Crop Protection 142 (2021) 105519

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Assessment of the environmental impacts of *Xylella fastidiosa* subsp. *pauca* in Puglia

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ARTICLE INFO

Keywords:
Biodiversity
Ecosystem services
Environmental risk assessment
Puglia
Xylella fastidiosa subsp. *pauca*

ABSTRACT

The introduction of *Xylella fastidiosa* subsp. *pauca* in Puglia (Italy) has disturbed the flow of ecosystem services (ES). We assessed the short- and long term impacts of this disease and the control measures against it on ES provisioning and biodiversity in the olive-producing agroecosystem of Puglia at a landscape level by using an ES framework in combination with expert knowledge elicitation. Experts estimated the minimum, maximum and most likely relative reductions in ES delivery and biodiversity components in the affected area. The estimates were used to fit a PERT distribution. Results show that the loss of olive trees (the main woody plant in the region) in general, and of centenarian olive trees in particular, has affected ES delivery. The delivery of ES is estimated to diminish by 34% and 30% in the short- and long term, respectively, mainly due to the impact of the disease on food (olive) production, ornamental resources, soil erosion regulation, primary production and cultural heritage. Biodiversity components are estimated to diminish by 28%, mainly due to the impact of the disease on genetic diversity and habitats of high conservation value. The study provides a first assessment of the wider environmental impacts of *Xylella fastdiosa* subsp. *pauca*, which can serve as a basis for formulating hypotheses for further investigation.

1. Introduction

Ecosystems contribute to the well-being of humans by providing essential ecosystem services (ES), which fall under four categories (Millennium Ecosystem Assessment (MEA), 2005): *provisioning* (e.g. food), *regulating* (e.g. erosion regulation), *cultural* (e.g. cultural heritage), and supporting *services* (e.g. photosynthesis). Following the sustainable development concept (World Commission on Environment and Development, 1987), there has been a growing attention to the "multifunctionality" of agricultural systems where environmental and social aspects are considered in the design and management of agricultural systems beyond the usual economic/productivity aspect (e.g. Hodbod et al., 2016; Wilson, 2008; Potter and Burney, 2002). Agricultural systems that are designed and managed based on "multifunctionality" provide more beneficial outcomes such as ensuring food and livelihood security, while also increasing the quantity and quality of several ES (e.g. Hodbod et al., 2016). It is therefore appropriate to assess the impact of invasive plant pathogens not only with respect to agricultural impacts but account as well for the broader suite of services provided by the agroecological system in its landscape context.

The introduction of invasive plant pests and diseases, like *Xylella fastidiosa* (*Xf*) may cause a substantial impairment of the flow of ES (Gilioli et al., 2017; EFSA PLH Panel, 2014). *Xf* belongs to the family of *Xanthomonadaceae* (Wells et al., 1987) and is one of the most dangerous plant pathogenic bacteria in the world causing major agricultural, environmental and social impacts (Bragard et al., 2019). It spreads from plant to plant by grafting and through xylem fluid-feeding insects (Cornara et al., 2018). Until recently, *Xf* was known to be endemic and confined to the Americas (Bragard et al., 2019). However, in 2013 the *pauca* subspecies was detected in Puglia/Apulia (Italy) on olive trees (*Olea europaea*), being the first detection in Europe (Bragard et al., 2019; Zarco-Tejada et al., 2018). This subspecies is associated with a new disease, named the *olive quick decline syndrome*, which is characterized by severe branch desiccation and rapid death of olive trees (Saponari et al., 2019a). Olive farming in the southern province of Puglia accounts for about 40% of Italy's olive oil production and is of major importance for the regional economy (ISMEA, 2015). Olive orchards are the symbol of the region and are closely connected to the identity of the people, providing multiple ES. The olive orchards have emotional and aesthetic value, and represent a cultural and natural heritage of the region, going

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https://doi.org/10.1016/j.cropro.2020.105519
Received 14 August 2020; Received in revised form 11 December 2020; Accepted 17 December 2020
Available online 21 December 2020

back to the pre-Roman times (Saponari et al., 2019a).

The climatic conditions of southern Europe in general, and Puglia in particular, are suitable for *Xf* (Bragard et al., 2019). The availability of grassy meadows and vegetation between the contiguous olive orchards, and the warm climate make the landscape of the olive-producing agroecosystem of Puglia suitable for *Philaenus spumarius* (the main insect vector in the region), and for the spread and establishment of *Xf* (Strona et al., 2017; Bragard et al., 2019). *P. spumarius* is present throughout the olive orchards in the region (Cornara et al., 2018). Moreover, the majority of olive orchards in the affected areas of Puglia contains traditional orchards of the two highly susceptible local cultivars '*Ogliarola salentina*' and '*Cellina di Nardò*' (Bragard et al., 2019). Currently, more than 30 other host plants than olive have been identified in Puglia, for instance almond (*Prunus dulcis*), cherry (*P. avium*), oleander (*Nerium oleander*) and *Acacia saligna* (Saponari et al., 2019a).

Since its first detection in 2013, several control measures have been implemented in Puglia to prevent further introduction and spread of *Xf* including uprooting of trees at infected sites, prohibition of planting of susceptible species, prohibition of transporting plants from the infected areas, and vector control through vegetation removal and chemical applications (Bragard et al., 2019). These measures were defined based on the European Commission Implementing Decisions (EU) 2014/87 and 2015/789 for preventing the introduction into and the spread within the EU of *Xf* (European Commission, 2015). Recently, replanting of partially resistant olive cultivars has been included as one of the control measures following Article 18 of the Commission Implementing Regulation (EU) 2020/1201 (European Commission, 2020). However, the implementation of the measures in Puglia has been limited, mainly due to local oppositions and misinformation campaigns (Saponari et al., 2019a; Almeida, 2016). Saponari et al. (2019a, p.175) stated that "implementation of containment measures encountered serious difficulties, including public reluctance to accept control measures, poor stakeholder cooperation, misinformation from some media outlets, and lack of robust responses by some governmental authorities". Consequently, the size of the infected area has been expanding (Saponari et al., 2019a) and eradication is no longer attempted due to the large size of the affected area, the contiguous nature of olive orchards, the presence of vectors and a wide range of host plants, and the hidden reservoir of symptomless but infectious host plants (Strona et al., 2017; Su et al., 2013). Besides the disease, the control measures themselves affect ES provisioning and biodiversity (e.g. chemical application on biodiversity; removal of ornamental plants on aesthetic values). Despite the large negative consequences of the introduction of *Xf* subsp. *pauca* for ES provisioning, to date, there are no studies on the impact of *Xf* on ES provisioning and biodiversity in Puglia. Taking stock of these impacts provides useful background information on which services need consideration when planning future control measures, considering both the negative impacts of the disease and the control measures against it.

Comprehensive and standardized frameworks for assessing the impact of invasive pests on ES provisioning have recently been developed by the European Food Safety Authority (EFSA) (e.g. Jeger et al., 2018; Gilioli et al., 2017; 2014; EFSA PLH Panel, 2011; 2014). Recently, quantitative pest Environmental Risk Assessment (ERA) models have also been proposed by EFSA (e.g. Jeger et al., 2018). However, quantification on the basis of real world information, e.g. from survey, can be very challenging and time consuming, and the risk exists that a quantification of impacts, based on data collection, would produce information on the impacts with much delay. Therefore, we use here Expert Knowledge Elicitation (EKE) (EFSA, 2014) to obtain a first assessment of impact, along with narratives explaining the nature and size of the impacts. The narratives provide useful information and insights to understand the 'actual' impact on ES provisioning which can serve as a basis for formulating hypotheses for further investigation. In this context, EKE does not substitute for future data collection in the field. Rather, soliciting information from experts allows conducting a first preliminary assessment, which can provide guidance when designing a more rigorous data-based assessment at a later stage. Furthermore, such preliminary assessment can play a role in current decision making on planning of control operations.

In the light of the foregoing, the objective of this study was to estimate the impacts of *Xf* subsp. *pauca* and the control measures against it on ES provisioning and biodiversity in the olive-producing agroecosystem of Puglia at a landscape level.

2. Materials and methods

The following sections present the ERA framework, assumptions for the impact assessment and the procedures followed in the EKE.

2.1. The pest environmental risk assessment framework

We adapted the EFSA qualitative framework (EFSA PLH Panel, 2011; 2014) to apply it to the case of *Xf* (Fig. 1). We used EKE for identifying the affected ES and the associated *service providing units* (e.g. species, functional groups, communities, ecosystems), and for quantifying the impacts (EFSA, 2014). The framework in Fig. 1 accounts for the efficacy and side-effects of control measures when conducting the impact assessment. Large scale vector control is key for reducing the impact of *Xf* (Bragard et al., 2019). Compulsory control measures, based on integrated pest management, have been practiced in the area under the supervision of the Phytosanitary Service of the Puglia Region (EFSA PLH Panel, 2015). These control measures include:

- Pruning and uprooting: at least every two years olive orchards must be pruned, and shoots/branches with early symptoms must be removed while heavily symptomatic plants must be uprooted.
- Applications of insecticides to control the main vector.
- Removal of vegetation cover that may host nymphs of the vector via mowing/tilling or herbicides. The removal of the host of the vector within the olive orchards reduces the abundance of *P. spumarius.*
- Replantation of partially resistant cultivars in affected areas (long-term strategy).
- Other measures: prohibition of transportation of the mown weeds; prohibition of production and marketing of susceptible propagation material of plants in the affected areas.

2.2. Assumptions for the impact assessment

The following scenario assumptions were made for the assessment.

- The entry, spread and establishment of *Xf* subsp. *pauca* have already occurred in Puglia. The EFSA PLH Panel (2015) concluded that "it is very likely, with low uncertainty, that the routine pest control strategies in the infected area are not effective enough to control the spread of *Xf*". For this ERA, we considered a landscape with an average land use for this region, and planted with susceptible cultivars of olive (e.g. '*Ogliarola salentina*') and more tolerant (e.g. '*Leccino*'). The prevalence of the disease (proportion of affected fields, proportion of affected trees in affected fields) is assumed to have reached the maximum typical for this region (i.e. the infected zone in the Salento peninsula, Fig. 2). The parts of Puglia where *Xf* is still spreading were not considered in the present study.
- This assessment was done at a landscape level, and considers the impact of the disease on the olive groves and their embedding landscape (e.g. other agricultural land use such as almond and cherry orchards as well as semi-natural habitats such as forest or grassland). Thus, we consider all the land used for farming as well as the surrounding uncultivated land, atmosphere, underlying soils, groundwater, vegetation and wildlife.
- The impacts were assessed for two time horizons (short- and long term). The short-term assessment considers impacts when the disease has been in the area for long enough to cause a maximum impact (e.

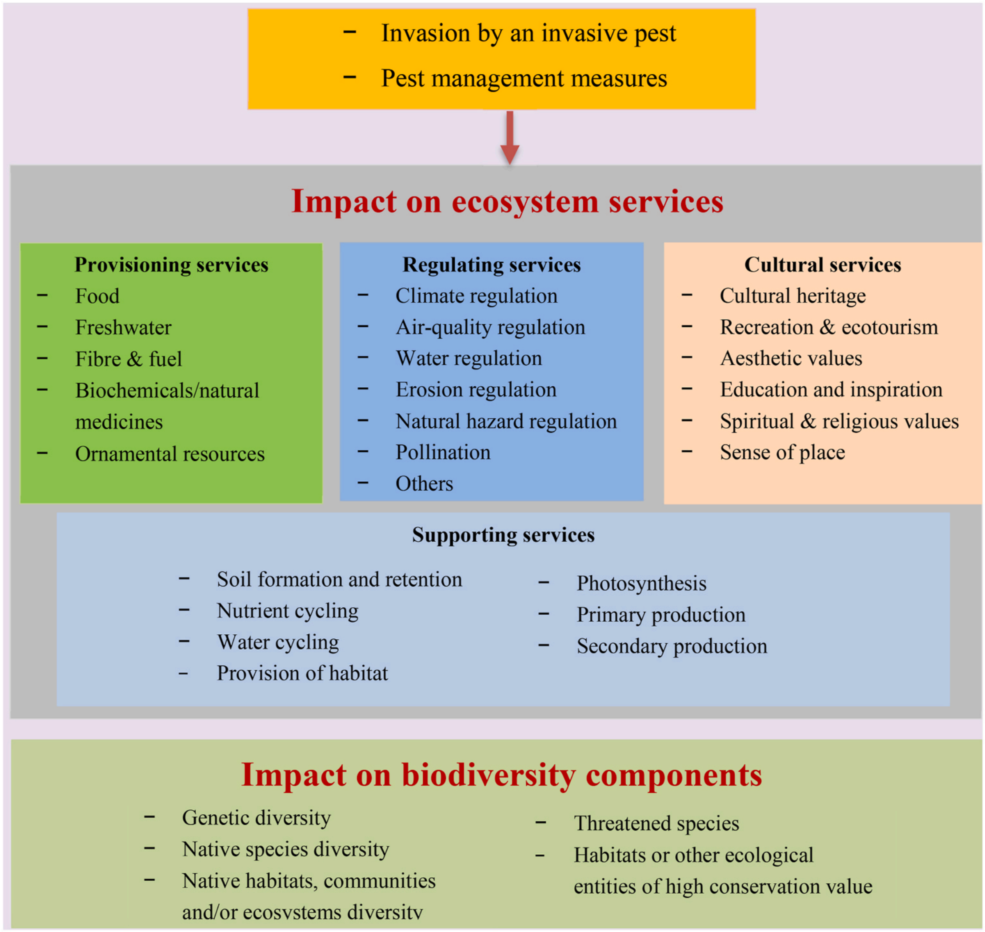

Fig. 1. Impacts of invasive pests and their control measures on ES and biodiversity. Adapted from MEA (2005).

g. 10 years after the establishment of *Xf*). It takes up to four years after inoculation for olive trees to have a 95% chance of developing the symptoms of *Xf* infection (Bragard et al., 2019). In the short term, the impact depends on the *resistance* of the ecosystem, and the efficacy and side-effects of control measures. The long term assessment considers the period after the ecosystems and human land users have had time to adapt to the new situation, for instance, by planting other more tolerant or resistant olive cultivars or alternative crops that are less vulnerable to the disease (e.g. 30 years after *Xf* establishment). In the long term, the *resilience* of the agroecosystem plays an important role for the ecosystem to stabilise and reach an equilibrium (Gilioli et al., 2014). Factors such as occurrence and establishment of natural enemies to the pathogen and its vector, and the expected (better) management measures (e.g. replantation of resistant cultivars) could potentially reduce impacts in the long-term compared to the short-term effects.

2.3. Expert knowledge elicitation

EKE was used to assess the short- and long term impacts in this ERA. EKE is a suitable method to conduct a first impact assessment based on ES provisioning, which can serve as a basis for formulating hypotheses for further scrutiny (EFSA, 2014). Six experts were identified for in depth interview (see *Supplementary Material A* for the list of experts and their areas of expertise).[1] First, the experts received a document providing general information on the scope of the ERA, by describing briefly the organism, the assessment area, and the scenario assumptions. The document also included a questionnaire, definitions of the different ES and a glossary of terms.[2] Next, the EKE was conducted in three steps.

Step 1: One-to-one Skype Interview (1.15 h). Each expert was asked to identify the affected ESs and biodiversity components from a long-list of ESs and biodiversity components (MEA, 2005) that might potentially be affected by *Xf* and the control measures. In order to identify the affected ESs (and biodiversity components), the experts were asked the question 'Do *Xf* subsp. *pauca* and the control measures against it negatively affect the flow of a given ES (biodiversity component) in the olive-producing agroecosystem of Puglia in the short- and long-term?'. They also explained how the disease and the control measures affect the

[1] Some of the ecosystem services elicited such as climate and air quality regulation, and soil formation and retention may have been out of the fields of expertise of the panellists at the time we consulted them. However, the narratives behind the estimated impact scores still provide useful information and insights to understand the 'actual' impact on provisioning of these services which can serve as a basis for formulating hypotheses for further investigation. Moreover, we have substantiated the estimated impact scores with available literature sources.

[2] The document including the questionnaire can be obtained on request from the authors.

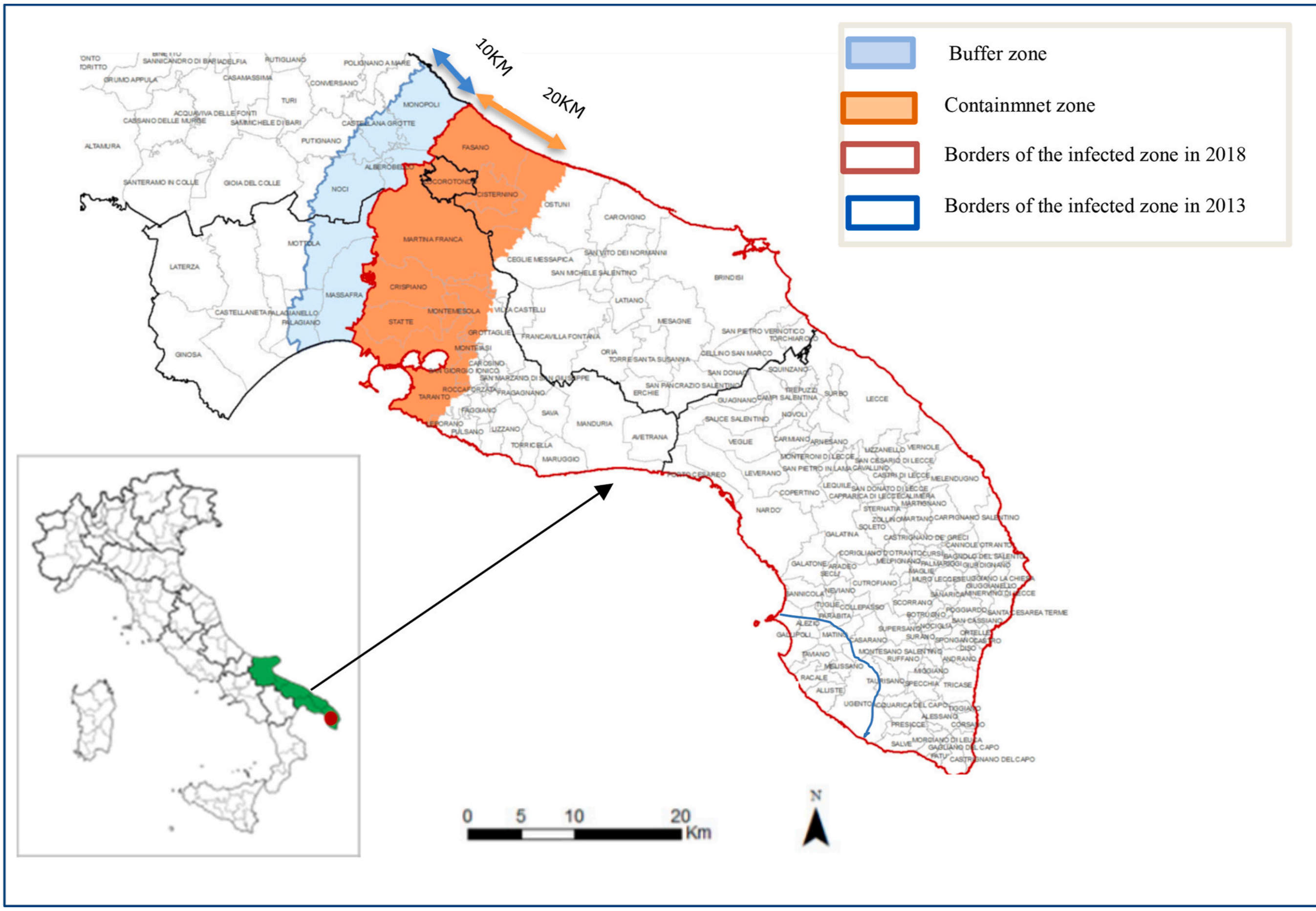

Fig. 2. Territories included in the three components of the demarcated area in Puglia after the August 2018 update. The red dot in the lower left map of Italy shows the Salento Peninsula, where *Xf* was first detected in 2013, in Puglia (green). Map by Maria Saponari. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

delivery of a given ES or biodiversity component by specifying the affected *service providing units* (e.g. species, communities, ecosystems, functional groups) that are responsible for the delivery of the affected ES (biodiversity components).

Step 2: Joint Skype Workshop (4 h). For a typically affected ecosystem, the experts were asked to quantify the reduction (in terms of percentage change) in the provisioning of each ES and biodiversity component due to *Xf* and the control measures. Impacts were quantified on a scale of 0 (no impact) to 100 (complete loss of a service or biodiversity component). The experts provided the minimum, maximum, and most likely impact first individually and then as a group after in depth discussion of motivation of differences in individual impact estimates to reach consensus on a group estimate. The individual estimates were derived by considering the situation in the infected zone as stated in *Section 2.2*. However, during the joint workshop, the experts agreed to derive the group estimates by considering the situation in the demarcated area. The demarcated area consists of two zones (Fig. 2): (i) infected zone (the area where most of the olive trees are severely affected by the disease), and (ii) buffer zone (the area without infected trees, which is targeted for surveillance to detect and if possible prevent any further expansion of the infected area). The infected zone also includes a containment zone[3] (the area where a few scattered trees are infected). The infected zone is by far the largest of the two zones of the demarcated area, covering altogether approximately 715,000 ha, i.e., 36% of the Puglia region in 2018 (Saponari et al., 2019a). The agreed definition allowed the experts to have a common understanding of the area of assessment for quantifying the impacts and to reach consensus on the group estimate.

For both the average and group estimates, the three-parameter estimates (i.e. minimum, maximum and mode) were used to fit a PERT[4] distribution using @Risk (Palisade Corporation, Ithaca, NY, USA), an add-in for MicroSoft Excel. The fitted PERT distribution is a scaled beta distribution such that the elicited minimum and maximum values as well the location of the mode correspond to the elicited values for the minimum, maximum and mode. The distributions for the average estimates were obtained in two steps from the individual estimates: (i) computation of the average values for the minimum, maximum and mode from the individual estimates of the six experts, and then (ii) derivation of the PERT distribution using these average values. By doing so, the variation among the individual estimates were not considered when deriving the distributions for the average estimates (i.e.

[3] Although control measures such as removal of infected trees and mandatory vector control are required to be implemented in the containment zone to contain the disease, the implementation of these measures was limited (Saponari et al., 2019a).

[4] A PERT distribution is a continuous probability distribution defined by the minimum (a), most likely (b) and maximum (c) values of a variable. It is a transformed beta-distribution with expected value of $(a+4b+c)/6$ and standard deviation of $(c-a)/6$. The distribution is fitted such that the minimum and maximum values are directly used as the lower and upper ends of the domain. Unlike a triangular distribution, which is also defined by the three parameters, a PERT distribution has a smooth shape.

uncertainties resulting from the differences in estimates of the individual experts were not included). The distributions derived from the group estimates (i.e. the estimates agreed in consensus during the joint workshop) were used for reporting the estimated reductions in the flow of ES and biodiversity components.

Step 3: Weight elicitation (by email). The reduction in the provisioning of each ES does not equally affect the 'multifunctionality' of the ecosystem since some ES could be more important than others (e.g. food provision is assigned greater importance in olive groves than freshwater). The experts were asked to divide 100 points among the four ES categories (provisioning, regulating, supporting and cultural) according to their importance in the region. Similarly, they were asked to divide 100 points among ES within each ES category, and among biodiversity components. More points allocated to an ES indicated greater importance of the particular ES to the region. The average weights were used for computing a weighted average percentage reduction in the flow of ES, and biodiversity components. *Supplementary Material B* presents the results of the weight elicitation.

The numerical results of the impact estimations are summarised in tables while the underlying justification for the elicited values is documented with narratives. The narratives provide useful information and insights to understand the 'actual' impact of the epidemic beyond what can be captured in the numerical values of percentage losses. The narratives are discussed in relation to the available literature. The assessment results are presented first for ES and then for biodiversity.

3. Results and discussion

3.1. Impact on the flow of ecosystem services

The EKE shows major impacts of the invasion of *Xf* subsp. *pauca* on the delivery of ES in Puglia (*Supplementary Material C*, Table S.C1). One of the experts indicated that "a simple aerial picture of the landscape from the infected zone in Salento (e.g. Fig. 3, Fig. 4) can effectively demonstrate the devastating impacts of the disease on olive cultivation, Mediterranean shrub vegetation, and the associated ecosystem". He described the impact as "no more millenarian or centenarian monumental olive trees are alive in the Salento area, with a "global" effect on the entire agroecosystem". "The concrete risk is that all the Puglia and Southern Italy areas in which olive is cultivated could be completely destroyed". It was stated that currently, "the control measures are not applied as they should be applied". According to one of the experts, there is a long delay in the application of the measures against the infected plants (e.g. tree felling) and the vector, due to the bureaucratic delays in obtaining the required documentation from the regional government for applying these measures. It takes up to a year, for example,

Fig. 3. Aerial view of *Xf* subsp. *pauca* affected olive-producing landscape in Puglia (A, B); *Polygala myrtifolia* at an early stage of invasion (C); Olive trees at an early stage of invasion (D) and the same trees died due to the invasion (E). Photo: (A) by Franco Nigro and the rest by Donato Boscia.

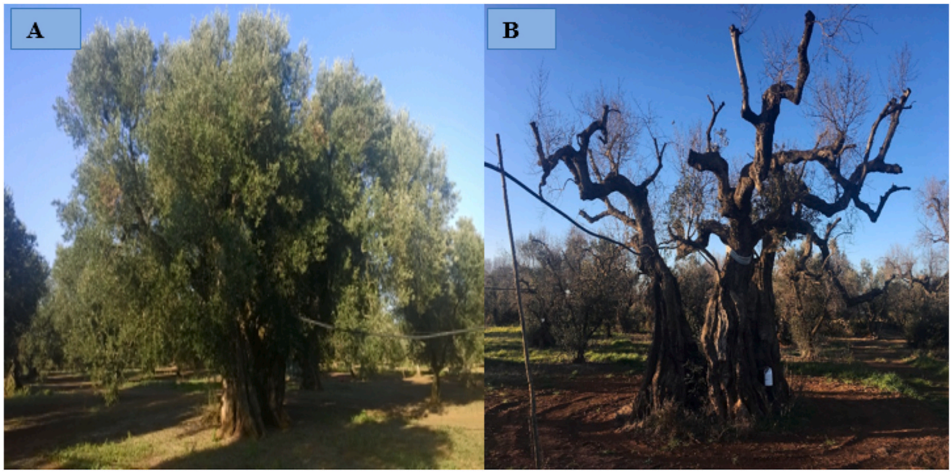

Fig. 4. Picture of *Giant of Alliste,* before (A) and after (B) the *Xf* invasion (Photo: Donato Boscia).

to uproot an infected tree while the bacterium could spread to other trees in the meantime, according to the expert. Saponari et al. (2019a, p.175) also stated that "implementation of containment measures encountered serious difficulties, including public reluctance to accept control measures, poor stakeholder cooperation, misinformation from some media outlets, and lack of robust responses by some governmental authorities". Furthermore, the reluctance of political leaders (at EU, national and local levels) to quickly act to implement control measures (including a lack of local political support for scientists) was a key reason for the lack of substantial action in controlling the devastating impact of the disease (Almeida, 2016).

The experts noted that the negative impacts on ES provisioning (and biodiversity) are mainly due to the disease, rather than due to the control measures such as chemical pesticides, weeding and pruning. The impact of control measures is rated as negligible as their application in the demarcated area is not different from the standard practices in the non-affected areas. The experts expressed the difficulty (and uncertainty) of predicting the future management of the landscape, which will influence the long-term impacts. Consequently, uncertainties associated with the long-term impact estimates are higher than the uncertainties associated with the short-term estimates. Moreover, the results show that the group estimates are lower than the average of individual estimates for most ES (and biodiversity components), for two reasons. First, there is a difference in the area of assessment. As described in *Section 2.3*, the individual estimates are derived by considering the situation in the infected zone whereas the group estimates are derived by considering the situation in the entire demarcated area which includes also the buffer zone (light blue in Fig. 2). Although the infected zone is the main component of the demarcated area with most infected trees, the consideration of the buffer zone (which is without infected trees) lowers the values of the group estimates (compared to the individual estimates). Second, during the joint workshop, the experts with a low estimate of the impact convinced their fellow experts of their point of view (e.g. by citing the potential of resistant cultivars for mitigating impact in the long term and clarifying the effect of variation in the proportion of infected trees across the infected zone on the impact). In the subsequent sections, the impacts on each ES are described.

3.1.1. Impact on provisioning services

Food. Table olive and olive oil production are expected to decline due to a reduction in the quantity and quality of fruits following the death, dieback and delayed growth of olive trees, and the prohibition of planting of susceptible varieties. Replantation of partially resistant olive cultivars is one of the most promising strategies to reduce the long-term impact (Abou Kubaa et al., 2019; Saponari et al., 2019b). However, it also results in a short term reduction in food provisioning due to the non- and less-productive periods of newly planted perennial crops. It requires up to 20 years in traditional and 5–8 years in intensive farming systems with irrigation for newly planted olive trees to become fully productive (Bragard et al., 2019). As one of the experts indicated, replanting of (resistant) olives is not anymore feasible in the rocky (hilly) areas of Puglia. Moreover, replanting of resistant cultivars may result in genetic uniformity that makes the cultivars susceptible to other pests/diseases, according to one of the experts.

Food production by other susceptible crop species is not directly affected in the demarcated area since these crops are hardly grown there. Only very few almond (and cherry) trees are grown within the presently affected area and only in scattered places. Yet, as one of the experts indicated, with the current *Xf* management practices, the disease could spread further north and establish in the main sweet cherry and almond producing areas of Puglia. Another expert also said that "unless the spread and further introduction of *Xf* is contained in the Salento peninsula [Fig. 2], the disease could have a huge impact on sweet cherry production in the northern part of Puglia where about 20,000 ha of cherry production is located". The experts also cited the indirect impact of the prohibition of plantation of host crops in the demarcated area on food provision. Food provision is (group) estimated to diminish by about 43% and 51% in the short- and long term, respectively (Table 1). The corresponding median losses are about 44% and 51%, respectively. Bragard et al. (2019) estimated a median olive yield loss, at EU level, of 35% for trees younger than 30 years and 69% for older trees.

Ornamental resources. All experts indicated that the disease poses a very serious threat to ornamental resources. To demonstrate the extent of the problem, one of the experts cited a case reported in a local newspaper that *Xf* has invaded a city-square in Lecce with oleander (*Nerium oleander*). The disease is also causing problems in private gardening. Host species that are grown as ornamental plants in the region, and some of which are severely affected, include oleander, *Acacia saligna*, rosemary (*Rosmarinus officinalis*), lavender (*Lavandula*), broom (*Spartium junceum*), *Eugenia myrtifolia*, *Polygala myrtifolia* and many other Mediterranean shrubby species. Besides the direct impact of the disease, control measures (e.g. weeding and prohibition of planting) are affecting the existence and planting of these host plants. For example, oleander is being destroyed from along the road-sides to prevent the possible spread of *Xf* along roads. The experts also noted that *Xf* has caused major impacts on the nursery market for ornamental plants following the prohibition of planting and "the prohibition of commercialisation from nurseries in the demarcated areas". The provisioning of ornamental resources is estimated to diminish by about 38% and 37% in the short- and long term, respectively (Table 1).

Freshwater, fibre and fuel, and *biochemicals/natural medicines* are the less important provisioning services in the region according to the

Table 1
Percentage reduction in the delivery of provisioning services in the olive-producing agro-ecosystem of Puglia due to the invasion of *Xf* subsp. *pauca*[a].

Provisioning services	Short-term estimates				Long-term estimates			
	Average		Group		Average		Group	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Food (olive oil and table olive)	48.1	6.0	43.3	7.5	57.8	6.6	50.8	10.4
Ornamental resources	35.0	4.2	38.0	5.6	54.7	6.2	36.7	10.2
Provisioning services (overall)	34.7	3.1	32.2	3.8	49.6	3.6	36.3	5.8

[a] Simulated results of the PERT-fitted distributions using @Risk, with 1000 iterations.

elicitation of weights (*Supplementary Material B,* Table S.B1). The narratives underlying the expert judgement for these services are provided in *Supplementary Material D*.

Overall impact on provisioning services. Based on the average weights assigned by the experts to each provisioning service (*Supplementary Material B,* Table S.B1), the expected (weighted average) reduction in the flow of provisioning services is about 32% in the short term and 36% in the long term. This is mainly due to the impact of the disease on the provision of food and ornamental resources.

3.1.2. Impact on regulating services

Climate regulation. Olive trees are the main woody plant cover in the demarcated area. According to the experts, the loss of these olive trees and their canopies results in an increase in soil temperature and evaporation, and a decrease in CO_2 sequestration. The experts indicated that the loss of foliage cover would result in an increase in temperature, and decrease in precipitation at a regional level. A loss of one century-old tree leads to a reduction in CO_2 sequestration of about 2600 kg CO_2 (Semeraro et al., 2019). Moreover, the dead olive tree stands are vulnerable to fire (as stated below under '*natural hazard regulation*'), which would release carbon into the atmosphere (Cheatham et al., 2009). The average estimates are greater than the group estimates (Table 2, see the reasons in *Section 3.1*). Climate regulation is estimated to diminish by about 8% and 22% in the short- and long term, respectively. Semeraro et al. (2019) estimated a medium negative impact on climate regulation (using a three point scale: low, medium and strong negative impact) following the loss of urban olive forests in Puglia due to the *Xf* invasion. The authors also noted that the negative impacts can be minimised in the long term through replanting of other arboreal plants.

Air quality regulation. The loss of olive trees and their canopies reduces the capacity of the ecosystem to purify the air "by producing new oxygen and by trapping small particles (dust) from the atmosphere". Moreover, the rise in temperature and evaporation, and reduction in precipitation (as stated above) reduce air quality. The impact of the chemical control measures on air quality was rated as negligible by the experts. The long term average estimates are more than twice the group estimates (Table 2, see the reasons in *Section 3.1*). Air quality regulation is expected to diminish by about 15% and 16% in the short- and long term, respectively. Semeraro et al. (2019) estimated a strong negative impact on air quality (gas) regulation following the loss of urban olive forests in Puglia due to the *Xf* invasion.

Erosion regulation. Soils in the demarcated area are vulnerable to erosion due to the hilliness of the region and the low organic matter content of the soil. Soil erosion by wind and water is expected to increase following the death of olive trees and associated vegetation growing under the cover of the trees. As one of the experts stated, in areas where olive trees are dying, other vegetation (e.g. weeds) are also dying due to lack of shade from the olive tree canopies that would normally stabilise air and soil temperature in the olive groves. The loss of soil cover increases the risk of erosion and loss of organic matter, and the problem is aggravated by other stressors (e.g. fire). Erosion regulation is expected to diminish by about 30% and 19% in the short- and long term, respectively (Table 2). The long-term impact is lower (than the short-term impact) since the experts expect that the landscape will be managed with olive or other tree plants that are less vulnerable to the disease. However, one of the experts noted that replanting of (resistant) olive or other trees is not feasible (at least very difficult) in the hilly areas.

Natural hazard regulation. The loss of plants exposes the landscape to natural hazards like flooding and wildfire. Many farmers started abandoning their olive orchards due to the drop in olive production as a result of *Xf*. The abandoned orchards contain dried vegetation (e.g. weeds) that increase the risk of fire (e.g. even from a "dropped smoked cigarette" as stated by one of the experts). On average, natural hazard regulation is estimated to diminish by about 30% and 13% in the short- and long term, respectively (Table 2). The experts expect the long term impact to be lower than the short term impact due to the fact that the risk of natural hazard will be less both in the case of an abandoned landscape (without olive or other woody plants) and a well-managed landscape (with olive and/or other forest trees).

Pollination. Although the flowers of olives do not require pollination by insects as many olive varieties are self-fertile and wind-pollinated, the loss of olive trees and other vegetation indirectly affects pollination since the olive flowers and associated vegetation are important sources of resources for the pollinator community (insects). The loss of pollinators following the loss in land cover affects the pollination of Mediterranean shrubs and other species. The experts also noted that the prohibition of planting of susceptible varieties may result in the planting of the partially-resistant cultivar '*Leccino*', which is not self-fertile for wind-pollination. Pollination is estimated to diminish by about 21% and 12% in the short- and long term, respectively (Table 2). The long term impacts are expected to be lower than the short term impacts since the experts expect the landscape to be managed with some other resistant plants.

Water regulation, *pest/disease regulation*, *invasion resistance*, and *water purification/soil remediation/waste treatment/decomposition* are the less important regulating services in the region according to the weight elicitation results (*Supplementary Material B,* Table S.B2). The narratives

Table 2
Percentage reduction in the provision of regulating services due to *Xf* subsp. *pauca*[a].

Regulating services	Short-term				Long-term			
	Average		Group		Average		Group	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Climate regulation	13.9	2.2	8.0	1.7	30.0	4.6	21.7	5.5
Air quality regulation	14.9	2.0	15.0	1.9	37.8	4.1	15.8	7.3
Erosion regulation	24.4	3.0	30.0	3.8	45.2	5.9	19.2	7.9
Natural hazard regulation	30.7	4.5	30.0	3.8	59.2	4.1	12.5	4.3
Pollination	26.6	4.5	20.8	6.6	37.0	6.5	11.7	3.6
Regulating services (overall)	25.5	1.2	20.3	1.3	42.5	2.0	16.0	2.4

[a] Simulated results of the PERT-fitted distributions using @Risk, with 1000 iterations.

underlying the expert judgement for these services are provided in *Supplementary Material D*.

Overall impact on regulating services. Based on the average weights assigned to each regulating service (*Supplementary Material B,* Table S.B2), the flow of regulating services is expected to diminish by about 20% and 16% in the short- and long term, respectively. This reduction is mainly due to the impact of *Xf* on the regulation of erosion and natural hazards.

3.1.3. Impact on supporting services

Soil formation and retention. The experts noted that olive trees are the only common woody plant in the affected area and an important source of litter that will turn into soil organic matter. The trees also serve as a reservoir of nutrients and carbon. Since soil formation is a long-term process, the disease does not affect soil formation and retention in the short-term. The long-term impact is through limiting the availability of litter (leaves and organic residues), lack of protection from stressors (e.g. heat), and a decline in soil microbial communities. The loss of other plant species (e.g. *Acacia saligna* that grows on the rocky soils along the coast) also affects soil formation. Moreover, vegetation cover (e.g. weeds) and soil fauna are negatively affected in areas where olive trees are dying due to lack of shade from the olive canopies that stabilise soil temperature and water availability. Soil formation and retention are estimated to diminish by about 12% in the long term (Table 3). Semeraro et al. (2019) also estimated a low negative impact on provisioning of soil formation and retention services following the loss of urban olive forests in Puglia due to the *Xf* invasion. The authors also noted these negative impacts can be minimised in the long term through replanting of other arboreal trees.

Provision of habitat. The experts estimated that *Xf* reduces the area of wildlife habitats such as cultivated crops (e.g. olives), Mediterranean and wild plant species. The loss of affected habitat (olive groves, Mediterranean wild vegetation) will negatively affect "all small animals, fauna, birds, foxes, insects, and microbial communities living with or within the olive trees [and other vegetation]" as summarised by one of the experts. On average, provision of habitats is estimated to diminish by about 27% and 32% in the short- and long term, respectively (Table 3).

Photosynthesis. A negative impact is expected on the overall photosynthetic CO_2 assimilation realized in the area due to the loss of olive trees, which are the main woody plant in the region. The density of (olive) trees is declining following the invasion, and the prohibition of plantation of susceptible crops (e.g. olive, cherry and almond). The decline of other wild plants such as the Mediterranean shrubs also affects photosynthesis. According to one of the experts there is a high risk that the disease could spread to the Atlantic side of the Salento peninsula, which may affect vegetation in the region and thereby impact photosynthesis as well. On average, photosynthesis is estimated to diminish by about 30% and 20% in the short- and long term, respectively (Table 3). The estimated long term impacts are lower than the short term impacts since the experts expect that the ecosystem and human land users will adapt, for example, by planting resistant olive cultivars or other less vulnerable crops or forest trees.

Primary production. The production of biomass declines since the main plant communities in the region (i.e. olive and Mediterranean shrubs) are affected by the disease. The prohibition of replanting of host plants of *Xf* also reduces primary production. Primary production is expected to diminish by about 30% in the short term and 28% in the long term (Table 3). The estimated long-term impacts are slightly lower than the short-term impacts since the experts expect that the landscape will be planted with resistant olive-varieties or other less vulnerable tree crops or forest trees in the future.

Nutrient cycling, water cycling and *secondary production* are the less important supporting services in the region according to the weight elicitation results (*Supplementary Material B,* Table S.B3). The narratives underlying the expert judgement for these services are provided in *Supplementary Material D*.

Overall impact on supporting ***services***. Based on the elicited weights (*Supplementary Material B,* Table S.B3), the flow of supporting services is estimated to diminish by about 21%. This is mainly attributed to the impact of the invasion on photosynthesis and primary production.

3.1.4. Impact on cultural services

Xf has caused major impacts on cultural services (*Supplementary Material C,* Table S.C1). Most of the control measures (e.g. insecticides and herbicides, weeding, pruning) do not affect cultural services according to the experts. Although the experts indicated that tree felling has caused an immediate devastating impact on cultural heritage, it should be noted that the trees surrounding infected trees will anyway die in the course of time due to the spread of the disease. Moreover, the implementation of tree felling was extremely limited in Puglia (Almeida, 2016).

Cultural heritage. Almeida (2016, *p.* 347) stated that "… The disease is killing irreplaceable trees, including those planted to mark the births of family members for generations. The harm to Apulian culture [cultural heritage] and society is perhaps beyond quantification". The ancient monumental trees are the symbol of Puglia, and represent the cultural and natural heritages of the region (Saponari et al., 2019a). The loss of these irreplaceable trees, has a devastating impact on cultural heritage. One of the experts described the impact as "… no more centenarian or millenarian monumental olive trees are alive in the Salento area, with a "global" effect on the entire agroecosystem". ***Giant of Alliste*** (Fig. 4), one of the oldest olive trees in the Mediterranean basin (about 1500 years old as claimed by the locals), which is the tree-symbol of Salento, has also died due to the disease. Besides, other cultural heritage linked with olive farming could be lost. According to one of the experts, "the traditional olive tree management techniques (e.g. manual pruning of a 12-m olive tree) could be lost with the loss of the big old trees". Moreover, "the typical small stone-walls around olive orchards" could also be lost in the future. Cultural heritage is estimated to diminish by 62% and 63% in the short- and long term, respectively (Table 4).

Recreation and ecotourism. Olive farming is highly linked with tourism. The olive-dominated landscape is a key attraction in Puglia (Almeida, 2016). Tourists use the shade of olive trees while camping. The loss of attractions (e.g. cultural heritage and ornamentals) following the invasion reduces opportunities for recreation and ecotourism. One of the experts stated that "the landscape is not anymore green; it is

Table 3
Percentage reduction in the provision of supporting services due to *Xf* subsp. *pauca*[a].

Supporting services	Short-term				Long-term			
	Average		Group		Average		Group	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Soil formation and retention	–	–	–	–	41.8	5.0	11.7	3.6
Provision of habitat	22.7	2.4	26.7	3.6	41.3	4.5	31.7	5.5
Photosynthesis	28.8	4.6	30.0	3.8	46.3	5.9	20.0	3.8
Primary production	33.5	3.8	30.0	3.8	53.5	4.9	27.5	6.3
Supporting services (overall)	27.0	1.5	21.0	1.4	46.6	2.2	21.3	2.1

[a] Simulated results of the PERT-fitted distributions using @Risk, with 1000 iterations.

Table 4
Percentage reduction in the provision of cultural services due to *Xf* subsp. *pauca* invasion[a].

Cultural services	Short-term				Long-term			
	Average		Group		Average		Group	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Cultural heritage	50.9	4.0	61.7	5.5	75.5	3.1	63.3	5.5
Recreation and ecotourism	50.3	3.4	51.7	5.5	78.8	4.8	31.7	5.5
Aesthetic values	62.2	2.0	61.7	5.5	80.8	5.5	50.0	3.8
Cultural services (overall)	51.4	1.5	56.7	2.4	73.5	1.9	44.7	2.2

[a] Simulated results of the PERT-fitted distributions using @Risk, with 1000 iterations.

converting into a desert". The businesses of a lot of farm houses in the countryside that are used by tourists are also affected. The provisioning of these services is expected to diminish by about 52% and 32% in the short- and long term, respectively (Table 4). The long term impact is expected to be lower since the experts expect that the ecosystem and human land users will adapt, for example, by planting resistant olive cultivars or other less vulnerable crops/trees. Semeraro et al. (2019) also estimated a strong negative impact on provisioning of recreation and ecotourism services following the loss of urban olive forests in Puglia due to the *Xf* invasion.

Aesthetic values. As olive trees are a major source of aesthetics in the region, *Xf* impairs the provision of aesthetic values. An expert stated that "each olive tree represents a single element for the attractiveness of the landscape". A pruned olive tree looks like a "*cylinder in the sky*", as he expressed. The invasion has reduced the attractiveness of the landscape. The impact on ornamental resources also reduces the beauty of the region. An expert said, "*Acacia saligna,* a beautiful plant along the sea coast is affected by the disease, which reduces the aesthetic value of the surrounding area". One of the experts also indicated that the epidemic may reduce the demand for country houses, which are part of the aesthetics of the region. The experts expect a 62% and 50% reduction in the aesthetic values in the short- and long term, respectively (Table 4). The long term estimates are lower than the short term estimates since the experts expect that the landscape will be managed in such a way that the aesthetic values are restored with other woody plants or resistant-olive cultivars. Semeraro et al. (2019) also estimated a strong negative impact on aesthetic values following the loss of urban olive forests in Puglia due to the *Xf* invasion.

Education and inspiration, spiritual and religious values, and *sense of place* are the less important cultural services in the region according to the weight elicitation results (*Supplementary Material B,* Table S.B4). The narratives of the expert judgement for these services are presented in *Supplementary Material D*.

Overall impact on cultural services. Based on the average weights of each service (*Supplementary Material B,* Table S.B4), the delivery of cultural services was estimated to diminish by about 57% and 45% in the short- and long term, respectively (Table 5); mainly due to the impact on cultural heritage, recreation and ecotourism, and aesthetic values.

Overall impact on ES. Fig. 5 summarizes the short term impact estimates for the different ES. Then, based on the average weights assigned by the experts for the four ES categories (*Supplementary Material B,* Table S.B5), the overall impact on ES was derived. The delivery of ES is estimated to diminish, on average, by about 34% and 30% in the short- and long term, respectively, mainly due to the impact of *Xf* on provisioning and cultural services. Modelling works based on satellite data also showed a direct (negative) relationship between the change in the incidence of the disease (i.e. *Xf*) and the rate of change in vegetation cover of olive orchards in Puglia between 2016 and 2017 (Hornero et al., 2020). Similarly, Poblete et al. (2020) and Zarco-Tejada et al. (2018) reported a major negative impact of *Xf* on tree cover and transpiration at landscape levels in Puglia, based on remote sensing models. Although these studies do not provide a full quantification of the impacts of *Xf* on ES provisioning, they make it clear that the impacts are major and detectable with satellites. As it has been described before, the loss of vegetation (mainly olive trees) impairs the provision of several ES.

Table 5
Percentage reduction in biodiversity components due to *Xf* subsp. *pauca* invasion[a].

iodiversity components	Short-term				Long-term			
	Average		Group		Average		Group	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Genetic diversity	32.1	3.5	23.3	3.6	46.2	4.9	20.0	3.8
Native habitats, communities and ecosystems diversity	40.2	3.8	35.0	3.8	55.5	6.5	31.7	3.6
Habitats of high conservation value	45.7	3.6	41.7	3.6	70.6	5.7	46.7	3.6
Biodiversity components (overall)	37.7	1.7	27.8	1.7	54.2	2.8	28.3	1.7

[a] Simulated results of the PERT-fitted distributions using @Risk, with 1000 iterations.

3.2. Impact on biodiversity components

Xf is also affecting biodiversity components in the region (*Supplementary Material C,* Table S.C2). Here also the results of the impact estimations are presented in the form of tables and illustrated with narratives. The results of the impact estimation show that the group estimates are lower than the average estimates for the same reasons stated in *Section 3.1*.

Genetic diversity. The invasion is expected to reduce the genetic diversity of olives following the loss of susceptible cultivars (e.g. '*Ogliarola salentina*' and '*Cellina di Nardò*'). According to one of the experts, other olive varieties that were introduced in the region to improve the quality of oil are also affected by the disease. The experts indicated that the possibility of introducing new olive varieties is restricted by the disease at the moment. A decline in genetic diversity is also expected, at least in short term, for cherry, almond and the Mediterranean shrubs such as oleander, broom, curry plant, rosemary and other wild host plants due to the prohibition of planting susceptible species and the direct impact of the invasion. Consequently, "all small animals, fauna, birds, insects, and microbial communities living with or within the olive trees (and the other vegetation)" could be negatively affected according to one of the experts. The long term impact depends on the future management of the landscape. Genetic diversity is estimated to diminish by about 23% in the short term and 20% in the long term (Table 5). The introduction of new or resistant crops is expected to mitigate the impact of the disease on genetic diversity in the long term. However, one of the experts noted that replanting of resistant olive cultivars may result in 'genetic uniformity'.

Composition and structure of native habitats, communities and ecosystems. According to one of the experts "the native olive agro-ecosystem, and the olive growers living in the area, as well as the surrounding Mediterranean shrublands" are affected. One of the experts stated that some animal species that depend on olive (e.g. Sardinian sparrow (*Passer hispagnolensis*), a bird that resides on olive trees during winter) might disappear from the region. The death of olive trees and Mediterranean shrubs, and the restriction on planting host plants are expected to result in a change in the landscape. One of the experts stated that "the densities, varieties and management of olives" are affected. The loss of olive could result in a completely different economic activity

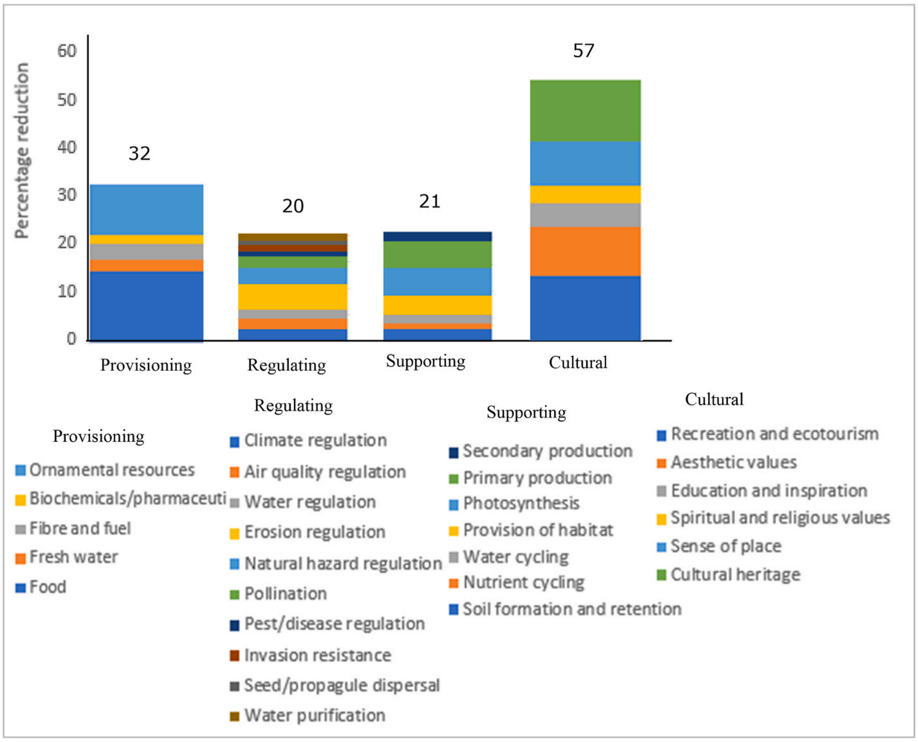

Fig. 5. Estimated short-term percentage reduction in ES provisioning due to *Xf* subsp. *pauca*.

(e.g. cereal production or forestry systems), which results in a loss of the current landscape. The gardening and landscaping are also expected to change since monumental trees and ornamental species are affected. On average, this biodiversity component is estimated to diminish by about 35% and 32% in the short- and long term, respectively (Table 5).

Habitats or other ecological entities of high conservation value. According to the experts, *Xf* is affecting habitats of high conservation values such as the *Plain of the Monumental Olive Trees*, which is a world heritage site in Puglia. As stated by one of the experts "there are no more alive millenarian/centenarian monumental olive trees in the Salento area, with a "global" effect on the entire agroecosystem". One of the oldest olive trees in the Mediterranean basin, *Giant of Alliste*, has also died due to *Xf* (Fig. 4). Habitats of high conservation values are estimated to diminish by about 42% and 47% in the short- and long term, respectively (Table 5).

Native species diversity and *threatened native species* are the less important biodiversity components in the region according to the weight elicitation (*Supplementary Material B,* Table S.B6). Assessments and narratives for these components are provided in *Supplementary Material C*.

Overall impact on biodiversity. Using the average weight of each component (*Supplementary Material B,* Table S.B6), biodiversity components were estimated to diminish, on average, by about 28%, mainly through the impact of the disease on genetic diversity and habitats of high conservation value.

4. Conclusions

Xylella fastidiosa subsp. *pauca* caused the *olive quick decline syndrome* in Italy, which is characterized by severe branch desiccation and rapid death of olive trees. Here we assessed the short- and long term environmental impacts of the invasion of *Xf* subsp. *pauca* on the Puglia peninsula. Using EKE, we quantified the impacts of the disease and the control measures against it on ES provisioning and biodiversity in the olive-producing agroecosystem of Puglia. The assessment was conducted at a landscape level. We identified the affected ES, biodiversity components and the associated *service providing units*, and (ii) quantified the impacts in terms of percentage reduction. The EKE method is suitable to provide a first impact assessment and to narrate the justifications of the experts behind the impact estimates.

The results show that *Xf* causes major impacts on ES provisioning and biodiversity in the region. The experts expect ES provisioning to diminish, on average, by about 34% and 30% in the short- and long term, respectively. This is mainly due to the impact of the disease on food (olive) production, ornamental resources, soil erosion regulation, primary production and cultural heritage. The loss of millenarian/centenarian trees, which are the identity of the region and the people, is identified as a massive loss to the history and cultural heritage of the region. Biodiversity is expected to diminish by about 28%, through the impact of the disease on genetic diversity and habitats of high conservation value. The experts noted that the negative impacts on ES provisioning (and biodiversity) are mainly due to the disease, rather than due to the control measures such as chemical applications, weeding and pruning. The impact of control measures is rated as negligible as their application in the demarcated area is not different from the standard practices in the non-affected areas.

The results showed that *Xf* has affected the provision of several ES besides food production (e.g. cultural heritage). This has a direct effect on the livelihoods of farmers and other economic agents who depend on the olive-value chain and olive-ecotourism. Since *Xf* is affecting the 'multifunctionality' of the ecosystem, policy makers (at national, regional and local levels) should consider involving a broad range of stakeholders (e.g. farmers, tourism sector, nurseries, environmental-concerned bodies) in the design and implementation of control measures to minimize the overall damage in the different sectors and to control the epidemic effectively and garner local support for measures. Therefore, any proposed control measure should be based on a thorough analysis regarding its effectiveness and side-effects on ES provisioning beyond food production.

This study contributes to a more informed decision making (e.g. selection of control measures) that considers the negative impacts of the disease and the control measures themselves on multiple ESs and biodiversity. However, as this study solely rely on EKE, the results should be interpreted cautiously, and further research will be needed to test hypotheses which can be formulated on the basis of the presented outcomes. Examples of such hypotheses would be: (i) the losses in cultural services due to the epidemic of *Xf* in Puglia are more important, when considering the assessed magnitude of losses and weights assigned by stakeholders, than the losses in provisioning services (including olive production), (ii) the current control measures do not have a significant negative impact on ES provisioning (compared to the standard practices in the non-affected areas), and (iii) assessing the magnitude of impacts and defining control measures based on the concept of ES provisioning rather than olive production increases the effectiveness of control measures [since the ES provisioning concept allows to effectively communicate impacts and engage key stakeholders in the design and implementation of measures].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the EU's Horizon 2020 research and innovation program under Pest Organisms Threatening Europe (POnTE) project with grant number 635646. We are very grateful to the experts. We are also very grateful to Maria Saponari and Donato Boscia for helping us in contacting the experts.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2020.105519.

References

Abou Kubaa, R., Giampetruzzi, A., Altamura, G., Zicca, S., Boscia, D., Saponari, M., Saldarelli, P., 2019. Insights into differential responses of olive cultivars to *Xylella fastidiosa* infections. In: Proceedings of the 2nd European Conference on *Xylella fastidiosa*, How Research Can Support Solutions; Ajaccio (France), 29-30 October 2019.

Almeida, R.P., 2016. Can Apulia's olive trees be saved? Science 353 (6297), 346–348.

Bragard, C., Dehnen-Schmutz, K., Di Serio, F., Gonthier, P., Jacques, M.A., et al., 2019. Update of the Scientific Opinion on the risks to plant health posed by *Xylella fastidiosa* in the EU territory. EFSA Journal 17 (5), e05665.

Cheatham, M.R., Rouse, M.N., Esker, P.D., Ignacio, S., Pradel, W., Raymundo, R., et al., 2009. Beyond yield: plant disease in the context of ecosystem services. Phytopathology 99 (11), 1228–1236.

Cornara, D., Bosco, D., Fereres, A., 2018. Philaenus spumarius: when an old acquaintance becomes a new threat to European agriculture. J. Pest. Sci. 91 (3), 957–972.

EFSA (European Food Safety Authority), 2014. Guidance on expert knowledge elicitation in food and feed safety risk assessment. EFSA Journal 12 (6), 3734.

EFSA PLH Panel (EFSA Panel on Plant Health, 2011. Guidance on the environmental risk assessment of plant pests. EFSA Journal 9 (12), 2460.

EFSA PLH Panel, 2014. Scientific Opinion on the environmental risk assessment of the apple snail for the EU. EFSA Journal 12 (4), 3641.

EFSA PLH Panel, 2015. Scientific opinion on the risks to plant health posed by *Xylella fastidiosa* in the EU territory, with the identification and evaluation of risk reduction options. EFSA Journal 13 (1), 3989.

European commission, 2015. Commission Implementing Decision (EU) 2015/789 of 18 May 2015 as regards measures to prevent the introduction into and the spread within the Union of *Xylella fastidiosa* (Wells et al.). Official Journal of the European Union L125, 36–53.

European commission, 2020. Commission Implementing Regulation (EU) 2020/1201 of 14 August 2020 as regards measures to prevent the introduction into and the spread within the Union of *Xylella fastidiosa* (Wells et al.). Official Journal of the European Union L269, 2–39.

Gilioli, G., Schrader, G., Baker, R.H.A., Ceglarska, E., Kertész, V.K., Lövei, G., et al., 2014. Environmental risk assessment for plant pests: a procedure to evaluate their impacts on ecosystem services. Sci. Total Environ. 468, 475–486.

Gilioli, G., Schrader, G., Carlsson, N., van Donk, E., van Leeuwen, C.H., Martín, P.R., et al., 2017. Environmental risk assessment for invasive alien species: a case study of apple snails affecting ecosystem services in Europe. Environ. Impact Assess. Rev. 65, 1–11.

Hodbod, J., Barreteau, O., Allen, C., Magda, D., 2016. Managing adaptively for multifunctionality in agricultural systems. J. Environ. Manag. 183, 379–388.

Hornero, A., Hernandez-Clemente, R., North, P.R.J., Beck, P.S.A., Boscia, D., Navas-Cortes, J.A., Zarco-Tejada, P.J., 2020. Monitoring the incidence of *Xylella fastidiosa* infection in olive orchards using ground-based evaluations, airborne imaging spectroscopy and Sentinel-2 time series through 3-D radiative transfer modelling. Rem. Sens. Environ. 236, 111480.

ISMEA, 2015. Istituto di Servizi per il Mercato Agricolo alimentare. Olio d'oliva - Dati - Scheda di settore.

Jeger, M., Bragard, C., Caffier, D., Candresse, T., Chatzivassiliou, E., et al., 2018. Guidance on quantitative pest risk assessment. EFSA Journal 16 (8), e05350.

Millennium Ecosystem Assessment (MEA, 2005. Ecosystems and Human Well-Being: Biodiversity Synthesis. World Resources Institute, Washington, DC, p. 86.

Poblete, T., Camino, C., Beck, P.S.A., Hornero, A., Kattenborn, T., Saponari, M., et al., 2020. Detection of *Xylella fastidiosa* infection symptoms with airborne multispectral and thermal imagery: assessing bandset reduction performance from hyperspectral analysis. ISPRS J. Photogrammetry Remote Sens. 162, 27–40.

Potter, C., Burney, J., 2002. Agricultural multifunctionality in the WTO—legitimate non-trade concern or disguised protectionism? J. Rural Stud. 18 (1), 35–47.

Saponari, M., Altamura, G., Abou Kubaa, R., Montilon, V., Saldarelli, P., et al., 2019b. Further acquisition on the response of a large number of olive cultivars to infections caused by *Xylella fastidiosa* subsp. *pauca*, ST53. In: Proc. Of the 2nd European Conference on *Xylella fastidiosa* 2019, How Research Can Support Solutions; Ajaccio (France), 29-30 Oct 2019.

Saponari, M., Giampetruzzi, A., Loconsole, G., Boscia, D., Saldarelli, P., 2019a. *Xylella fastidiosa* in olive in Apulia: where we stand. Phytopathology 109 (2), 175–186.

Semeraro, T., Gatto, E., Buccolieri, R., Vergine, M., Gao, Z., De Bellis, L., Luvisi, A., 2019. Changes in olive urban forests infected by *Xylella fastidiosa*: impact on microclimate and social health. Int. J. Environ. Res. Publ. Health 16 (15), 2642.

Strona, G., Carstens, C.J., Beck, P.S., 2017. Network analysis reveals why *Xylella fastidiosa* will persist in Europe. Sci. Rep. 7 (1), 71.

Su, C.C., Chang, C.J., Chang, C.M., Shih, H.T., Tzeng, K.C., Jan, F.J., et al., 2013. Pierce's disease of grapevines in Taiwan: isolation, cultivation and pathogenicity of *Xylella fastidiosa*. J. Phytopathol. 161 (6), 389–396.

Wilson, G.A., 2008. From 'weak' to 'strong' multifunctionality: conceptualising farm-level multifunctional transitional pathways. J. Rural Stud. 24 (3), 367–383.

World Commission on Environment and Development, 1987. Our Common Future. Oxford University Press, New York, p. 43.

Zarco-Tejada, P.J., Camino, C., Beck, P.S.A., Calderon, R., Hornero, A., Hernández-Clemente, R., et al., 2018. Previsual symptoms of *Xylella fastidiosa* infection revealed in spectral plant-trait alterations. Nature Plants 4 (7), 432.