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The potential direct economic impact and private management costs of an invasive alien species: *Xylella fastidiosa* on Lebanese wine grapes

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Abstract

Since its outbreak in 2013 in Italy, the harmful bacterium *Xylella fastidiosa* has continued to spread throughout the Euro-Mediterranean basin and, more recently, in the Middle East region. *Xylella fastidiosa* subsp. *fastidiosa* is the causal agent of Pierce's disease on grapevines. At present, this alien subspecies has not been reported in Lebanon but if this biological invader was to spread with no cost-effective and sustainable management, it would put Lebanese vineyards at a certain level of risk. In the absence of an *Xylella fastidiosa* subsp. *fastidiosa* outbreak, the gross revenue generated by Lebanese wine growers is estimated as close to US$22 million/year for an average period of 5 years (2015–2019). The potential quantitative economic impacts of an *Xylella fastidiosa* subsp. *fastidiosa* outbreak and particularly, the private control costs have not been assessed yet for this country as well as for others which *Xylella fastidiosa* may invade. Here, we have aimed to estimate the potential direct economic impact on growers' livelihoods and provide the first estimate of the private management costs that a theoretical *Xylella fastidiosa* subsp. *fastidiosa* outbreak in Lebanon would involve. For this purpose, we used a Partial Budget approach at the farm gate. For the country as a whole, we estimated that a hypothetical full spread of *Xylella fastidiosa* subsp. *fastidiosa* on Lebanese wine grapes would lead to maximum potential gross revenue losses of almost US$ 11 million for an average recovery period of

4 years, to around US$ 82.44 million for an average grapevine life span period of 30 years in which infected plants are not replaced at all. The first yearly estimated additional management cost is US$853 per potentially infected hectare. For a recovery period of 4 years, the aggregate estimated additional cost would reach US$2374/ha, while the aggregate net change in profit would be US$-4046/ha. Furthermore, additional work will be needed to estimate the public costs of an *Xylella fastidiosa* subsp. *fastidiosa* outbreak in Lebanon. The observed costs in this study support the concerned policy makers and stakeholders to implement a set of reduction management options against *Xylella fastidiosa* subsp. *fastidiosa* at both national and wine growers' levels. This re-emerging alien biota should not be neglected in this country. This understanding of the potential direct economic impact of *Xylella fastidiosa* subsp. *fastidiosa* and the private management costs can also benefit further larger-scale studies covering other potential infection areas and plant hosts.

Keywords
Alien species, biological invasion impact, crop protection, economic impact, partial budget, pest outbreak, pest risk analysis, *Xylella fastidiosa*

Introduction

The biological invasion of alien species is increased by global trade, climate change and economic activities through the transport of humans and plants (McDermott 2015; Chapman et al. 2017; Pratt et al. 2017), and has the potential to cause direct and indirect market, and non-market impacts. The global costs of invasive insects have been determined at a "minimum of US$70.0 billion and more than US$6.9 billion per year for goods and services as well as for human health" respectively (Bradshaw et al. 2016). Further, the economic damages induced by invasive species were estimated for at least close to US$1.3 trillion across the world (Zenni et al. 2021).

Xylella fastidiosa[1], an aerobic gram-negative endophyte bacterium in the Xanthomonadaceae family (Wells et al. 1987), is a good example of this biological invasion process. *Xylella fastidiosa* (Fig. 1) is recognized as a very high-risk pathogen due to: (i) its latency period in many plant species, which favors its conservation and diffusion, (ii) efficient transmission by numerous xylem feeding insect-vectors (spittlebugs, sharpshooters, and/or leafhoppers), (iii) adaptability to varied climatic conditions, (iv) polyphagia, (v) severity of symptoms (common symptoms are leaf scorch, burnt edges of older leaves, stem yellowing and dieback), and (vi) its serious economic, social and ecological impacts (Henneberger et al. 2004; European Food Safety Authority 2015, 2018, 2019). *Xylella fastidiosa* has been a major concern worldwide due to its potential transmission through plant materials across borders and because it is the causal agent for the worldwide spread of many plants diseases (Mette et al. 2019). Furthermore, due to the lack of efficient airport inspection procedures and phytosanitary regulations in

1 An overview on the biology and ecology of *Xylella fastidiosa*, its distribution worldwide as well as its private management control is stressed in the Suppl. material 1 *Xylella fastidiosa*: a bio-ecology review of a re-emerging alien biota. The link https://gd.eppo.int/taxon/XYLEFA/distribution would grasp the extent of invasions by *Xylella fastidiosa* worldwide as also outlined in the Suppl. material 1: Table S1.

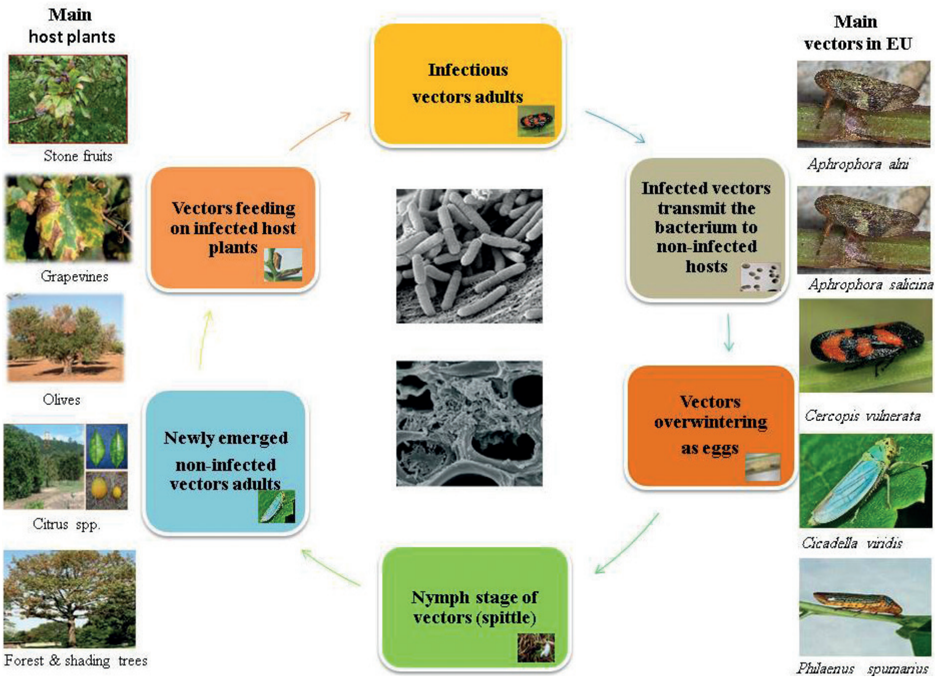

Figure 1. Overview of the life cycle of *Xylella fastidiosa*, its main host plants and vectors in Europe.

the Middle East and North Africa (MENA) region, humans can act as dynamic vectors transmitting potentially *Xylella fastidiosa*-infected planting materials or any infrastructure product carrying insect vectors. Therefore, there is a continual risk of spreading *Xylella fastidiosa* across the world, which has led to recent serious outbreaks. Consequently, countries classified in the high-risk zone should constantly perform specialized pest risk analysis (PRA), implement preventive phytosanitary measures, and focus on enhancing inspection systems, while raising awareness about *Xylella fastidiosa* in order to reduce its economic and ecological impacts (Castrignanò et al. 2020; Frem et al. 2020) and ensure its early detection in asymptomatic plants and vectors (Riefolo et al. 2021).

According to the European and Mediterranean Plant Protection Organization (EPPO 2015, 2016, 2019a, 2019b) *Xylella fastidiosa* was introduced from its native area in the Americas into Asia and Europe. The first European outbreak of *Xylella fastidiosa* occurred in Italy in 2013 (Saponari et al. 2013), followed by France in 2015 (EPPO 2015), Spain in 2016 (Olmo et al. 2017), Germany in 2016 (EPPO 2016), and Portugal in 2019 (EPPO 2019a). Since 2013, *Xylella fastidiosa* has become one of the most harmful pests of vulnerable economic crops (European Food Safety Authority 2019), mainly olives, grapes, fruit stones and ornamental plants, causing socio-economic and landscape damage, and driving economic assessment of potential outbreaks in new countries, such Lebanon. Frem et al. (2020) predicted that the risk level for *Xylella fastidiosa* entry into Lebanon is medium, although the risk of its establishment in the country is at the highest level in the Middle East and North Africa (MENA) region. In order to prevent entry of *Xylella fastidiosa*, Lebanon has imposed specific quarantine measures (Habib et al. 2016; Choueiri 2017) and its country-level of technical readiness is considered as sufficient with medium entry risk (Cardone et al. 2021). Therefore, the diffusion of *Xylella fastidiosa* would put the Lebanese vineyard landscape at a certain level of risk. At present, the bacterium is absent from the study area but we believe that if it spreads without cost-effective management, the economic, social, cultural and environmental consequences will be negative, and a hypothetical outbreak of *Xylella fastidiosa* subsp. *fastidiosa* in Lebanon would involve significant private (i.e. at farm gate) and public costs. Given this, it is useful to assess the potential economic impact of *Xylella fastidiosa* subsp. *fastidiosa* on the Lebanese grape industry, which produces table grapes (70%) and wine grapes (30%). The most common wine grape varieties grown in Lebanon, including red and white cultivars, are characterized in the Suppl. material 2: Table S2.

In this context, this paper aims to assess the quantitative economic impact of a hypothetical *Xylella fastidiosa* subsp. *fastidiosa* outbreak on Lebanese wine growers' livelihoods and, to provide the first estimate of the private management costs that would be involved in tackling this potential invasion. For these purposes, a holistic yield loss model (European Food Safety Authority 2019) within a partial budget conceptual approach (Soliman et al. 2010) will be used as suitable economic methodological tools. The added-value of the present research is twofold. Firstly, the economic impact of *Xylella fastidiosa* subsp. *fastidiosa*, based simultaneously on primary and secondary data, has never been assessed in Lebanon. As such, the lack of economic damages of invasive species (potential or observed costs) in Lebanon (Kourantidou et al. 2021) provides some context to this study. The analysis contained in the present research aims to redress this lack of study and to contribute to the scientific literature on economic impact in PRA. In fact, researches based on primary data are lacking from the literature review for the assessment of the economic impact and costs of management of alien species such as *Xylella fastidiosa* subsp. *fastidiosa*. As such, this research provides a useful referential case study that can also be applied in other areas while *Xylella fastidiosa* may spread. In addition, the global reported costs of invasive microbes, and especially bacteria, are very low compared to other more studied taxonomic groups (Leroy et al. 2021) As such, this observation suggests that microbes may be severely understudied, and so any study in this direction, such as the one presented here, will, secondly, enrich the scientific literature on the economic impact of invasive species.

Methods

Previous researches have stressed that economic tools constitute effective measures to manage invasive species which entail crucial costs in terms of control measures or impact (McDermott 2013; Pratt et al. 2017; Barbet-Massin et al. 2020). A range of methodological techniques can be used to analyze the economic impact of an alien species invasion (Pimentel et al. 2001; Born et al. 2005; Pimentel et al. 2005; Olson 2006; Soliman et al. 2010; De Ros 2015; Pratt et al. 2017). In this paper, we have divided the economic assessment approach into two major steps: (i) the potential direct economic impact on wine growers' livelihoods, and (ii) *Xylella fastidiosa* subsp. *fastidiosa* management costs. As such, the Methods section is structured into three parts as follows: (i) data compilation, (ii) estimation method for potential direct economic impact and, (iii) estimation method for private management costs.

Data compilation

For the potential economic impact of *Xylella fastidiosa* subsp. *fastidiosa* on wine growers' livelihoods, we obtained the correspondent secondary data (area, yield and value of wine grapes) between 2015 and 2019 from the Food and Agriculture Organization, FAOSTAT database (www.fao.org/faostat/en/) and the Ministry of Agriculture (2017). There are no official updated data available relating to the price per ton of wine grapes at farm level. Estimates were therefore obtained from the field survey in the study area. Further, there are no quantitative data on the running production costs and additional costs of a hypothetical *Xylella fastidiosa* subsp. *fastidiosa* outbreak at vineyard level in Lebanon (Kourantidou et al. 2021). In order to quantify these costs (Table 1), given the absence of updated reliable primary data concerning the production costs in the country, and the need to construct pre-invasion and post invasion scenarios for *Xylella fastidiosa* subsp. *fastidiosa*, we collected and calculated the concerned costs through a specific field survey questionnaire (Suppl. material 9: Field survey) involving a focus group of 76 representative farmers, who are experts in vineyard production. The questionnaire has three sections. The first section collects information about the key farmer and the work-force in the vineyard farming system in the survey region. The second section collects current technical and financial data about the key grape farm (i.e. cultural practices, cultivars, production, cost of production, etc.) within the context of a normal agricultural situation without an *Xylella fastidiosa* subsp. *fastidiosa* outbreak (i.e. scenario A). The third section aims to estimate the additional costs that could be involved over a recovery period of 4 years in order to cope with a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak (i.e. scenario B). For this purpose, we selected farmers from the western area of the Beqaa Valley (Fig. 2), the central region of Lebanon, where *Xylella fastidiosa* subsp. *fastidiosa* may reasonably be expected to have the greatest potential direct economic impact. The selection of this field survey area was based on: (i)

Table 1. Additional costs that could be involved by a hypothetical *Xylella fastidiosa* subsp. *fastidiosa* outbreak based on the literature review of main control strategies at farm gate. The table outlines the principal additional costs that could be involved in a hypothetical *Xylella fastidiosa* subsp. *fastidiosa* outbreak over a recovery period of 4 years (2020–2023) required for a vine to become productive after replanting (EFSA 2019).

Type of additional costs	Justification
Labor	Removal and disposal of diseased or dead vines as soon as PD appears in the vineyard, in order to reduce its infection rate.
	Physical removal of weeds under vine plants.
	Visual monitoring and inspection of vectors with a sweep net. Spraying of chemicals. Pruning: effective pruning on detection of early symptoms.
Insecticides	To reduce the potential population of *Xylella fastidiosa* subsp. *fastidiosa* vectors (leafhoppers insects), adjacent habitats in areas close to the vineyards must be sprayed, mainly in spring.
Herbicides	Soil management: chemical removal of weeds under vines.
Sticky traps	To monitor or observe the movement of potential *Xylella fastidiosa* subsp. *fastidiosa* vectors.

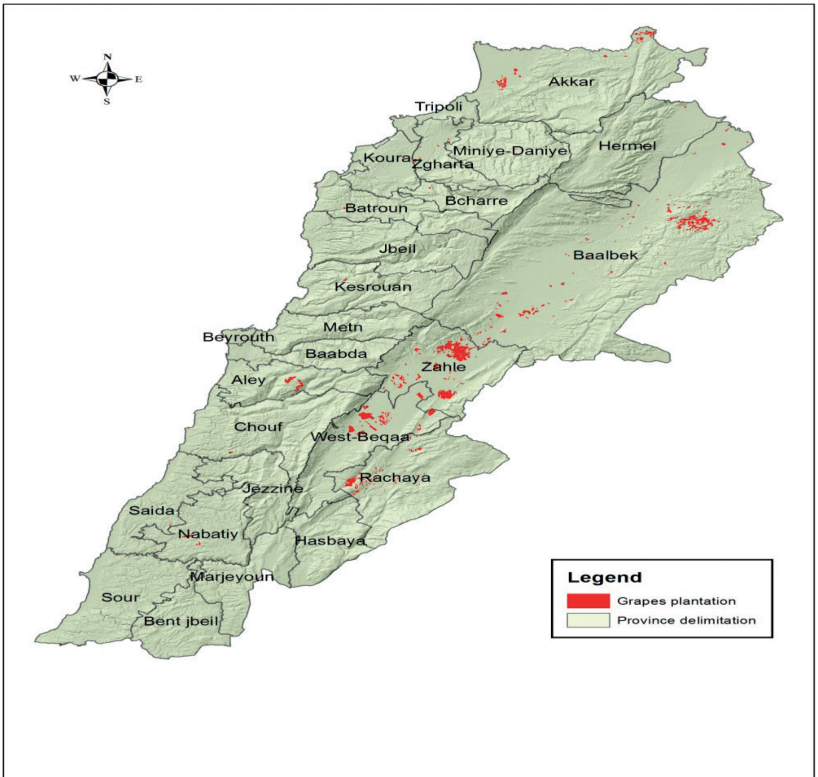

Figure 2. Wine grape plantations in Lebanon based on data from the Ministry of Agriculture (2017). The map highlights the importance of wine grape plantations in Zahlé and West Beqaa that were considered as a field study area in our estimation model.

its suitable quarter summer temperatures (Suppl. material 3: Table S3) for *Xylella fastidiosa* subsp. *fastidiosa* diffusion (around 25–32 °C) as examined by Feil and Purcell (2001), and (ii) its economic importance. In fact, this region is one of Lebanon's most important and oldest commercial wine grape production areas (El Chami and El Moujabber 2014). According to the Ministry of Agriculture (2017), out of 992 farmers (cultivating approximately 3,057 ha of wine grapes) in Lebanon, approximately 600 work in the Beqaa Valley, which has a wine grape surface area of 1,941 hectares, distributed between its main provinces: Baalbek (35%), Zahlé and West Beqaa (65%). At present, 70% of the national wine output is produced mainly by 4 Beqaa Valley wine producers (Chateau Ksara, Chateau Kefraya, Chateau Musar and Chateau Saint Thomas) from grapes grown in this valley with a heritage value. Furthermore, 50% of the region's wine production is exported abroad.

Estimation method for the potential direct economic impact

We estimated the potential gross revenue losses in wine grapes based on yield losses as estimated by EFSA (2019), where the yield loss on wine grapes would oscillate between 1.2% (low impact), 2.1% (medium impact) and 8.1% (high impact). Here, we considered these 3 pressure levels in order to consider the uncertainty of results which would be influenced by winter climate unsuitability (freezing temperatures may reduce proliferation of the bacterium in the production areas, up to 1000 m above sea level), the unknown density of *Xylella fastidiosa* subsp. *fastidiosa* vectors (lack of field studies to confirm their activity, low or high abundance), the short period of effective infection (2 to 3 months starting in June) and cultural practices (vineyard irrigation, insecticide use, heavy pruning of plants, etc.) would give a lower incidence rate.

Estimation method for the private management costs

We based this estimate on the Partial Budget (PB) method (Table 2) as outlined by Soliman et al. (2010) due to: (i) its relevance for the purpose of calculating the additional costs (control costs) and the reduced farmers' incomes (yield loss) of a potential *Xylella fastidiosa* subsp. *fastidiosa* invasion, and (ii) its simplicity, transparency of credibility of results. PB is a basic economic tool that analyzes the changes in costs and revenues due to any unplanned change, such as a pest invasion or management measures (use of insecticides, herbicides, fungicides, weed management, cultural alterations, etc.) in farming systems (MacLeod et al. 2004). Table 2 illustrates PB and Fig. 3 highlights the principal quantitative economic impact assessment methods used in PRA (Soliman et al. 2010)

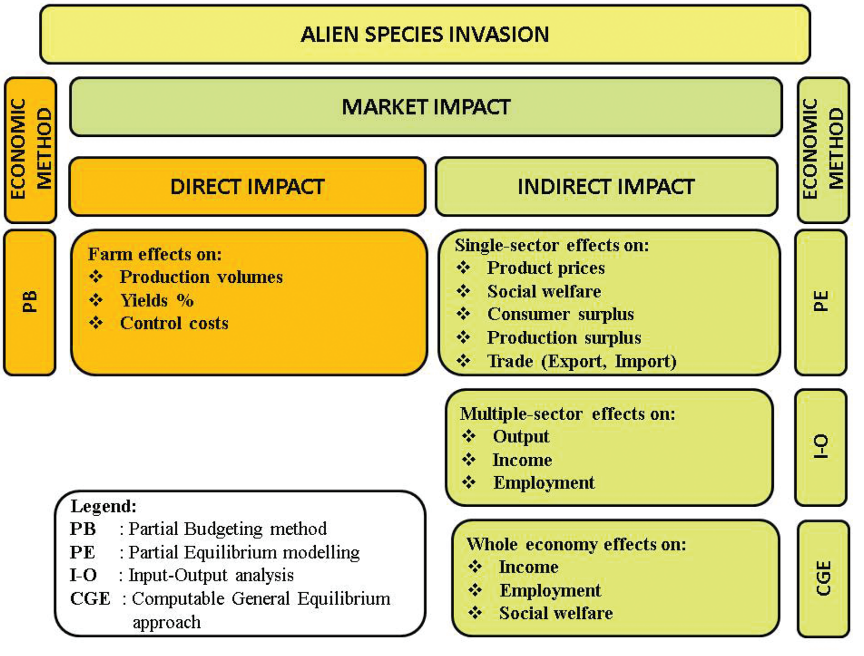

Figure 3. Overview of the direct and indirect market impacts of an alien species invasion in a new location. The diagram highlights the principal quantitative economic impact assessment methods used in pest risk analysis where the Partial Budgeting apapproach was considered in this research. The overview is based on Soliman et al. (2010) and De Ros et al. (2015).

Table 2. Overview of the partial budgeting of *Xylella fastidiosa* subsp. *fastidiosa* invasion on wine grapes, based on the general layout of Soliman et al. (2010). The table aggregates the specific costs and benefits considered in our economic impact model.

Costs	$US	Benefits	$US
Additional costs **(A)**		Additional revenues **(C)**	
Control & protection costs			
Reduced revenues **(B)**		Reduced costs **(D)**	
Yield and/or Quality losses			
Total costs: (A) + (B)		**Total benefits: (C) + (D)**	
Net change in profit: (C) + (D) - (A) - (B)			

and the direct and indirect market impacts of an alien species invasion in a new location (De Ros et al. 2015). According to the Food and Agriculture Organization (FAO 2004), the economic impact assessment of a quarantine pest like *Xylella fastidiosa* subsp. *fastidiosa* is a fundamental component of PRA. PRA aims to outline "economic evidence helping the phytosanitary authority in each country to determine if the studied organism is a pest, whether it should be regulated, and the enhancement of any phytosanitary measures to be undertaken against it" (FAO 2007). Consequently, FAO (2007) has established an international phytosanitary standard (ISPM N°11) focusing on the qualitative (i.e. expert judgement) and quantitative approaches to conduct PRA without giving any preference for the use of either method. The qualitative scheme(s), through focus group expertise, are well structured and cost-effective but appear more subjective because they are based on the opinions of experts and there is a lack of transparency and repeatability.

Results

Economic impact of *Xylella fastidiosa* subsp. *fastidiosa* on wine grapes growers' livelihoods

As an ex-ante situation (i.e. absence of a hypothetical *Xylella fastidiosa* subsp. *fastidiosa* outbreak/Scenario A), the gross revenue generated by wine growers is estimated as close to US$22 million, almost 33% of which emanates from the study area. With a potential *Xylella fastidiosa* subsp. *fastidiosa* invasion (Scenario B), the estimated potential annual economic losses to wine grape growers would range from US$ 1.32 to almost 2.75 million (Table 3). Consequently, the upper potential gross revenue losses would be close to US$ 11 million for an average period of 4 years (EFSA 2019) if the infected vines were to be replaced by tolerant/resistant cultivars. If the growers will not be able to uproot and replace their infected plants, the total cultivated wine grapes will not generate any revenue and the upper potential gross revenue losses will amount to approximately US$ 82.44 million for an average grapevine life span of 30 years (EFSA 2019). These values depend on a set of factors: the average area of wine grapes (about 3,082 ha in 2015–2019, i.e. 34% of the total cultivated area of grapes in Lebanon), the average production of wine grapes (about 28,262 tons in the same period), the range of yield loss (low, medium

Table 3. Potential gross revenue losses (US$) of wine grape growers (average based on the period 2015–2019) as retrieved from the FAO database and the range of yield loss as addressed by EFSA (2019).

Period of loss*	Lower impact (Yield loss: 1.2%)	Medium impact (Yield loss: 2.1%)	Upper impact (Yield loss: 8.1%)
1 year	1,322,841	1,503,816	2,748,019
4 years	5,291,364	6,015,264	10,992,076
30 years	39,685,230	45,114,480	82,440,570

*(1) year refers to the first year after a full *Xylella fastidiosa* subsp. *fastidiosa* invasion; (4) years refer to the period of replacement of infected vines and for new vines to bear fruits; (30) years refers to the lifespan of grape vines, if there is no replacement of infected vines. The total wine grape growing area in Lebanon and the price at grower level were assumed to be constant for the entire replacement and lifespan periods.

and high), and the average price ($US734/Ton) of most cultivated Lebanese wine grape cultivars. The average price was estimated from the field survey in which *Chardonnay* has the highest price and *Petit Verdot* the lowest (Suppl. material 4: Table S4).

Private management costs due to *Xylella fastidiosa* subsp. *fastidiosa* spreading

For this purpose, the official currency rate change (US$1 = LBP 1515, year 2019) has been used. The average running cost of wine grape production is US$ 3,824/ha/year prior to an *Xylella fastidiosa* subsp. *fastidiosa* outbreak in the study area (Table 4). In these routine conditions (Scenario A), labor costs were estimated at US$1,269 per ha per year, constituting the highest single cost (33%), followed by the hiring of machinery for plowing and spraying (32%). However, around 3% (US$110/ha per year) of production costs involve by insecticides without specific control of *Xylella fastidiosa* subsp. *fastidiosa* vectors, and almost 7% (US$264/ha per year) involve fungicides. The cost of replacing diseased plants is close to 2%, which may reflect the current good management of vineyards, limiting the impact of diseases.

However, the average additional management costs which could be involved in tackling a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak (Scenario B) at the vineyard level are approximately US$ 853/ha for the first year of the recovery period in which a high infestation rate (40%) and an upper impact on yield loss (8.1%) as shown in Table 5. 8% represents the costs of labor for eradication in terms of removal and disposal of diseased or dead vines as soon as PD appears in the vineyard, in order to control the infection rate. The physical removal of weeds under vine plants accounts for around 4%. The costs of labor for visual monitoring and inspection of vectors with a sweep net, for the spraying of chemicals, and for effective pruning at early symptom onset account for 2%, 5% and 13% of the total additional management costs, respectively. Replantation with resistant plants accounts for the greatest cost, around 33% based on an average price of US$1.70/plant and on an average density of around 2,032 plants/ha for all cultivated cultivars, in which "Merlot" cultivar presents the highest density of around 3,100 plants/ha (Suppl. material 6: Table S6). Most cultivated varieties in Lebanon are very susceptible to PD. However, replantation of varieties less susceptible to PD may affect the quality and the revenues of wine grapes. The use of additional insecticides to reduce the population of *Xylella fastidiosa* subsp. *fastidiosa* vectors (leafhoppers insects) amounts to around 8% of additional costs. It was also assumed that

Table 4. The estimated average running costs of wine grape production (US$/ha/year) in the study area in the context of a normal agricultural situation characterized by the absence of a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak, based on the 2019–2020 production cycle.

Activity	Unit	Average Quantity/ha	Average annual rate	Unit cost	Total (US$/ha)
Replacement of infected plants	Plants	36	1	2	61.20
Plowing hire	Hours	5	1	65	389.57
Sprayer hire	Hours	7	5	23.76	831.68
Total machinery			**1,282.46**		
Chemical fertilizer application	Man-days	3	1	15.18	52.36
Organic fertilizer application	Man-days	5	1	11.22	65.85
Herbicide application	Man-days	3	1	9.24	27.72
Insecticide & fungicide application	Man-days	3	4	9.24	110.85
Irrigation control & maintenance	Man-days	11	2	15.84	370.30
Harvesting	Man-days	26	1	9.24	243.69
Pruning	Man-days	17	1	23.76	397.75
Total labor			**1,268.52**		
Chemical fertilizers – NPK	Kg	220	1	1.00	220.00
Organic fertilizers	Kg	206	1	0.80	164.80
Manure	Tons	2	1	203.30	406.60
Total fertilization			**791.40**		
Mineral oil	Liter	1	3	5.33	15.99
Alpha-cypermethrin	Liter	0.15	3	17.50	6.56
Chlorpyrifos-ethyl	Liter	0.80	3	14.63	38.50
Deltamethrin	Liter	0.20	3	13.00	7.80
Imidachloprid	Liter	0.25	3	11.00	8.25
Indoxacarb	Liter	0.25	4	21.00	21.00
Lambda-cyhalolthrin	Liter	0.20	4	15.00	12.00
Total insecticides					**110.11**
Copper Hydroxide	Kg	1	3	7.00	17.85
Difenoconazole	Liter	0.30	1	19.00	5.70
Micronized sulfur	Kg	4	3	2.00	24.00
Myclobutanil	Liter	0.25	2	33.00	16.50
Penconazole	Kg	0.25	3	36.00	27.00
Sulfur powder	Kg	20	2	4.00	160.00
Trifloxystrobin	Kg	0.13	4	24.00	12.48
Total fungicides					**263.53**
Herbicides	Liter	6	1	6.00	**36.00**
Fuel for pumping	20 L tank	1	6	12.00	**71.00**
Total running costs					**3,823.01**

adjacent habitats would be sprayed in areas close to the vineyards, mainly in spring. Effective active ingredients should be used for successful control of *Xylella fastidiosa* subsp. *fastidiosa* vectors. Regarding the soil management/weeded area, the costs of additional chemicals for the removal of weeds under vine plants constitutes 5% of additional costs, while the use of traps to monitor or observe the movement of potential vectors from surrounding areas into the vineyards constitutes close to 11% of the total additional costs.

Consequently, the gross margin on wine grape production appears to be reduced from 26.33% (i.e. *Xylella fastidiosa* subsp. *fastidiosa* outbreak absent) to around 2% (i.e. *Xylella fastidiosa* subsp. *fastidiosa* outbreak present) in the first year of invasion as described in Table 6 and Table 7. Over a recovery period of 4 years, the aggregate of the additional costs would reach approximately US$2374/ha. For the same period, the aggregate amount of revenues lost due to a yield loss of 8.1% (EFSA 2019) would be about US$1672/ha. As a consequence of a potential *Xylella fastidiosa* subsp. *fastidiosa* invasion, the wine grape farming system (MacLeod et al. 2004) would suffer a loss of US$4,046/ha per 4 years as a net change in profit (Table 2). For the study area, where the total area of wine grapes is about 1,256 ha (41% of the total cultivated area), wine growers would be exposed to a loss of around US$ 5 million, while losses would amount to around US$12.4 million across the country (3,057 ha of wine grapes) for the entire recovery period of 4 years in which the price at grower level was assumed to be constant (Suppl. material 7: S7, Suppl. material 8: Table S8).

Table 5. The estimated average additional management costs of wine grape production (US$/ha/1st year of infection) due to a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak, based on the 2019–2020 production cycle.

Activity	Additional management costs (US$/ha/1st year of infection)
Machinery for spraying	99
Labor for uprooting infected plants	66
Labor for mechanical removal of weeds	33
Labor for monitoring of *Xylella fastidiosa* subsp. *fastidiosa* vectors	17
Labor for spraying insecticides	46
Labor for pruning	112
New resistant plants(1)	280
Insecticides	65
Herbicides	45
Traps for *Xylella fastidiosa* subsp. *fastidiosa* vectors	90
Total additional costs (presence of *Xylella fastidiosa* subsp. *fastidiosa* outbreak)	**853**

Table 6. The estimated average gross margin budget (US$/ha/year) in the study area within the context of a normal agricultural situation characterized by the absence of a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak based on the 2019–2020 production cycle.

Component	(US$/ha/year)
Total variable costs	3,823
Average yield (Ton/ha)	7.07
Average price (US$/Ton)	734
Gross revenues (US$)	5,189
Gross margin (US$/ha)	1,366
Gross margin (%)	**26.33**

Table 7. The estimated average gross margin budget (US$/ha/1st year of infection), in the study area within the context of an agricultural situation characterized by a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak, based on the 2019–2020 production cycle.

Component	(US$/ha/1st year of infection)
Total premium costs (absence of *Xylella fastidiosa* subsp. *fastidiosa* outbreak)	3,823
Total additional costs (presence of *Xylella fastidiosa* subsp. *fastidiosa* outbreak)	853
Average yield (Ton/ha)(1)	6.5
Average price (US$/Ton)	734
Gross revenues (US$)	4,771
Gross margin (US$/ha)	95
Gross margin (%)	**2**

(1) We assumed an upper impact on yield loss (8.1%) in the study area as outlined by EFSA (2019).

Discussion

Main findings at a glance

On average, Lebanon produces 83,125 tons of grapes per year from a harvested area of 9,066 ha, generating a yield of around 9 Tons/Ha in 2015–2019. In 2018, the gross production value of Lebanon's grapes amounted to $US 120 million, representing 4% of the total value of the country's agricultural production (FAO 2020). In the same year, the wine industry produced approximately 8 million bottles (75 cl), and exported around 2,322 tons of grapes, representing 50% of total production with an export value of $US 20.3 million (Banque du Liban et d'Outre Mer 2019). In this paper, we estimated that a hypothetical full spread of *Xylella fastidiosa* subsp. *fastidiosa* on the whole Lebanese wine grapes would lead to maximum potential gross revenue losses of almost US$ 11 million for an average recovery period of 4 years, to around US$ 82.44 million for an average grapevine life span period of 30 years in which infected plants are not replaced at all. Concerning the estimated additional management cost, the amount is US$853 per potentially infected hectare in the first year. For a recovery period of 4 years, the aggregate estimated additional cost would reach US$2374/ha, while the aggregate net change in profit would be US$-4046/ha.

Importance and implications of the findings

The findings explored above provide a clear picture of the potential economic impact and private costs management assessments of a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak on Lebanese wine grapes. Here, we connect the observed results to the existing literature and derive some policy and private implications from our findings. Firstly, our research highlights an economic impact level of a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak in order to manage and identify the control measures to reduce the incidence rate and severity of PD on Lebanese grapevines. Previous studies papers (Soliman et al. 2010; McDermott 2013; Pratt et al. 2017; Barbet-Massin et al. 2020) also assumed the importance of the assessment of the economic impact of invasive species for sustainable policy planning and for the implementation of cost-efficient and environmentally-friendly pest management strategies (Rapicavoli et al. 2018; El Chami et al. 2020). The absence of such a study and the lack of updated and reliable primary data on the costs of production and pest control for Lebanese vineyards is a critical constraint to the design of sustainable management control to mitigate its severe impacts of an invasion pest like *Xylella fastidiosa* subsp. *fastidiosa*, which may affect a total cultivated area of around 3,000 ha of wine grapes in Lebanon. Obviously, wine growers were found ready to adopt an integrated management approach and to put into practice the additional necessary measures to limit *Xylella fastidiosa* subsp. *fastidiosa* damage, which mostly consist of the removal of diseased plants, replantation with resistant/tolerant cultivars, use of appropriate insecticides to control *Xylella fastidiosa* subsp. *fastidiosa* vectors, and soil management. Kyrkou et al. (2018) has summarized the private control strategies against *Xylella fastidiosa* on grapes in 2 categories: (i) prophylactic/preventive measures (i.e. "control of insect-vectors, control of non-vine host plants and vine propagation material, alteration to cropping techniques, breeding PD-resistant/tolerant *Vitis vinifera*, control via avirulent *XYLEFA* strains and control via other beneficial bacteria and fungi") and (ii) therapeutic/curative measures (i.e. "use of bacteriophages of *Xylella fastidiosa* subsp. *fastidiosa*, use of an antagonistic bacterium *Paraburkholderia phytofirmans* strain PsJN, use of natural, antibacterial substances, and use of defense-stimulating compounds"). As the bacterium has high potential to spread in Lebanon through imports of infected host plants or the accidental entry of vectors, the Lebanese policy makers should keep pursuing management strategies to limit *Xylella fastidiosa* epidemics which may remain undetectable up until diseases like PD on grapevines become established. Further, strict policy limitations on the importation, marketing, and transport of plants from countries that are sources of *Xylella fastidiosa* infection are therefore essential in the management program to limit *Xylella fastidiosa* entry and spread. Further public control strategies to *Xylella fastidiosa* subsp. *fastidiosa* outbreak such as monitoring and inspection, certification, screen-house production, and clean (i.e. *Xylella fastidiosa* subsp. *fastidiosa*-free) propagation material (López et al. 2017) should be implemented by the competent local authorities. In addition, local public field trials strategies should be performed to determine the number and timing of spraying and the types of chemical treatments to use in Lebanese vineyards to best control *Xylella fastidiosa* subsp. *fastidiosa* vector populations. In fact, if *Xylella fastidiosa* subsp. *fastidiosa* vectors are not carefully managed, the bacterium has the potential to spread widely in the study area. Further, the lack of early PD notification (intended or unintended by growers or by the local competent authorities) and therefore, any delay in taking immediate action against this plant disease would lead to a spillover into other regions of Lebanon and *Xylella fastidiosa* subsp. *fastidiosa* would spread to other economically vulnerable crops and alternative habitats. Thus, it would probably lead to the expansion of PD across Lebanon, involving further management costs and the potential loss of local and international markets for the country's wines as well as other crops' value chain. Secondly, our analysis shows that the highest private additional costs will be incurred in the first year of infection due to the costs of labor for the removal and purchase of resistant/tolerant plants in order to continue or restart the production of wine grapes within a recovery period of around 4 years. Meanwhile, the analysis of the gross margin highlights that wine grape cultivation is relatively profitable in the study area. Farmers manage their vineyards well in terms of controlling insects, wine grape diseases and weeds. Thirdly, the findings are also important for wine growers and local wineries as the latter are vertically integrated in the farming system, and Lebanon is a net exporter of wines In fact, the potential replacement of the current cultivars of vines, which are mostly susceptible to *Xylella fastidiosa* subsp. *fastidiosa*, or their substitution by PD resistant cultivars, may affect the wine quality and revenues, as well as creating imbalances in supply and demand. Finally, our findings support the concept of multiple "known-on effects" as stressed by Macleod et al. (2004). Nevertheless, the technical measures outlined in this paper would probably not have critical financial consequences for the growers but would generate multiple "known-on effects" in terms of reducing the impacts for local wineries and limiting social effects (unemployment). In the case of an *Xylella fastidiosa* subsp. *fastidiosa* outbreak, local wineries will acquire grapes from other districts to encounter disruption in supply and this will involve additional transactional costs. On the other hand, a hypothetical *Xylella fastidiosa* subsp. *fastidiosa* outbreak may seriously affect the small grape producers, whose livelihoods will decrease in the context of the continuous drastic financial and economical current crisis facing the country.

Comparison of findings with other countries

Although the onset of *Xylella fastidiosa* epidemics is commonly followed by significant economic losses (Rapicavoli et al. 2018), few previous studies have estimated the annual control costs of *Xylella fastidiosa* outbreaks. In USA, annual control costs for Californian oleanders were estimated at US$125.0 million (Henry et al. 1997) and at US$104.0 million for grapevines across 346,000 ha of grapes in California (Tumber et al. 2014; California Department of Food and Agriculture 2018). The total cost of PD attacking grapevines was estimated at almost US$105 million per year (California Department of Food and Agriculture 2018). Using an evaluation model to assess PD impacts, knowing that glassy-winged sharpshooter (GWSS) is its vector in California, the total annual cost of disease control to growers has been estimated as rising by US$189 million per year (cost of replanting and chemical control), with an increase in the grape prices (Alston et al. 2013). This cost excludes the extra US$50 million spent every year on prophylactic phytosanitary measures such as insect control. In Brazil, the annual control costs of *Xylella fastidiosa* on oranges were estimated at US$120.0 million (International Plant Protection Convention 2017). In the absence of effective preventive biosecurity systems, Brazilian orange production has been dramatically affected by *Xylella fastidiosa*. Researchers have estimated an annual loss of US$120 million, corresponding to approximately 6% of total production value in 2003 (Mette et al. 2019). Nevertheless, *Xylella fastidiosa* infection was reduced from 37.6% to 1.3% in 6 years between 2012 and 2018 (Barros 2018), due to the successful implementation of compulsory requirements for importation of certified trees (Almeida and Nunney 2015). Recently, several studies have also been undertaken to estimate the potential economic impact of *Xylella fastidiosa* outbreaks: (i) the costs could vary between US$2.3 billion to US$7.9 billion over 50 years on Australian wine grapes and wineries (Australian Bureau of Agriculture and Resource Economics and Sciences 2018), (ii) annual production losses could reach €5.5 billion over 50 years on European olives (Schneider et al. 2020), and (iii) the values of grapes, olives and citrus spp. production losses have been estimated at around US$10.0 million, US$218.35 million and US$1.0 billion on grapes, citrus *spp*. and olives respectively in nine countries in the MENA region (Cardone et al. 2021). Besides, this pathogen could also affect ecosystem services by damaging rural landscapes, such as Italy's impressive olive orchards, for which the average socio-ecological value of loss has been estimated at between €1,017 and €1,059 per ha (Frem et al. 2021).

Limits of the study

The results explored here underestimate the potential impacts of *Xylella fastidiosa* subsp. *fastidiosa* in Lebanon. Indeed, they represent a fraction of the real potential costs if *Xylella fastidiosa* subsp. *fastidiosa* invades the full territory of the country. Important limits of this research include its assessment of one crop, one region, reliance on direct market impact, missing the indirect market impact and non-market impact of a hypothetical *Xylella fastidiosa* invasion in the country. The main reason of these limitations was the lack of reliable, accurate and updated specific data in the country. Future studies, based on other quantitative economic impact assessment methods (as illustrated in Fig. 2), could use enough resources, generate the requested information and try to assess the indirect market impact of a hypothetical or real *Xylella fastidiosa* invasion at: (i) one single-sector level (effects of *Xylella fastidiosa* on product prices, social welfare, consumer surplus, production surplus, trade), (ii) multiple sectors level (effects of *Xylella fastidiosa* on output, income, employment) and/or, (iii) entire economy level (effects of *Xylella fastidiosa* on income, employment and social welfare). In addition, *Xylella fastidiosa* may also affect seriously other valuable Lebanese economically crops (Citrus spp. stone fruits, olives, etc.) and the entire Lebanese landscape ecosystem (forest and urban trees). As such, the present research, with more specific field surveys, could be extended to include the non-market impact/costs of a potential or real *Xylella fastidiosa* invasion on the ecosystem (provisioning, regulating and cultural services as highlighted in Fig. 2), in the study area and/or in other locations of the country in which the bacterium could lead to serious outbreaks under specific conditions, such as the climate (mainly the quarter summer temperature – Bio10) and habitat (crops, urban ornamental plants and forests) that favor the establishment and spread of *Xylella fastidiosa* (Frem et al. 2020). The discrete choice experiment method would be useful for this purpose.

Conclusion

The potential spread of *Xylella fastidiosa* subsp. *fastidiosa* to new countries like Lebanon is highly likely due to the climatic suitability of grapevine regions. As such, our study illustrates the principal additional management costs that could be involved in tackling a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak at the vineyard level. This research provides important data and valuable information in terms of potential compensation measures to be adopted by policy makers and/or private or international donors if *Xylella fastidiosa* subsp. *fastidiosa* was to spread in Lebanon. On the other hand, in order to reinforce vineyard biosecurity actions, and to encourage early reporting of PD to local authorities for better monitoring and surveillance, we suggest that Lebanese producers potentially affected by *Xylella fastidiosa* subsp. *fastidiosa* should be compensated or receive incentives to offset their losses over the recovery period. Finally, this research could be extended to cover the costs of these types of interventions in order to provide an exhaustive picture of the additional public and private costs of managing a potential *Xylella fastidiosa* subsp. *fastidiosa* outbreak in Lebanon.

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Supplementary material 1

Table S1

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: World distribution of *Xylella fastidiosa*.

Link: https://doi.org/10.3897/neobiota.70.72280.suppl1

Supplementary material 2

Table S2

Authors: Michel Frem, Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: Main characteristics of the most grapevines cultivated in Lebanon. http://www.winepros.org/wine101/wine101.htm

Link: https://doi.org/10.3897/neobiota.70.72280.suppl2

Supplementary material 3

Table S3

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: The monthly average temperatures (°C) in Zahlé and West-Beqaa, Lebanon.

Link: https://doi.org/10.3897/neobiota.70.72280.suppl3

Supplementary material 4

Table S4

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: The average price (USD/Ton at growers' level) of the most wine grapes cultivars in Lebanon.

Link: https://doi.org/10.3897/neobiota.70.72280.suppl4

Supplementary material 5

Table S5

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: The average yield (Ton/ha) of the most wine grapes cultivars in Lebanon.

Link: https://doi.org/10.3897/neobiota.70.72280.suppl5

Supplementary material 6

Table S6

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: The average density (plants/ha) of the most wine grapes cultivars in Lebanon.

Link: https://doi.org/10.3897/neobiota.70.72280.suppl6

Supplementary material 7

Table S7

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: The study area and countrywide additional management costs in the first year of the recovery period (baseline year: 2020).

Link: https://doi.org/10.3897/neobiota.70.72280.suppl7

Supplementary material 8

Table S8

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: The net changes in profit over a recovery period of 4 years (2020–2023).

Link: https://doi.org/10.3897/neobiota.70.72280.suppl8

Supplementary material 9

Field survey questionnaire

Authors: Michel Frem , Vincenzo Fucilli, Franco Nigro,Maroun El Moujabber, Raied Abou Kubaa, Pierfederico La Notte, Francesco Bozzo, Elia Choueiri

Data type: Occurences

Explanation note: Questionnaire field survey related to the potential economic imapct and private management costs of *Xylella fastidiosa* on Lebanese vineyards.

Link: https://doi.org/10.3897/neobiota.70.72280.suppl9