe. Regulations on the different host plants of *Gymnosporangium* spp. have been put in place in Europe to avoid their introduction.

Puccinia hemerocallidis, causing daylily rust, is of Siberian origin and results in severe losses to gardeners and nurseries in North America. The fungus has already been detected in imported plants in the United Kingdom, showing that trade of infested plants could be a pathway of entry. Once established, its eradication would be difficult since the fungus can survive as a latent infection. Therefore, this pathogen has been recommended recently by EPPO to be regulated as a quarantine pest.

9.5.4.2 Bacteria

Huanglongbing or citrus greening (associated with *Candidatus* Liberibacter asiaticus, *Ca.* L. africanus, *Ca.* L. americanus), a severe disease of citrus, presents a high risk for the Mediterranean regions of Europe, provided its insect vectors (*Diaphorina citri* and *Trioza erytreae*—also regulated as quarantine pests in many European countries), were also introduced. So far huanglongbing has never been detected in Europe, but isolated findings of ~~one psyllid~~ vector~~, *Trioza*~~ *erytreae*, were reported in Madeira (Portugal) in 1994 and in the Canary Islands (Spain) in the 2000s, stressing that particular attention should be paid to this disease.

Xanthomonas axonopodis pv. *citri*, the cause of bacterial canker of citrus, is recognized as a significant problem in countries where it occurs. In Europe, to protect citrus production against severe diseases such as huanglongbing or citrus canker, importation of citrus plants from outside the region is prohibited.

Xylella fastidiosa, the cause of Pierce's disease of grapevine and related diseases on peach trees, citrus, and other woody plants, could destroy vineyards and prevent grapevine cultivations in European countries. The insect vectors present in America are not found in Europe, but because transmission of the bacterium is not vector specific, the bacterium could most probably find a suitable vector in Europe. *X. fastidiosa*, together with other damaging grapevine pests, is one of the reasons why imports of *Vitis* plants from outside Europe are prohibited.

9.5.4.3 Viruses

EPPO considers potato viruses of South American origin (e.g., ~~potato Andean mottle virus~~, ~~potato black ringspot virus~~, ~~potato virus T~~, ~~potato yellow dwarf virus~~, and ~~potato yellowing virus~~) to be serious threats to potato seed production in Europe. If introduced, they would increase the cost and difficulty in operating the seed production schemes. As a consequence, most EPPO member countries prohibit the importation of potatoes from outside Europe.

9.6 Conclusion

Invasive plant pathogens still represent a main threat to cultivated and wild plants in Europe. Pathogens introduced decades ago still have a huge direct economic impact, represented by yield and quality loss and the cost of fungicides required to protect crops with high cash value, such as grapevine and potato. In the future, farmers will have to use less fungicide to follow European and national regulations and rely on more sustainable methods of disease management to decrease crop loss.

For noncrop ecosystems, there is increasing consensus toward an evaluation of impacts accounting for not only the direct, economic loss but also the damage caused to the ecosystemic value of the attacked plants. Due to the increase in international trade of nursery stocks and planted trees, native plant communities, woodlands, and landscapes face an increasing risk of invasion by pathogens.[36]

The strict enforcement of quarantine rules is critical to keep potentially invasive pathogens at bay. Quarantine lists based on PRA should be regularly updated to prevent disastrous introductions—or, at least, to increase awareness of pathogens that are poorly known outside their native areas. However, the traditional European species-targeted approach has inherent limits since it can only apply to known species. Many recent emerging diseases, especially in noncrop plants, were caused by previously undescribed species of unknown origin, such as *P. ramorum* or *C. fraxinea*. A pathway approach to prevent the movement of pests and pathogens in international trade is therefore increasingly considered, in addition to the species approach. For example, a global standard on wood packaging material[69] is now being implemented by many countries around the world, and a new standard on plants for planting is under preparation.

Solving the difficulties encountered in predicting the invasive behavior of plant pathogens and taking appropriate actions against them certainly remains a challenge for all stakeholders, from the growers, plant traders, economists and plant health policymakers to plant pathologists.

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