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Analysis

On consumer impact from *Xylella fastidiosa* subspecies *pauca*

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ABSTRACT

The introduction of *Xylella fastidiosa* in Apulia has resulted in the desiccation of millions of olive trees. Here, we employ a multi-country partial equilibrium model to analyze the possible distribution of economic impacts among olive oil processors and consumers. The results suggest that the majority of the impacts would fall on consumers as a consequence of higher prices. If the disease disperses beyond the current extent in Italy the decline in consumer welfare ranges from 4.1 billion to 10.3 billion Euro over the course of 50 years depending on the rate of disease spread. In other words, each of the 195 million households in Europe would incur additional costs ranging 63 cents to 1.6 Euro every year over the course of 50 years. Introductions of the pathogen into Greece or Spain could cost European consumers between 0.4 billion to 3.3 billion Euro and 1.8 billion to 53 billion Euro, respectively. This would correspond to additional annual household costs ranging 6 to 51 cents and 27 cents to 8.2 Euro, respectively. As significant economic consequences from further dispersal of the disease are borne by consumers, the economic threat is not limited to producers but should be contextualized as a societal problem.

1. Introduction

The introduction of invasive species can have major impacts on economies, ecosystems and societies, and can cost taxpayers billions of dollars annually (Pimentel et al., 2005; Charles and Dukes, 2008). New invasive species introductions are driven by global trade and travel (Hulme, 2009; Levine and D'Antonio, 2003). While the majority of introductions do not result in significant impacts (Levine et al., 2003), introductions of hazardous organisms can have severe consequences. The agricultural sector is particularly vulnerable to introductions of livestock diseases or plant pathogenic organisms (Paini et al., 2016). Here, invasive species can lead to a reduction of food supply which can adversely affect consumers through higher prices (Mangen and Burrell, 2003; Knight-Jones and Rushton, 2013), as well as reduced food quality, food safety (Lehner and Stephan, 2004), and food security (Cook et al., 2011).

Olives have been at the agronomical, cultural and culinary heart of the Mediterranean basin for centuries (Kiritsakis et al., 2005; Vossen, 2007). Olive trees can get very old, in the order of hundreds of years (Rallo et al., 2014), and old trees contribute to the agro-ecological landscape and cultural heritage in the Mediterranean basin. The vast majority of the harvested olives are processed into oil (Vossen, 2007; Eurostat, 2016). Around 3 billion tonnes of olive oil are produced globally out of which nearly three quarters originate from Italy, Greece and Spain (Eurostat, 2016).

The European olive production is under threat due to the invasion of the bacterium *Xylella fastidiosa* subspecies *pauca* (Xfp). *Xylella fastidiosa* (Xf) can infect several hundred plant species and is considered one of the most dangerous plant pathogenic bacteria worldwide (EFSA, 2018; Hopkins and Purcell, 2002). The subspecies *pauca* was first detected in the European territory in 2013 and is causing the Olive Quick Decline Syndrome which has spread across the southern part of the province Apulia in Italy (Saponari et al., 2016). In susceptible hosts, Xf obstructs the xylem leading to desiccation (Hopkins, 1989; Saponari et al., 2017). The detection of the bacterium and the devastating impacts of the disease led to the enactment of control measures including vector control and felling of healthy trees to prevent spread by establishing a cordon sanitaire around the infected area (European Commission, 2015, 2017). The implementation of tree felling as a measure raised dramatic societal unrest in the affected region (Almeida, 2016; Stokstad, 2015). Insights into potential consequences to citizens from further spread of the pathogen could inform the public debate on appropriate measures against Xfp.

Market responses to further spread of the pathogen, and

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consequences to consumers, will crucially depend on the ability of suppliers to adapt. The elasticity of supply provides a measure of the responsiveness of a production system to price changes. Various factors determine the ability of producers to adapt the production volume to price changes, such as the length of a production cycle, the mobility of the operation and the ability to store the product. Price responses following reductions in supply due to an invasive species can be particularly severe if the supply of the host plant is inelastic. Inelastic supply is inherently connected with the production of olives, which requires considerable up-front investments (Stillitano et al., 2016), putting a 'natural' barrier on market entry; in addition, olive trees take several years to reach a full bearing state (Rallo et al., 2014), thereby causing a considerable delay between a price signal and adaptations in production.[1]

This paper aims to inform the ongoing discussion on measures against invasive species by developing insights into potential economic consequences to European consumers in the case of Xfp. It is argued that the problem of invasive species should be contextualized as a societal challenge in public debates on appropriate management strategies since negative consequences arise to both affected producers and consumers. From a methodological point of view, this paper stresses the need to employ multi-country models in the context of biological invasions into interdependent markets (Petucco et al., 2020). Furthermore, we show how a joint use of scenarios, global sensitivity analyses and stochastic evaluations can prioritize future work for policy makers and scholars under uncertainty. This study contributes to the literature in several ways. To the best of our knowledge, multi-country partial equilibrium models are rarely used in the analysis of the economic consequences of invasive species, whereas global sensitivity analyses have not been used yet in the context of partial equilibrium modeling. Furthermore, this paper adds to the literature by being the first to generate insights on consumer impacts for the case of Xfp in Europe.

2. Materials and methods

This study employs a suite of models. First, a prediction of climatic suitability is generated to delineate the national supply which could potentially be affected by the pathogen and the areas through which dispersal might occur. Second, simulations of future spread provide scenario-based estimates of the olive oil supply affected at each time step depending on the spread rate. The disease spread simulations are based on an assumption of radial invasion of the climatically suitable habitat while taking the spatial distribution of olive orchards into account. We account for the uncertainty in the annual rate of dispersal by using three quantiles of an expert-elicited distribution of spread rates (Bragard et al., 2019). The corresponding spread rates are 1.10 (RR05), 5.18 (RR50) and 12.35 (RR95) km per year. The economic model assumes that the percentage of orchards infected in a country equals the percentage of the country's olive oil supply affected. The simulation results project the expected supply reductions from further dispersal of the pathogen over 50 years in Italy and new introductions into Greece or Spain. Lastly, a multi-country partial equilibrium model on the olive oil market is computed to shed light on the potential economic impact of Xfp to European consumers. The model explicitly projects welfare changes for Italy, Greece, Spain and the Rest of Europe (RoEU). The economic model computes changes in welfare to affected processors, non-affected processors and consumers compared to the baseline in which Xfp is absent. Impact is computed over a 50-year time horizon and presented as present values.

2.1. Climatic suitability map

The main purpose of the climatic suitability map is to predict the area of production within each country that could potentially be affected by the disease. Furthermore, dispersal paths within the disease spread simulations were limited to climatically suitable habitat. Consequently, the realized speed of the invasion depended on the continuity of the predicted climatically suitable area within a region. In principle, disease introductions into climatically suitable regions could remain contained by climatic barriers if these were to surround the area of introduction. Hence, a prediction of the climatically suitable area is crucial to delineate the potential maximum extent of the invasion as well as to obtain a more realistic spread progression by taking geographic information on climatic suitability into account within the disease spread simulation.

The climatic suitability map is described in more detail within Schneider et al. (2020). Disease occurrences were filtered by keeping only confirmed positives with precise coordinates under natural inoculum pressure (i.e. records from greenhouses, screenhouses and interceptions were omitted). To reduce spatial autocorrelation, the remaining presence points were thinned by enforcing a minimum distance of 5 km between points which is equal to the spatial resolution of the climate data. Due to the randomness associated with the thinning, the procedure was repeated four times. Ten species distribution models (bioclim, boosted and regression trees, classification and regression trees, domain, generalized additive models, multivariate adaptive regression splines, maximum entropy, random forest, recursive partitioning and regression trees and support vector machines) were used to explore the relationship between occurrences of Xf and environmental variables. Subsequently, an ensemble prediction was generated taking the relative model performances into account. The ensemble prediction provided a continuous score ranging from zero to one for locations in Europe. These scores were bilinearly interpolate from a 5 km to a 1 km resolution to meet the needs of the disease spread model. Lastly, the downscaled map was converted to a binary map, i.e. indicating whether a given location is suitable or not, using three different thresholds. Threshold 1 (0.165) is particularly informative for models based on presence-only data and ensures that a correct prediction on species presence of at least 90% is made. Threshold 2 (0.132) was used to maximize the sum of the accuracy of predicting occupied sites to be suitable and unoccupied sites to be unsuitable (i.e. sum of sensitivity and specificity) and Threshold 3 (0.093) was used to minimize the difference between the accuracy of predicting occupied sites to be suitable and unoccupied sites to be unsuitable (i.e. minimum difference between sensitivity and specificity) (Jiménez-Valverde and Lobo, 2007).

2.2. Disease spread simulation

The purpose of the disease spread simulation is to provide the dynamic change of the area of production affected by the pathogen over the time horizon of 50 years. This is particularly important in dynamic economic assessments, because future impacts must be discounted (Rich et al., 2005). As there are still significant uncertainties on crucial aspects of the dispersal process of Xfp such as long-distance jumps (White et al., 2017), we simulated various spread scenarios.

The disease spread simulation is described in more detail within Schneider et al. (2020). Spread was modelled as a radial range expansion process (Robinet et al., 2012). Dispersal characteristics are collapsed into a single parameter described as the rate of radial range expansion (*rr*). To circumvent the issue of simulating an expanding circle using grid cells, the radial dispersal is simulated using a cellular automaton model with alternating step-types, namely rook and queen's

[1] Additional production as a results of higher prices might stem from more input usage on existing plots or from the establishment of new orchards. While high tree density systems reach their full-bearing state in three to four years, olives are often cultivated on marginal land due to their robustness. Traditional orchards may take up to a decade to reach their full-bearing state (Rallo et al., 2014). Environmental and social factors will constrain the establishment of new plots. For example, the availability of ground water for irrigation and learning costs will influence the decision of producers to establish olives as a modern high density system or as a traditional orchard.

case contiguity, at a ratio of $2-\sqrt{2}$ and $2-\sqrt{1}$, respectively (Farkas et al., 2006). The annual time-steps are broken down into within-year-time-steps such that the elicited rate is obtained. Step-types are randomly assigned to every within-year-step such that the aforementioned ratios are obtained. As a result, a spread pattern is generated which resembles a regular octagon. As spread is slightly over-predicted into corner-directions of the octagon, the radial range model is used to tightly contain the newly infected cells within the elicited radius by removing over-predicted cells.

Invasion into a cell is only accepted if the cell is climatically suitable, however, does not depend on whether or not olives are present. While this ensures that climatically unsuitable territories are not travelled through, the model implicitly assumes that alternative hosts assist dispersal of Xfp. We justify this assumption by the facts that the host range of the pathogen spans several hundred plant species and any xylem feeding insect is currently considered to be a potential vector (EFSA, 2018; Bragard et al., 2019).

To acknowledge the uncertainty on future disease spread, nine scenarios were analyzed for Italy resulting from three climatic suitability thresholds and three spread rates. While for Italy spread was simulated beyond the currently infected zone, the uncertainty on the point of introduction in Greece and Spain was evaluated by stochastic simulations with points of introduction randomly selected from the olive cells within the climatically suitable territory. For all combinations of climatic suitability threshold and spread rate, 1000 points of introduction were generated for both Greece and Spain. Consequently, 9000 instances of future epidemics were generated for each of the countries.

2.3. Economic model

Let t denote discrete annual points in time and the time horizon within which the impacts are assessed as T. Italy, Greece, Spain and the Rest of Europe (RoEU) were included as interdependent markets (C) into the analysis. The markets within Europe are denoted by the subscript c. The following set of equations are solved on a European level. Thereby, we implicitly model intra-European trade and assume that supply can freely flow within Europe to meet demand. The European market interacts with the Rest of the World (ROW) through trade of excess supply or demand.[2]

To model the change in supply due to reduced yields and changes in operational costs, the spread simulations were used to compute the newly infected share of the national areas in the four included countries ($z_{ct,\,ax}$). Different ages of infection are denoted with ax. We assume a one to one translation of the percentage of orchards infected to the percent of national supply of olive oil affected. We discuss this limitation in more detail below. We denote D_t and S_t as the total demand and total supply in the European Union at time t, respectively. SA_t and SN_t denote the supply by the affected and non-affected producers, respectively. P_{tc} is the equilibrium price in market c at time t. The market-specific equilibrium prices are coupled to the world market price WP_t, and only differ by a constant country-specific wedge, μ_c. The wedges capture, for example, differences in transportation costs among countries and are assumed to be constant over time. η_c and θ_c denote the elasticities of demand and supply in the different European markets. χ_c and ρ_c are parameters of the demand and supply function, respectively. The parameter h denotes the horizontal percentage shift in the supply curve due to a reduction in yield (i.e. h equals -0.10 for an annual yield decrease of 10%). g denotes a simultaneous vertical percentage shift in the supply curve due to the increased production costs (i.e. g equals -0.10 for an annual cost increase of 10%). Parameters h, g, and $z_{ct,\,ax}$ represent the supply shifter N_{ct} within the equation for the producer surplus (iPS_t) below. The European market can be depicted as follows:

$$D_t = \sum_{c\in C} \chi_c \cdot P_{tc}^{-\eta_c} \tag{1}$$

$$S_t = SA_t + SN_t \tag{2}$$

$$SA_t = \sum_{c\in C}\sum_{ax=1}^{T} (1+h)^{ax}\cdot\rho_c\cdot\left((1+g)^{ax}\cdot P_{tc}\right)^{\theta_c}\cdot z_{ct,ax} \tag{3}$$

$$SN_t = \sum_{c\in C}\rho_c\cdot(P_{tc})^{\theta_c}\cdot\left(1-\sum_{ax=1}^{T} z_{ct,ax}\right) \tag{4}$$

$$WP_t = P_{tc} - \mu_c \tag{5}$$

We let E_t and X_t denote the excess supply and demand of the European Union, respectively. ω denotes the elasticity of excess demand (negative) or supply (positive) in the rest of the world. ν is a parameter calibrated on market data. The European Union interacts with the rest of the world via excess domestic supply or demand as follows:

$$E_t = S_t - D_t \tag{6}$$

$$X_t = \nu\cdot(WP_t)^{\omega} \tag{7}$$

$$X_t = E_t \tag{8}$$

The economic impact is computed as the sum of total discounted future welfare losses (iTW), due to the spread of the disease and associated changes in the equilibrium price and quantity (Surkov et al., 2009). Impact on total welfare comprises the sum of impacts on total producer surplus (iPS_t) and total consumer surplus (iCS_t) which are expressed in monetary units. The total producer and consumer surpluses on the European level comprise the producer and consumer surpluses in the included countries. The producer surplus, consumer surplus and as a result the overall impact are discounted using the discount rate r. We let $S_t^0(\cdot)$ denote the supply function in absence of the infection, while $S_t^1(\cdot)$ is the supply function after introduction of the pathogen. a and b denote the intersection of the supply curves with the y-axis. N_{ct} denotes the supply shifter for the different countries. The supply and demand function adhere to the following properties (Surkov et al., 2009): $\frac{\delta S_t}{\delta P_t} > 0$, $\frac{\delta S_t}{\delta N_t} < 0$ and $\frac{\delta D_t}{\delta P_t} < 0$

$$iPS_t = \sum_{c\in C}\left(\left(\int_a^{P_{tc}} S_t^0(P_{tc})\delta P_{tc} - \int_b^{P_{t+1,c}} S_t^1(P_{tc},N_{ct})\delta P_{tc}\right)\cdot(1+r)^{-t}\right) \tag{9}$$

$$iCS_t = \sum_{c\in C}\left(\left(\int_{P_{tc}}^{P_{t+1,c}} D_t(P_{tc})\delta P_{tc}\right)\cdot(1+r)^{-t}\right) \tag{10}$$

$$iTW = \sum_{t=1}^{T}(iPS_t + iCS_t) \tag{11}$$

2.3.1. Estimation of the supply elasticity

The absence of published information on supply elasticities was approached by estimating a European supply elasticity econometrically. We used panel data for the years 1990 to 2016 (see section 2.4), to estimate a partial adjustment model (eq. 12) which is also known as the Nerlove Supply Response Model (Nerlove, 1956). Using the Cobb-Douglas functional form, we included a time trend (*Year*), country-fixed effects (*Country*), first lags of prices ($Price_{t-1}$) and first lags of production (Q_{t-1}) and regressed on current production (Q_t). α, τ, β and μ are parameters and κ a vector of parameters. λ captures the inertia and is generally expected to be $0<\lambda<1$. The model was estimated as eq. 13 in which ϕ denote the set of parameters and υ_t the error term (R^2 of 0.921). The formulation allows to derive short-run and long-run supply elasticities. The short run elasticity is obtained through the coefficient estimate for first lags of prices (ϕ_3). The long run elasticity (β) is obtained

[2] Europe is a net-exporter of olive oil and remained so in the disease spread scenarios.

Table 1
Overview of the economic parameter values.

Parameter	Symbol	Dimension	Deterministic	Global Sensitivity Analysis		
				Distribution	Mean/Min.	SD/Max.
Demand Italy	D_t	1000 tons	559.96	truncated normal	559.96	67.72
Demand Greece	D_t	1000 tons	139.00	truncated normal	139.00	24.17
Demand Spain	D_t	1000 tons	488.26	truncated normal	488.26	26.26
Demand RoEU	D_t	1000 tons	416.70	truncated normal	416.70	8.69
Supply Italy	S_t	1000 tons	351.62	truncated normal	351.62	124.29
Supply Greece	S_t	1000 tons	260.98	truncated normal	260.98	84.13
Supply Spain	S_t	1000 tons	1187.16	truncated normal	1187.16	413.13
Supply RoEU	S_t	1000 tons	91.28	truncated normal	91.28	21.82
Price Italy	$P_{t,\,c}$	Euro per ton	4067.22	truncated normal	4067.22	685.98
Price Greece	$P_{t,\,c}$	Euro per ton	2855.42	truncated normal	2855.42	364.92
Price Spain	$P_{t,\,c}$	Euro per ton	2611.02	truncated normal	2611.02	498.28
Price RoEU	$P_{t,\,c}$	Euro per ton	4242.16	truncated normal	4242.16	522.46
Demand elasticity Italy	η_c	Dimensionless	−0.842	uniform	−1.263	−0.421
Demand elasticity Greece	η_c	Dimensionless	−0.760	uniform	−1.140	−0.380
Demand elasticity Spain	η_c	Dimensionless	−0.485	uniform	−0.728	−0.243
Demand elasticity RoEU	η_c	Dimensionless	−0.350	uniform	−0.525	−0.175
Demand elasticity RoW	ω	Dimensionless	−0.350	uniform	−0.525	−0.175
Supply elasticity Italy	θ_c	Dimensionless	0.3241	uniform	0.1621	0.4862
Supply elasticity Greece	θ_c	Dimensionless	0.3241	uniform	0.1621	0.4862
Supply elasticity Spain	θ_c	Dimensionless	0.3241	uniform	0.1621	0.4862
Supply elasticity RoEU	θ_c	Dimensionless	0.3241	uniform	0.1621	0.4862
Yield decline	h	percent	−10	uniform	−100	−5
Cost change	g	percent	−10	uniform	−100	−5
Discount rate	r	percent	3	uniform	3	7

D_t and S_t denote European demand and supply at time t and are obtained by aggregating over the four markets.

by computing the expectation of λ and dividing the coefficient for the first lag prices by this expectation (eq. 14 and 15). In the deterministic calculations, we used the estimate for the long run supply elasticity (0.3241). In the global sensitivity analysis, this estimate was varied by plus and minus 50%. The resulting interval comprises the estimated short run supply elasticity (0.2513). Table 5 in the Supplementary Material depicts the fitted model.

$$Q_t = \lambda(\alpha + \tau Year + \kappa Country + \beta Price_{t-1} + \epsilon_t) + (1-\lambda)\mu Q_{t-1} \quad (12)$$

$$Q_t = \phi_0 + \phi_1 Year + \phi_2 Country + \phi_3 Price_{t-1} + \phi_4 Q_{t-1} + \upsilon_t \quad (13)$$

$$\widehat{\lambda} = 1 - \phi_4 \quad (14)$$

$$\widehat{\beta} = \phi_3 / \widehat{\lambda} \quad (15)$$

Notably, our approach is not able to capture structural changes of actors' behavior over the 50-year time horizon. The sizable market shock within some of the spread scenarios and our long time horizon of 50 years could fundamentally alter actors' ability to respond to price signals. Our reliance on historical data to estimate the supply elasticity and our assumption that this estimate is constant over the 50-year time horizon are critical limitations of our analysis. We address these limitations through sensitivity analyses (see section Sensitivity Analyses), and through further discussion below.

2.4. Data

For the climatic suitability modeling, presence data was derived from the Update of the Xf host database (EFSA, 2018), data from the national plant protection organizations and records of outbreaks in Porto, Tuscany and Hula Valley (EPPO Reporting Service, 2019a, 2019b, 2019c). Weighted pseudo-absence data was simulated at a prevalence of 0.1. Climate data ranging from 1979 to 2013 was obtained from Chelsa Climatology at a 5 km spatial resolution (Karger et al., 2017).

For the disease spread simulations, data on olive production sites was obtained from the Coordination of Information on the Environment (CORINE) land cover map and aggregated to a 1 km resolution to reduce the computational time. For *rr*, we used the 5, 50 and 95% quantiles of a distribution elicited from experts (Bragard et al., 2019). The elicitation followed a structured methodology as described in Benford et al. (2018) and Baker et al. (2019). The seven invited experts are internationally recognized experts on the disease and on relevant agricultural practices. The parameter was defined as the mean distance, in kilometers, which will comprise 90% of the area containing the newly infected plants around an infected area within one year (Bragard et al., 2019). The elicited quantiles correspond to a radial range expansion of 1.10, 5.18 and 12.35 km per year.[3]

To calibrate the economic model, various data were gathered (Table 1). The total production and consumption for the European Union, Italy, Greece and Spain was obtained from the International Olive Oil Council (2018a, 2018b). Five-year averages, for 2012 to 2016, were constructed and used as estimates of the equilibrium quantities. Corresponding standard deviations were computed for use in the global sensitivity analysis. Country-specific prices for olive oil were obtained from Eurostat. Five-year averages for the same time-period were used as estimates of the equilibrium prices. For the rest of the European Union (RoEU), the five-year average price was constructed as a, by production-share, weighted price of Croatia, Portugal and Slovania as these countries represent the other European producers besides Italy, Greece and Spain. Again, standard deviations were computed for use in the global sensitivity analysis. The world price was computed as the, by production-share, weighted average European price. This is justified by the fact that the European market is the world leader in olive oil production and consumption (Eurostat, 2016). Hence, the world market price can be expected to be determined by the European market. Country specific price wedges were calibrated by subtracting the country prices from the world price. Information on the demand elasticities was gathered from the scientific literature (Gil et al., 2004; Pierani and Rizzi, 1991; Rosa, 2002). For the global sensitivity analysis, these estimates were varied by plus and minus 50%. To estimate the supply elasticity, the same data from the International Olive Oil Council

[3] The climatic suitability map and spread simulations can be accessed via Zenodo (https://doi.org/10.5281/zenodo.3672794). Visualizations of both maps are provided in the paper and supplementary material by Schneider et al. (2020).

(2018a, 2018b) and Eurostat were used but for the years 1990 to 2016 (see section 2.3.1). Notably, highly incomplete timeseries for Croatia and Slovania forced us to rely on data for Portugal as proxy for the RoEU.

2.5. Sensitivity analyses

The sensitivity of the results with regard to the parameter values used was explored using a global sensitivity analysis through variance decomposition (Saltelli et al., 2010). To calculate the Sobol sensitivity indices (Saltelli et al., 2008), a computational experiment was set up in which input parameters were sampled out of defined distributions (Table 1). To sample the input parameter space, 10,000 draws were generated from each input distribution. The computational time was improved by applying the Saltelli (2002) sampler which generated an input matrix of length $N(k+2)$ where N is the number of draws (10,000) and k is the number of model inputs. The implementation was achieved via the *sensitivity* package for R (Iooss et al., 2020), using the improved formulas of Jansen (1999) and Saltelli et al. (2010). In total, 24 parameters were included which resulted in 260,000 rows of input values for which impact was computed for one spread simulation (Italy following RR50 and threshold T2).

In addition to the global sensitivity analysis, the influence of parameter uncertainty on welfare changes was analyzed in more detail for the supply elasticities (θ_c), the yield decline (h) and the cost change (g). The reason for this selection is our reliance on historical data for the estimation of the supply elasticity, and the absence of scientific information on the other two parameter. To analyze the influence of uncertainty in these parameters, 10,000 draws from their distributions (Table 1) were generated. Subsequently, while fixing all other parameter at their deterministic values welfare changes were computed using all draws for θ_c, h or g.

3. Results

The climatic suitability modeling shows that the vast majority of olive orchards are within the climatically suitable territory for establishment and spread of Xfp (Schneider et al., 2020). Thereby, Xfp is threatening nearly three quarters of the world's production of olive oil. The different spread scenarios resulted in varying price responses across Europe (Table 2). Following spread beyond the current extent in Italy, for RR05 the prices for olive oil increased by 5.2% in Greece, 5.7% in Spain, 3.6% in Italy and 3.4% in the RoEU irrespective of the climatic suitability threshold. For RR50, prices increased up to 13.6, 14.9, 9.3 and 8.9% in Greece, Spain, Italy and the RoEU, respectively (under threshold T3). For RR95, prices increased up to 21.3, 23.5, 14.6 and 14.0% in Greece, Spain, Italy and the RoEU, respectively (under threshold T3). As a consequence of higher prices, the consumption in Europe declined between 2.5% for RR05 and 9.2% for RR95 (Fig. 1).

Following spread in Greece, on average over the 1000 points of introduction for RR05 prices increased up to 1.2% in Greece, 1.3% in Spain, 0.8% in Italy and 0.8% in the RoEU. For RR50, prices increased up to 4.8, 5.3, 3.3 and 3.1% in Greece, Spain, Italy and the RoEU, respectively (under threshold T1 & 2). For RR95, prices increased up to 6.9, 7.6, 4.7 and 4.5% in Greece, Spain, Italy and the RoEU, respectively (under threshold T2). The decline in the total European consumption ranged between 0.6% for RR05 to 3.2% for RR95.

Following spread in Spain, on average over the 1000 points of introduction for RR05 prices increased up to 8.4% in Greece, 9.3% in Spain, 5.7% in Italy and 5.5% in the RoEU (under threshold T3). For RR50, prices increased up to 93.1, 102.7, 63.6 and 60.8% in Greece, Spain, Italy and the RoEU, respectively (under threshold T3). For RR95, prices increased up to 187.6, 207.0, 128.1 and 122.5% in Greece, Spain, Italy and the RoEU, respectively (under threshold T3). The decline in the total European consumption ranged between 3.6% for RR05 to 40.8% for RR95.

Table 2
Change in prices and consumption over 50 years.

Spread Scenario		Spread in Italy					Spread in Greece*					Spread in Spain*				
Suitability Threshold	Spread Rate	Price Increase (%)				Consumption	Price Increase (%)				Consumption	Price Increase (%)				Consumption
		EL	ES	IT	RoEU	EU (%)	EL	ES	IT	RoEU	EU (%)	EL	ES	IT	RoEU	EU (%)
T1	RR05	5.2	5.7	3.6	3.4	−2.5	1.2	1.3	0.8	0.8	−0.6	7.8	8.6	5.3	5.1	−3.6
T2	RR05	5.2	5.7	3.6	3.4	−2.5	1.2	1.3	0.8	0.8	−0.6	8.0	8.8	5.5	5.2	−3.6
T3	RR05	5.2	5.7	3.6	3.4	−2.5	1.2	1.3	0.8	0.8	−0.6	8.4	9.3	5.7	5.5	−3.8
T1	RR50	12.8	14.1	8.7	8.4	−5.8	4.8	5.3	3.3	3.1	−2.3	77.0	85.0	52.6	50.3	−23.7
T2	RR50	13.0	14.3	8.9	8.5	−5.9	4.8	5.3	3.3	3.1	−2.3	86.8	95.8	59.3	56.7	−25.3
T3	RR50	13.6	14.9	9.3	8.9	−6.1	4.7	5.2	3.2	3.1	−2.2	93.1	102.7	63.6	60.8	−26.5
T1	RR95	19.6	21.6	13.4	12.8	−8.5	6.3	7.0	4.3	4.1	−3.0	120.9	133.3	82.6	78.9	−32.1
T2	RR95	20.0	22.0	13.7	13.1	−8.7	6.9	7.6	4.7	4.5	−3.2	145.5	160.5	99.4	95.0	−35.2
T3	RR95	21.3	23.5	14.6	14.0	−9.2	6.8	7.5	4.6	4.4	−3.2	187.6	207.0	128.1	122.5	−40.8

*averaged over all random points of introduction. EL = Greece, ES=Spain, IT = Italy, RoEU = Rest of Europe.

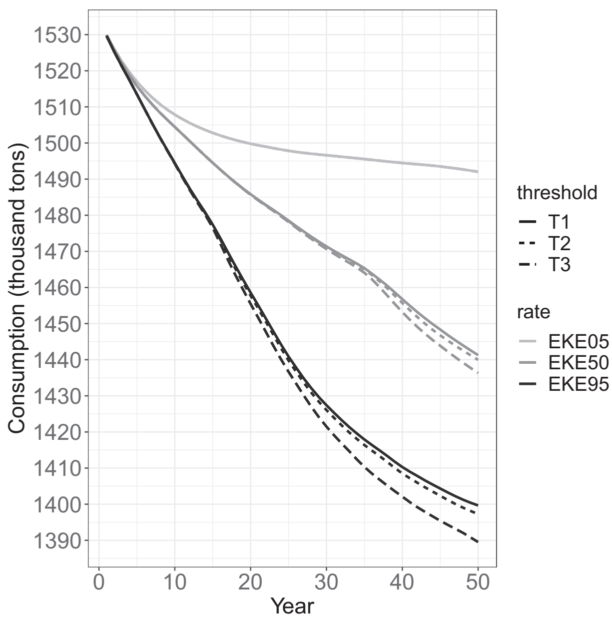

Fig. 1. Change in the consumption of olive oil for spread of Xfp in Italy beyond the current extent.

Table 3 depicts the welfare changes over 50 years expressed as present value based on a discounting rate of 3% per year. We advise to read the table as follows: The three horizontal blocks correspond to Xfp spread simulations in Italy, Greece and Spain. The rows within each block depict different scenarios for the climatic suitability threshold and the spread rate. Readers might start by looking at the column on the very right hand side which depicts the total impact to welfare across Europe obtained by summing the total welfare changes for each country. As changes in total welfare comprises changes in producer surplus and consumer surplus, readers might want to continue by looking at these columns. Total change to consumer and producer surplus is discussed below and was computed by aggregating over countries. Surplus generated by affected producers pertains to affected producers in the country in which spread was simulated (i.e. Italy, or Greece, or Spain). Results for country specific changes to welfare are depicted in Tables 6 to 8 in the Supplementary Material.

If the pathogen spreads beyond the current extent in Italy, the decline in consumer welfare due to higher prices for olive oil ranged between 4.1 billion for RR05 to 10.3 billion Euro for RR95 across Europe. While total producer surplus increased between 0.2 and 0.4 billion Euro across Europe, producer surplus in Italy declined between 3.8 and 9.9 billion Euro.

Results from introductions of Xfp into Greece and Spain are presented as averages across the 1000 randomized points of introduction. The distributions of welfare changes over all points of introduction for one climatic suitability threshold (T2) are depicted in Fig. 2a and 2b. Following spread in Greece, consumer welfare across Europe declined between 0.4 billion to 3.3 billion Euro. Total producer surplus increased between 0.1 and 1.3 billion Euro across Europe and declined in Greece between 0.2 and 2.2 billion Euro. Following spread in Spain, consumer welfare across Europe declined between 1.8 billion and 53 billion Euro. Total producer surplus in Europe increased between 0.8 and 22.6 billion Euro, and producer surplus in Spain declined between 0.1 and 13.3 billion Euro.

The results of the sensitivity analysis show that out of 24 parameters only four parameters had statistically significant first order indices at the critical 5% level (Table 4). Uncertainty regarding supply from Italy and Spain, price of olive oil in Italy and the discount rate had statistically significant first order indices. For example, the variation in the Italian

Table 3
Changes in welfare over 50 years in billion Euro for all spread scenarios.

Spread Scenario		Consumer	Producer	Non-Affected Producer	Affected Producer	Total
Threshold Rate	Spread Rate					
Spread in Italy						
T1	RR05	−4.09	0.18	−0.50	0.68	−3.91
T2	RR05	−4.09	0.18	−0.50	0.68	−3.91
T3	RR05	−4.09	0.18	−0.50	0.68	−3.91
T1	RR50	−6.27	0.19	−1.02	1.21	−6.08
T2	RR50	−6.32	0.19	−1.03	1.22	−6.12
T3	RR50	−6.40	0.18	−1.07	1.25	−6.20
T1	RR95	−9.80	0.36	−1.46	1.82	−9.45
T2	RR95	−9.91	0.36	−1.49	1.85	−9.56
T3	RR95	−10.29	0.38	−1.56	1.94	−9.91
*Spread in Greece**						
T1	RR05	−0.37	0.13	0.07	0.06	−0.24
T2	RR05	−0.36	0.13	0.07	0.06	−0.22
T3	RR05	−0.37	0.13	0.07	0.06	−0.22
T1	RR50	−1.82	0.70	0.43	0.27	−1.12
T2	RR50	−1.79	0.69	0.42	0.26	−1.10
T3	RR50	−1.79	0.69	0.43	0.26	−1.09
T1	RR95	−3.23	1.28	0.87	0.41	−1.96
T2	RR95	−3.31	1.30	0.86	0.43	−2.02
T3	RR95	−3.27	1.29	0.86	0.43	−1.98
*Spread in Spain**						
T1	RR05	−1.76	0.77	0.46	0.31	−0.99
T2	RR05	−1.76	0.77	0.45	0.32	−0.99
T3	RR05	−1.81	0.78	0.45	0.33	−1.03
T1	RR50	−18.64	8.02	5.16	2.86	−10.63
T2	RR50	−20.31	8.68	5.55	3.13	−11.63
T3	RR50	−21.33	9.08	5.77	3.31	−12.25
T1	RR95	−42.64	18.62	13.55	5.07	−24.02
T2	RR95	−47.58	20.56	14.83	5.73	−27.03
T3	RR95	−53.00	22.57	15.84	6.72	−30.43

*averaged over all random points of introduction. EL = Greece. ES=Spain. IT = Italy. RoEU = Rest of Europe.

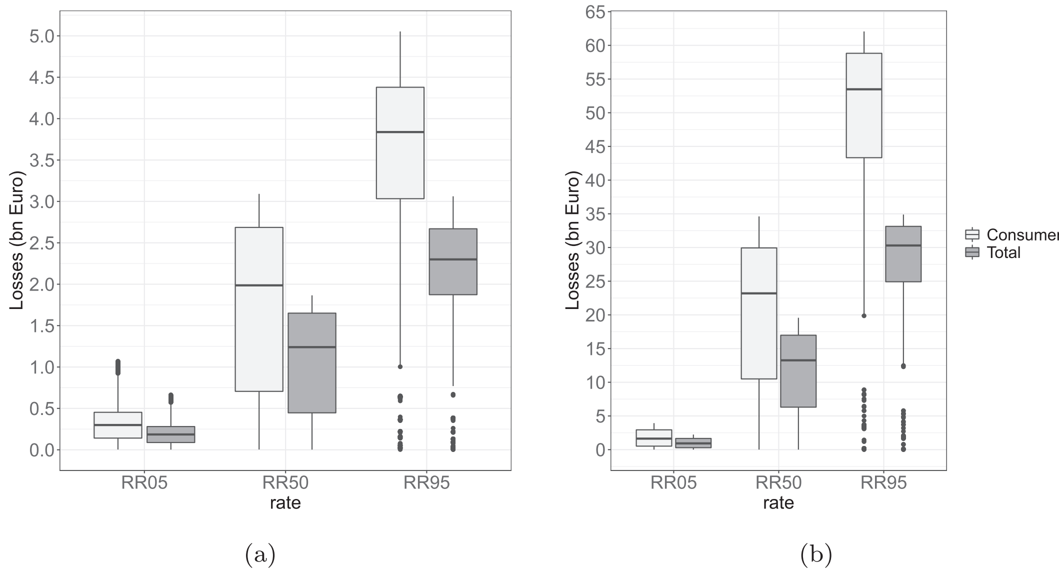

Fig. 2. Distribution of changes in total welfare and consumer surplus following introductions of Xfp into Greece (a) or Spain (b) and spread over 50 years with a suitability threshold of 0.135.

Table 4
First and total order sensitivity indices of statistically significant economic parameters ($P < 0.05$).

Parameter	First Order			Total Order		
	Index	Min.	Max.	Index	Min.	Max.
Supply Italy	0.213	0.175	0.258	0.335	0.316	0.354
Supply Spain	0.219	0.180	0.260	0.345	0.327	0.363
Price Italy	0.108	0.069	0.152	0.186	0.176	0.195
Discount Rate	0.113	0.072	0.160	0.208	0.199	0.217

supply caused 33.5% in the variance of impact to total welfare through direct effects (21.3%) and higher order interactions with other parameter. Sensitivity indices for all economic parameter are shown in Table 9 in the Supplementary Material.

For the deterministic economic analyses (Table 3), we used an econometrically estimated long run supply elasticity and very conservative values for the yield decline and cost change under Xfp pressure. The absence of scientific information for the yield decline and cost change under infection as well as our reliance on historical data to estimate suppliers' adaptability to price changes was approached through stochastic evaluations for one spread scenario (Fig. 3). The deterministic results for spread in Italy, following RR50 with a suitability threshold T2, were a decline of 6.3 billion Euro in consumer welfare and 6.1 billion Euro in total welfare. The evaluated range of the supply elasticity resulted in impacts to consumers ranging 5.8 to 7.1 billion Euro and total impacts ranging 5.9 to 6.4 billion Euro. The evaluated range of the yield decline under Xfp resulted in impacts to consumers ranging 5.3 to 8.4 billion Euro and total impacts ranging 6.0 to 7.0 billion Euro. The evaluated range of the cost change under Xfp resulted in impacts to consumers ranging 6.1 to 8.3 billion Euro and total impacts ranging 5.7 to 7.0 billion Euro. In comparison to the uncertainty on the spread rate or likely points of introductions in Greece and Spain, these intervals for impact are narrow (cf. Table 3 and Fig. 2).

As evident from Fig. 3a, more inelastic supply elasticities widened the gap between consumer impact and total impact. In other words, markets characterized by less adaptable producers resulted in higher prices following supply shocks due to Xfp which left consumers worse off as a result. Comparable insights were obtained for the yield decline and the cost change under Xfp (Fig. 3b and 3c). Both parameters determine the annual reduction in supply of affected producers. Higher values resulted in more drastic reductions and in turn higher prices for olive oil which left consumers significantly worse off compared to the deterministic results. Consequently, while we believe that our derived conclusions are robust to our assumptions on these parameters the deterministic results are likely conservative estimates.

4. Discussion

Our analysis shows that consumers can be expected to bear the majority of the economic impacts from further dispersal or new introductions of Xfp in Europe. While producer surplus in affected countries might decline, increasing prices for olive oil across Europe would generate additional profits to processors at the expense of consumers. Consequently, control measures to prevent future spread of the disease can be expected to more strongly benefit consumers rather than processors. In turn, regulatory measures such as the preventive felling of trees should find public acceptance with regard to economic considerations. Unfortunately, consumers might not be aware that they are beneficiaries of the control of invasive plant diseases such as Xfp. This stresses the need for improving the communication of pest risk assessments to the public.

The results highlight that introductions of Xfp into Spain can be expected to significantly disrupt the European olive oil market. Spain is the world's largest producer of olive oil. Consequently, reductions in supply from Spain sensitively affect world prices. Public actions to foster vigilance among growers and citizens to prevent an introduction and further spread of Xfp in other olive growing regions of Europe are crucial. Further dissemination of information on Xfp to citizens in olive growing hot-spots could increase awareness and thereby improve the likelihood of spotting possible introductions promptly. Unfortunately, in-field detection is aggravated due to the absence of precise information on the asymptomatic period following infection (Saponari et al., 2017). Therefore, further research on the epidemiology and early detection methods is important (Zarco-Tejada et al., 2018; White et al., 2020).

Preferences for invasive species control vary among citizens (Sharp et al., 2011; Estévez et al., 2015), and economic concerns could very well not be the first priority for some. Unfortunately, Xfp is currently not curable under field conditions and sensitive cultivars can be expected to die off quickly following infection (Bragard et al., 2019). Consequently, the establishment of a cordon sanitaire to prevent spread of the disease through felling of healthy trees is likely to spare many more trees than

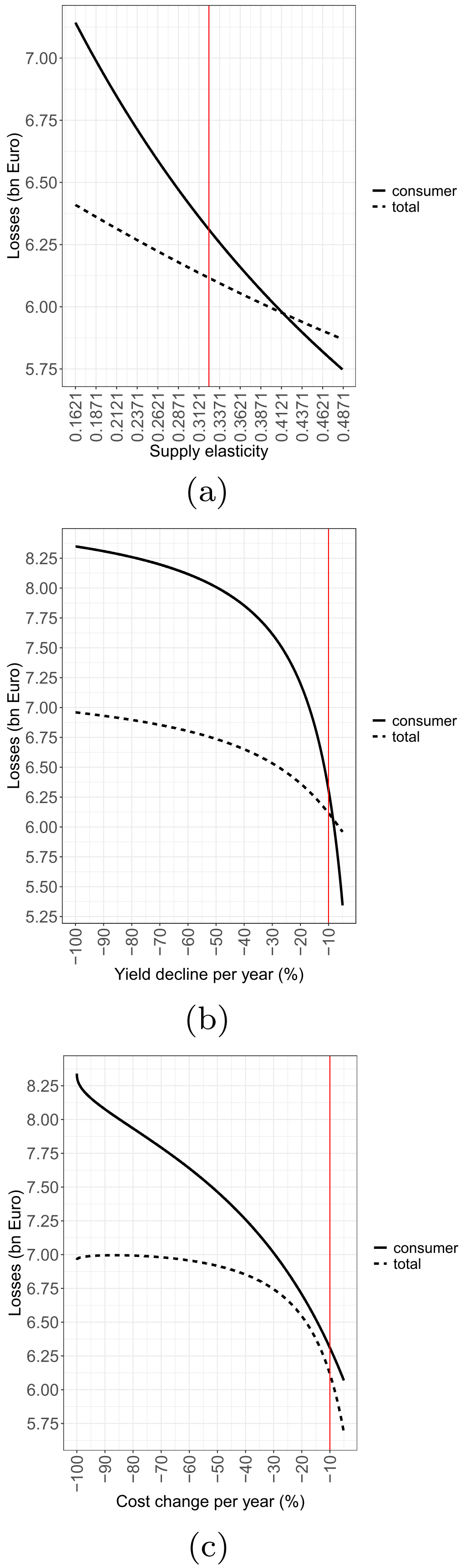

Fig. 3. Stochastic evaluation of welfare changes under uncertainty of supply elasticity (a), yield decline (b) and cost change (c). The vertical line depicts the deterministic value used.

are felled. An intelligible communication of this information to stakeholders maybe could have prevented the societal unrest in the affected region.

The results of our analysis demonstrate that affected producers and consumers jointly carry the economic risk associated with Xfp. To mitigate the risk, research currently targets the identification of resistant traits in olive varieties (De Pascali et al., 2019; Sabella et al., 2018; Baù et al., 2017; Luvisi et al., 2017a, 2017b; Caserta et al., 2017; Giampetruzzi et al., 2016), biological control of the vectors (Baccari et al., 2019), early detection of the disease (Zarco-Tejada et al., 2018), and the establishment of a cordon sanitaire by removing host plants near the infected zone. Evidently, all these measures aim at growers taking action to prevent further impacts. Unfortunately, most strategies have in common that they pose a significant financial burden on growers in the affected area, and with profit margins for olives historically being small already (European Commission, 2012), this could result in a significant portion of farmers having to cease production entirely. The prevention of further spread can be seen as a public good and, therefore, compensation payments are justified (Oude Lansink, 2011). Policy makers must ensure that compensation schemes are intelligible and appropriately budgeted to minimize adverse behavior of not reporting possible infections (Porteous et al., 2015; Herzon et al., 2018; Vergamini et al., 2020). Further research could investigate to which extent market instruments might assist growers' risk mitigation. For example, farmers nearby the infected zone might not yet classify for official compensation schemes, however, they could already benefit from participation in insurance programs which aim at alleviating possible financial burden associated with replanting orchards with a resistant variety in case Xfp continuous to spread.

The case on the Olive Quick Decline Syndrome exemplifies the drastic impact to consumers which can arise from biological invasions solely through price responses following reductions in supply. Fortunately, other aspects such as food safety and food security are not affected here. However, the losses in cultural heritage and landscape value from the desiccation of century old olive trees are additional factors which need to be considered in the design of policy. Given the existing level of globalization, the risk of biological invasions is likely to prevail in the future (Hulme, 2009). For inelastic production systems in particular, consumers can be expected to bear a sizeable share of the economic consequences. Therefore, regulators should ensure that phytosanitary authorities can react promptly to emerging threats. To improve response, information exchange between public bodies, science and farmers must be fostered. In addition to continued support of policy makers for research on adaptation strategies to Xfp in Europe, it is essential that both public bodies and scientists play a role in involving citizens through intelligible communication of new insights.

While our analysis aims at contributing to the ongoing public debate on Xfp through an exploration of potential consequences to consumers, uncertainty on various aspects on the side of the pathogen as well as absence of more granular economic data resulted in some limitation. In what follows, we discuss these limitations and possible consequences of our assumptions.

We assumed that the percentage of orchards infected in a country equals the percentage of the country's olive oil supply affected. This simplification is required because the used land-cover data only provides a binary indication of whether olives are present in a given grid cell. To obtain a grid cell specific contribution to the national production, information on the olive density within a grid, or ideally data on the grid cell specific production, would be needed. While the inclusion of the binary land-cover data still added significantly to the disease spread simulation, it might well be that our simulation of the olive oil supply affected fails to account for granular differences in the areas' contribution to the national supply.

The disease spread model employed, while being relatively straightforward, predicted past population expansions well (Hudgins et al., 2017), and the model has been proposed as a suitable tool for pest risk assessments (Robinet et al., 2012). Nevertheless, strengthening the integration among all employed models would be desirable. Information on the relation between climatic suitability and the spread rate of Xfp might improve the disease spread simulations by allowing for varying spread rates depending on local conditions. Furthermore, insights into the efficacy of management strategies, such as vector control, on the spread rate would allow to better link economic models with the disease spread simulations for Xfp and thereby enable analyses of different strategies.

The olive oil market is known to be a segmented market with different quality grades. However, due to the absence of data on production volumes of different olive oil quality grades and cross price elasticities between qualities, the model developed for this analysis assumes one composite olive oil market and thereby is not able to demonstrate impacts for producers of high versus low quality olive oils. As a response to price increases, consumers may substitute high quality olive oil with a lower quality alternative which could worsen the economic impacts for high quality olive oil producers in Italy, Greece and Spain.

The absence of information on the countries' supply elasticities was approached with an econometric estimation using panel data ranging the years 1990 to 2016. Through the use of a global sensitivity analysis and stochastic evaluations of the economic impact under different values for this parameter, we provided additional insights and points for discussion. However, market shocks as severe as simulated in some of the disease spread scenarios could very well fundamentally alter actors' behavior and thereby contradict estimates obtained from historical data alone. Nevertheless, our analysis shows that improving producers' adaptability to price changes is likely to reduce total impacts and in particular impacts to consumers. Consequently, regulatory support to foster adaptability of producers is called for.

5. Conclusions

While previous research has analyzed possible impacts of *Xylella fastidiosa* subspecies *pauca* to olive growers (Schneider et al., 2020), the distribution of economic consequences among olive oil producers and consumers has not yet found attention. By using a multi-country partial equilibrium model, we show that price responses following reductions in supply due to the invader are likely to redistribute the negative economic impacts to consumers. This market response is expected to be particularly strong due to the inelastic nature of the production system. If the pathogen spreads beyond the current extent in Italy, the decline in European consumer welfare, due to higher prices for olive oil, ranged between 4.1 billion and 10.3 billion Euro over the course of 50 years depending on the spread rate. In other words, each of the 195 million households in Europe (Eurostat, 2021), would incur additional costs ranging approximately 63 cents to 1.6 Euro every year over the course of 50 years..[4] Introductions into Greece and Spain could cost consumers between 0.4 and 3.3 and 1.8 to 53 billion Euro depending on the spread rate, respectively. This would correspond to additional annual costs ranging approximately 6 to 51 cents and 27 cents to 8.2 Euro for every household in Europe, respectively.

Our analysis stresses the importance of public actions to foster vigilance among growers and citizens to prevent additional introductions and further spread of the disease. Improving the communication of pest risk assessments to the public is crucial to create a better understand of the economic consequences if control measures were to be unsuccessful. Given the mutual ownership, between consumers and producers, of the risks associated with invasive species, the problem should be contextualized as a societal challenge in public debates on appropriate management strategies.

Further research is crucial on various fronts. Insights into the impact the pathogen has on yields and costs for different cultivars under different cultivation practices are important. Our understanding of the epidemiology needs to be deepened through further analyses of drivers for spread and speed with which dispersal might occur. It seems unlikely that *Xylella fastidiosa* subspecies *pauca* will be eradicated from Europe. Consequently, science and stakeholders must collaborate in finding feasible strategies for long term adaptation. Here, the development of resistant varieties and improved means of environmentally responsible vector control are invaluable avenues for further work. The need for enduring surveillance and control calls for additional research on cost effective detection methods.

[4] Equivalent annual costs of the losses to consumers were computed by dividing the total present value losses to consumers (see Table 3) by the annuity factor (Copeland et al., 2005), using a discount rate of 3% and a time horizon of 50 years. The equivalent annual costs were then divided by the number of households in the EU-27 in 2019 (Eurostat, 2021)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2021.107024.

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