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Assessing the potential economic impact of invasive plant pests

Advances in monitoring of native and invasive insect pests of crops

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Chapter 9

Assessing the potential economic impact of invasive plant pests

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1 Introduction

Although most introduced, non-native, pest species (including insects and pathogens) are relatively innocuous (Holmes et al., 2009), some could lead to massive economic impacts in the invaded region. Examples of recent invaders with widespread economic impacts are Emerald ash borer (*Agrilus planipennis*), *Phytophtora ramorum*, *Hymenoscyphus fraxineus*, the pine wood nematode (*Bursaphelenchus xylophilus*) and *Xylella fastidiosa* (Aukema et al., 2011; Petucco et al., 2019; Hill et al., 2019; Soliman et al., 2012b; Schneider et al., 2020).

Economic impact assessments form part of a pest risk analysis to determine whether the introduction of a pest will result in unacceptable economic consequences. In cases where consequences are judged to be unacceptable, phytosanitary measures need to be considered to reduce the economic risk to an acceptable level. Hence, economic impact assessments are essential in developing and prioritizing invasive species management (Holmes et al., 2009; Epanchin-Niell, 2017).

Economic impact assessments need to account for the bio-economic characteristics of the invasion (Kovacs et al., 2010; Haight et al., 2011).

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Information on hosts at risk should be integrated with information on the potential area of establishment and spread, the development of the pest population density over time and space, the biophysical and harvest-related damage caused by the pest and the resulting economic consequences on society. However, due to the dynamic and spatial complexity of a pest invasion, impact estimations can be challenging.

A basic approach often applied in economic impact assessments of invasive pests is centered on the identification of the potential amount of host resource at risk (potential production losses), multiplied by some unit market price (e.g. Pimentel et al., 2005). However, this approach does not account for biological invasions being spatial and dynamic processes where the economic well-being of stakeholders is affected in different ways and intensity (Holmes et al., 2009).

The economic impact of invasive species consists of direct and indirect market impacts. Direct impacts are related to expected losses in biomass production, either in quality and/or quantity (often referred to as yield), resulting from damage to the crops, trees and/or their products. Indirect impacts are related to the consequential market responses to the altered biomass supply as reflected by changes in market prices, producer and consumer responses to price changes and effects on international trade (Soliman et al., 2012b; Petucco et al., 2019; Schneider et al., 2021).

Appropriate techniques to assess the various economic impacts consist of partial budgeting, partial equilibrium models, input–output models and computable general equilibrium models (Soliman et al., 2010; Welsh et al., 2021). These methods differ in the width of economic scope and consequently in their ability to assess the economic effects of a pest introduction. A wider scope generally requires more elaborated data and skills. In this chapter, we evaluate each method in terms of its economic concepts, scope and required data and skills, followed by a general reflection on the question of how to select the most appropriate technique, considering the trade-off between completeness in economic scope and resources required.

The chapter concludes with two case studies of recent pest threats in Europe (*B. xylophilus*, a nematode infecting pine, and *X. fastidiosa*, an insect-vectored bacterial disease in olive trees), illustrating the potential of the most commonly applied methods.

2 Methods to assess the potential economic impact of invasive plant pests

2.1 Partial budgeting

Partial budgeting is a straightforward approach in which the net direct impact of a change in a system, like a plant pest invasion, is obtained by assessing

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the associated negative effects (i.e. additional costs and reduced returns) and positive effects (i.e. additional returns and reduced costs). In general, direct impacts related to a pest invasion include only negative effects, viz. yield losses and additional production costs (Soliman et al., 2010).

When applying partial budgeting, spatially explicit data on host plants, pest spread and climate need to be combined to determine the endangered area, i.e. the area where the pest can establish at a given time and cause damage. Subsequently, a relationship between the defined endangered area and the likely level of damage (production loss expressed in quantity and/or quality losses) needs to be identified. Ideally, this level of production loss is estimated as a function of pest population density. However, it is often very difficult to reliably model the density of an invasive pest population, and so instead, spread models are more often used to generate spatial data on the presence–absence of the pest, which can only be used to delimit the endangered area (Robinet et al., 2012). In those cases, additional data are needed to serve as a proxy for the missing population data, e.g. climate and/or other ecological features that are highly correlated with the pest density (Kriticos et al., 2013; Soliman et al., 2012a,b).

Direct impacts could be estimated as cumulative sums over time and space from the start of the invasion till a steady-state situation or other arbitrary end point, or as yearly flows in a steady state. To account for the time value of money concept (a euro today is worth more than it would be next year, due to the opportunity to invest and gain interest over a period of a year), costs accrued over time are aggregated by discounting their values to the present value (e.g. Hillier et al., 2020).

Although the method is designed to evaluate the direct impact at the producer level, partial budgeting can also be used at the national or continental level by scaling up the budgetary impacts (Rich et al., 2005). MacLeod et al. (2004) used partial budgeting, for instance, at the national level to assess the impact of an uncontrolled melon thrips, *Thrips palmi*, invasion in England. To this end, the potential damage resulting from yield and quality losses in horticulture, export losses and costs related to additional research requirements and plant health certifications were evaluated over a period of 10 years after invasion.

By comparing the evaluated direct impact to the estimated costs of potential control measures, decisions on mitigation can be supported if the resulting ratio is sufficiently high. In the study of MacLeod et al. (2004), the resulting benefit (= the value of losses prevented) to cost ratio was at least 4:1, justifying the implementation of the evaluated mitigation measures.

Soliman et al. (2012a) used the partial budgeting approach at a continental scale to estimate the direct impacts of an unregulated spread of Potato Spindle Tuber viroid (PSTVd) in Europe. Direct impacts on potato and tomato producers were estimated by accounting for expected yield losses and

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additional crop protection costs in the expected established steady state. Yield losses were estimated for spatial explicit agri-environmental zones to account for host distribution and temperature-dependent damage levels of the pest. Aggregation of the losses and additional crop protection costs over the spatial zones indicated a direct annual impact on potato growers of 2.1 M€ and on tomato producers of 3.5 M€. Implemented phytosanitary measures to prevent spread within Europe accounted for, approximately, 5 M€ a year, indicating that the implementation of these measures is economically questionable when considering only the direct impacts (Soliman et al., 2012a).

The strength of the partial budgeting approach is its simplicity and transparency. It has little complexity in terms of its resource needs, as it requires a limited amount of data, expertise and time investment (Holland, 2007). However, partial budgeting is not suitable for measuring long-term effects or impacts in other sectors of the economy as it only accounts for the direct impact of a change in an isolated setting, assuming fixed budgets and market prices. Changes in production volume caused by a pest invasion will, however, have long-term effects on total market supply and prices, thereby affecting other producers and other sectors of the economy, such as the processing industry (Petucco et al., 2019), but also consumers. This will especially be the case with forest pests, where an invasion will not only reduce the present availability of the affected tree species but also its future availability (Soliman et al., 2012b; Petucco et al., 2019). The partial budgeting technique is not able to assess these indirect market effects. This shortcoming can be counterbalanced by a complementary use of the partial equilibrium modeling technique.

2.2 Partial equilibrium modeling

Partial equilibrium modeling requires the definition of functional relationships describing the supply and demand of the product of interest in the market to determine the so-called market equilibrium. Market equilibrium occurs when the supply in the market meets the demand in the market, reflecting the combination of price and quantity that maximizes economic welfare. Maximum economic welfare is realized when producers and consumers maximize their profits and utilities (Mas-Colell et al., 1995).

Figure 1 illustrates this concept in more detail by showing a downward-sloping demand curve, reflecting the diminishing marginal utility of an increased consumption, and an upward-sloping supply curve, reflecting increasing marginal costs of production. The market equilibrium, where quantity supplied equals quantity demanded, occurs at an equilibrium price of P_E and quantity Q_E. The difference between P_E and the demand curve represents how much consumers benefit by being able to purchase the product for a price (P_E) that is

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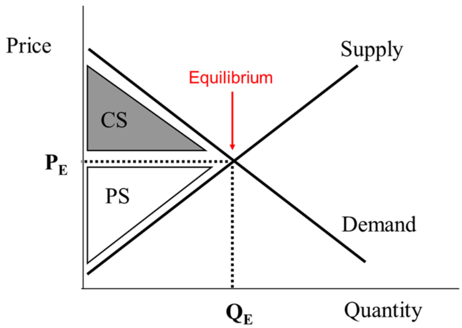

Figure 1 Illustration market equilibrium concept.

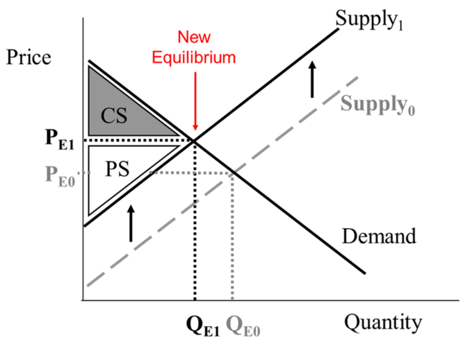

Figure 2 Illustration impact pest invasion on market equilibrium.

less than they would be willing to pay. The total benefit derived by consumers, or consumer surplus, is represented by the triangle CS.

Since the supply curve represents the marginal variable cost of production, the area below the curve equals the total variable costs. The revenues from sales are equal to price (P_E) times quantity (Q_E), which is the area enclosed between the dashed lines. Hence the producer surplus, defined as the difference between total revenue and total variable costs, is reflected by the triangle PS. Total economic welfare is the sum of consumer surplus and producer surplus (Mas-Colell et al., 1995).

At market equilibrium, P_E will not change unless an external factor – like a pest invasion – changes the supply or demand, which results in a disruption of the equilibrium and, subsequently, in a change in economic welfare. By partial equilibrium modeling, these pest-induced changes in economic welfare can be assessed by measuring the differences in equilibrium price and quantity before and after the pest invasion.

Pest invasions may lead to a loss in yield and an increase in production costs, resulting in an upward shift in the supply curve (Fig. 2). This shift in the supply curve alters the equilibrium point, implying a decrease in quantity

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supplied (from Q_{E0} to Q_{E1}) and an increase in market price (from P_{E0} to P_{E1}). Consumer losses, or the reduction in consumer welfare, that result from the new equilibrium point can be calculated by comparing CS before and after invasion. In the same way, changes in producer welfare can be calculated.

Partial equilibrium modeling can be conducted with respect to one sector (a single-sector model) or multiple sectors (a multi-market model). Multi-market models link related markets and are, therefore, able to capture spillover effects between main markets. Within each partial equilibrium model, main assumptions need to be made to define the behavior of the affected market(s) (e.g. perfect or imperfect competition), the level of homogeneity for products from exogenous markets and the influence of domestic producers on the world market. Data requirements can be substantial (Mas-Colell et al., 1995; Petucco et al., 2019) as data are needed to reflect the affected markets, including data on prices, production and consumption quantities, market prices and international trade, to determine price elasticities of both supply and demand (i.e. the degrees to which supply and demand respond to a change in price).

The strength of the partial equilibrium approach is the consideration of both direct and indirect impacts by analyzing the change in consumer and producer welfare. Results provide insight into the total economic impact, including the extent to which producers can transfer part of the negative direct impact to consumers. Following upon the earlier described evaluation of the direct impacts of an unregulated PSTVd spread in Europe by partial budgeting, Soliman et al. (2012a) also applied a partial equilibrium modeling approach to consider the indirect market effects resulting from the reduced supply and increased production costs. Change in total welfare equaled to a loss of 4.4 M€ for potato producers and consumers and of 5.7 M€ for tomato producers and consumers. Consumers, however, bore 92% of the total welfare loss in the case of affected potato production and 77% in the case of affected tomato production, indicating a considerable transfer of direct impacts from producers (i.e. 2.1 M€ on potato growers and of 3.5 M€ on tomato producers) to consumers. Hence, the economic impact of PSTVd appeared to be important (and therefore the justification for restrictive measures) when accounting for the expected market impact, but questionable if only the direct impact was considered.

Most recent examples of partial equilibrium applications in invasive plant pest economic impact are the analyses performed by Petucco et al. (2019) and Schneider et al. (2021). Petucco et al. (2019) applied the partial equilibrium approach to assessing the impact on economic welfare caused by the ash dieback invasion in France. Schneider et al. (2021) used the approach to evaluate the potential indirect market impact of an uncontrolled *X. fastidiosa* infestation at a European scale (see Section 5).

Despite its suitability for evaluating market effects, partial equilibrium modeling is limited in its ability to account for economy-wide effects. Economic

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impact assessments using partial equilibrium models are therefore only appropriate when the indirect market effects of the pest are not expected to affect other markets or cause measurable macroeconomic changes (e.g. changes in employment). For applications that require an economy-wide scope, input–output analysis (Section 2.3) or computable general equilibrium modeling (Section 2.4) approaches can be considered.

2.3 Input–output analysis

Input–output (I-O) analyses focus on the interdependencies of sectors in an economy (regional or national), making it an appropriate technique to predict the ripple effects throughout an economy due to a shock within a particular sector (Leontief, 1986). Central to an I-O analysis is the specification of the monetary flows of inputs and outputs among the productive sectors of an economy (Miller and Blair, 1985), reflected by so-called input–output tables. In an I-O table, each sector is represented by a row and a column. The rows specify the distribution of the total output of a specific sector sold to other sectors (intermediate demand) or to final demand (final consumption and exports). The columns refer to the production side of a specific sector, by indicating the value of the inputs of each sector needed to produce output.

Any change in the final demand for the products of an industry has both direct and indirect effects on the economy as a whole. Changes cause primary ripples by directly changing the purchasing patterns of the affected sector. Suppliers to the affected sector must change their purchasing patterns to meet the demand of the sector originally affected by the change in final demand, creating a smaller secondary ripple. Those who meet the needs of the suppliers must in turn change their purchasing patterns to meet the demand of the suppliers of the affected sector and so on.

The relationship between the initial change and the total effects generated by the change is known as the multiplier effect of the sector, or the impact of the sector on the economy. To compute this multiplier effect, I-O tables are mathematically converted into matrices of multipliers that reflect the amount by which production, employment and income would alter because of one-unit change in final demand (Miller and Blair, 1985).

Based on I-O analysis, the impact of a pest invasion on an economy can be evaluated by adjusting the final demand in the affected sector (such as agriculture or forestry) according to the expected shock to demand (such as decrease in the production of agricultural commodities or reduction in exports), multiplied by the multiplier matrices. Examples of I-O applications in pest risk assessment are the analyses of Elliston et al. (2005) and Juliá et al. (2007). Elliston et al. (2005) investigated the regional economic impact of a potential invasion of Karnal bunt (caused by the fungus *Tilletia indica*) in wheat

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in Queensland. In the scenario of a widespread incursion, the direct effect on the wheat and other grain industries was estimated as an AUD M$89 decline in output and a loss of 400 full-time jobs over a 15-year planning horizon. The indirect effects in all other industries resulted in a decline of AUD M$38 in output and a decline in employment of 200 full-time jobs.

In the I-O analysis of Juliá et al. (2007), direct and indirect economic effects of the invasive weed, yellow starthistle (*Centaurea solstitialis*), in the rangelands of Idaho were determined in relation to its interference with agricultural and non-agricultural benefits (e.g. wildlife recreation expenditure and water quality). Agriculture-related economic impacts accounted for 79% of the total impact on the rangeland economy, and non-agricultural impacts for the remaining 21%.

Apart from the high data requirements, application of an I-O analysis is generally limited by two fundamental assumptions. First, I-O models only account for changes in the economy induced by shifts in demand. Supply is assumed to be perfectly elastic (e.g. there are no restrictions to inputs), which in practice is often not the case. Especially in agriculture and forestry, supply is often limited, which means that an I-O analysis of a pest introduction may not capture all the important economic effects. Second, I-O models are static and cannot account for changes in prices or for changes in the structure of a sector over time. This means that I-O models assume fixed prices, no substitution between inputs and constant returns to scale (e.g. underlying data and relationships are not affected by the economic changes). However, this static assumption can be justified if the I-O technique is used to analyze only short-term impacts.

In conclusion, the I-O approach provides an opportunity to measure short-term, spillover effects across sectors of the economy given a shock in a particular sector that affect the demand side only. For assessments that require the economy-wide scope of I-O models as well as the economic realism of partial equilibrium models (price effects), a computable general equilibrium (CGE) modeling approach would be more appropriate.

2.4 Computable general equilibrium modeling

The CGE modeling approach uses I-O tables to represent all sectors in the economy with the inclusion of functional relationships between these sectors as in a PE model. By the specification of demand relationships, production technologies, relationships between domestic and imported goods, prices, household income and equilibrium conditions, CGE models address questions concerning impacts across sectors as well as price changes and longer-run impacts. This capacity, however, makes CGE models highly complex (Sadoulet and de Janvry, 1995; Dixon and Parmenter, 1996).

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Incorporating the whole economy in one model requires a high level of aggregation to keep it practical. High levels of aggregation, however, make it difficult to analyze a change in a subsector of the economy. Many agriculture-oriented CGE models are disaggregated into only two subsectors, such as tradable and non-tradable crops, or food and cash crops (Bourguignon and Pereira da Silva, 2003). The economic consequences of a pest that causes large damages in only a subset of crops might remain unnoticed due to the level of aggregations. Applications of CGE models are, therefore, only appropriate to address large-scale problems that generate measurable macroeconomic impacts. Pest invasions rarely trigger changes in overall employment, income or the inflation rate. Consequently, there are only a few applications of CGE applications in pest risk assessments known.

McDermott et al. (2013) developed a CGE model for the state of Ohio to estimate the economic impact caused by the invasive Emerald ash borer, *A. planipennis*. Annual economic impact of the beetle was estimated at USD M$70. Most of the damage (~80%) was incurred by recreation sectors, households and state government. Recreation sectors had to add the costs of removing infested ash trees to their production costs. The cost of ash removal reduced the disposable income of households, while these expenditures flow to the garden sector due to an increase in the demand for their services. The government had to adjust revenues to account for ash removal, shifting this expenditure to the garden sector.

3 Selection of appropriate level of complexity

3.1 Context setting economic impact assessment

Invading plant pests impose economic consequences that vary across stakeholders (plant growers, forest managers, residents/homeowners, industries or sectors, consumers, government) and regions, and are dynamic over time. Induced disturbances do not only reduce the present availability of affected hosts but also alter their future availability, population structure and distribution. Due to this three-dimensional context (scope, scale, timeline), economic impact assessments require explicit settings of each of these impact dimensions, resulting in a specific demarcation (objective) of the analysis.

- The scope dimension refers to the perspective (level) of the assessment. Is it only accounting for the impacts experienced by specific stakeholders (producers, residents/homeowners, industries or sectors, consumers, government) or is it performed from the perspective of society as a whole? The selected perspective is of primary importance with respect to the identification of the most relevant impacts; an analysis from the

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perspective of forest managers will neglect potential impacts on, for instance, residents/homeowners, industries, or consumers, while an analysis from the perspective of a national government ideally considers all main societal impacts.

- The scale dimension refers to the geographical dimension of the analyses. Is the assessment conducted on a local, regional, national or international scale? Data availability is of primary importance in determining the scale to which a quantitative economic impact assessment can be applied.
- The time dimension refers to the time horizon of the assessment, which is key in economic impact assessments. The economic impacts could be estimated as cumulative sums over time and space from the start of the invasion till a steady-state situation or other arbitrary end point, or as yearly flows in a steady state. Modeling the development of the economic impacts over time requires a detailed modeling of spread. With an increase in timespan, uncertainty in the evaluated economic systems increases, primarily due to behavioral responses (adaptation) of stakeholders who attempt to cope with the invasion. Producers can, for instance, decrease negative impacts by adapting their crop mix or crop management. A first action involves switching to resistant varieties of the same crop or to crops that are not vulnerable to the pest. Producers may also change their crop management to decrease the negative consequences of pests and diseases. In fact, it is unrealistic to assume that crop management practices will remain unchanged following a pest invasion; nevertheless, economic impact studies rarely account for such adaptations (Epanchin-Niell, 2017; Petucco et al., 2019).

3.2 Selection of appropriate assessment method

In general, the first step in the assessment of economic impacts in most pest risk analyses consists of a quick qualitative analysis of the expected impacts, based on experts' judgments. For this purpose, plant protection agencies generally apply structured decision support schemes as outlined in the International Standards on Phytosanitary Measures (ISPM) No. 11 (FAO, 2004). These schemes consist of a logical sequence of questions to capture experts' opinions. For each question, experts provide their answer by selecting a score within some predefined ordinal risk classification scheme. In such a scheme, economic consequences are only described in broad qualitative terms, without strict guidelines defining time frame and scope. Economic impacts are assessed by questions considering the expected yield or quality losses, the potential impact on international trade and expected control costs. Although this approach is helpful for classifying pest impacts (acceptable, unacceptable), the assessment is too weak to justify or select the appropriate

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level of management measures. For this purpose, a quantitative assessment is needed (Soliman et al., 2015).

The four evaluated assessment techniques that can be applied for this purpose differ markedly in terms of the scope of impacts covered and consequently also in terms of data requirements and model complexity (Table 1) (Soliman et al., 2015; Welsh et al., 2021). While partial budgeting is a basic and easily understood technique for assessing direct impacts, its scope does not include indirect effects of pest damage resulting from effects on market prices, supply and demand, nor does it address spillover effects to other sectors of the economy. Partial equilibrium or CGE modeling techniques widen the scope to include indirect effects, in the case of partial equilibrium only for the sector of the affected commodity and in the case of CGE for the economy (society) as a whole. A technique between partial budgeting and equilibrium modeling is I-O analysis, as it accounts for the spillover effects of a reduction in the production of an agricultural commodity to other sectors in the economy without addressing the effects of price changes.

Given the differences between the four techniques (Table 1), each risk analyst faces the question: what is the appropriate method to choose? As the scope and size of impacts can differ for each pest and host (commodity), an 'one size fits all' selection procedure of the most appropriate method is not existing. However, some guidance can be provided based on (1) the defined objective (demarcation) of the analysis, indicating the desired scope of insights into economic impacts, and (2) the available resources in terms of data, skills and time. The remainder of this section reflects on the extent to which each assessment method aligns with these considerations.

Despite its limitations, the partial budgeting approach remains the default method of choice for an assessment of the economic impacts of pests and diseases. This technique provides insight into the direct impacts of the pest, while its results are easily understood and communicated to stakeholders such as policymakers. The required data can often be obtained at a reasonable level of accuracy, either through secondary data collection or, in the absence of

Table 1 Illustration of the extent to which the assessment methods differ in their economic width (scope), resource requirements and output credibility

Method	Economic width	Data and skill requirement	Output credibility
Partial budgeting			
Partial equilibrium modeling			
Input–output analysis			
Computable general equilibrium modeling			

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these, through expert elicitation, and the technical expertise needed to apply the method is modest. In addition, the results of partial budgeting evaluations provide insights that can be used to determine whether further analysis is needed using more sophisticated techniques. If the outcome of the partial budgeting shows the direct economic impacts are devastating, then there is no rationale for conducting further analysis in the context of a pest risk analysis (i.e. answering the question of whether the pest needs to be controlled or not).

If the objective goes beyond a first assessment of the costs of pest introduction, or if indirect impacts are expected to substantially alter the outcome of the evaluation, then more sophisticated techniques are warranted. Partial equilibrium modeling is worth considering if the expected changes in production volumes are very large, while demand or supply is inelastic; in such cases, substantial price effects are very likely to occur. Generally, a pest invasion reduces the supply of crops, thereby increasing the price. However, with the occurrence of price effects, part of these invasion costs is transferred from affected producers to consumers who pay a higher price for the consumables, whereas non-affected producers may even benefit (see case studies). These insights are relevant in deciding on the need for supporting policy responses, e.g. compensation policies. Partial equilibrium modeling requires more advanced data and skills (knowledge) compared to partial budgeting. The complexity of the model will vary with the spatial scale of the analysis, the number of sectors considered, the functional specification of the supply and demand functions and the market structure (e.g. monopoly or oligopoly). A more broad-based economic technique like I-O analysis or CGE modeling could be considered if large spillover effects to other sectors of the economy are expected such as transport, trade and tourism. However, these techniques have rarely been used in pest assessment due to the large data and skill requirements as well as the fact that pest invasions rarely generate measurable macroeconomic impacts. Hence, in most cases, a combination of partial budgeting and partial equilibrium modeling can provide a sufficient scope in those cases where both direct and indirect impacts are expected to occur (Rich et al., 2005; Soliman et al., 2015; Welsh et al., 2021).

Generally, it is best to start by means of a partial budget analysis and to incorporate only as much detail and complexity as is needed to achieve the defined objective of the assessment. A fundamental dilemma underlying the choice of developing a partial equilibrium model in addition to a partial budgeting analysis is that it is difficult to know in advance whether the more advanced partial equilibrium modeling technique is justified without applying the method. The results of a partial budgeting analysis do not inform about the occurrence of potential market effects and, hence, about the need of using a partial equilibrium modeling approach. This can only be evaluated by exploring data on the price elasticity of supply and demand. The more inelastic

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the demand or supply, the greater the likelihood of price effects and thus the likelihood that a partial equilibrium model approach will provide additional insights that could alter the conclusion from the partial budgeting model.

Although the presented techniques provide useful assessment models to obtain insights into the potential economic consequences of invasive pests, it is important to note that these models do not provide exact predictions. Uncertainties arise in different stages of an economic impact assessment as many aspects of both invasion dynamics and affected processes are highly uncertain. Prior to or early in a pest invasion, for example, little may be known about the future pattern of spread and the potential damages that the invader might cause. Usually, economic assessment models account for uncertainty by assuming 'known' distributions of uncertain parameters and subsequently calculate the probability-weighted average across potential outcomes that arise from the uncertainty, viz. the expected outcome (Epanchin-Niell, 2017). In reality, uncertainty about ecological and economic parameters related to plant pest invasions can be severe, which makes sensitivity analyses a required part of the assessment to see how changes in the underlying model assumptions affect the estimated total economic impact.

Generally, the credibility of the outcomes of economic models decreases with their level of sophistication, because the greater sophistication entails making assumptions (i.e. introducing uncertainty) about processes that may work quite differently from how they are modeled. Thus, partial budgeting has a greater potential of giving credible results, particularly in the short run, while confidence is bolstered as anybody can check the assumptions underlying its calculations. Partial equilibrium and CGE techniques give more uncertain results because relationships between prices and supply and demand of affected commodities must be specified in simplified mathematical models, which impose strong assumptions on producer and consumer behavior. This is not to say that any sophisticated model is wrong. The models are theoretically correct, but they are simplifications of economic reality. Therefore, the outcomes of such models should be interpreted as plausible trends, inferred from past behavior, and should be used to complement the results of a partial budgeting rather than replace them. Results of partial equilibrium and CGE modeling should, in particular, be interpreted with caution as to the absolute magnitude of the effects. It is well-known that small changes in price elasticities may have large effects on the magnitude of economic effects.

4 Economic analyses to support pest risk management

Economic impact risk assessments raise awareness about the size of the economic impacts due to a pest invasion but cannot be used directly to support managerial responses. Hence, additional decision analyses are needed to

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evaluate the costs and benefits associated with potential management strategies. Generally, decision analyses on the mitigation of invading/emerging pest species rely on the concept of optimal resource allocation (Clark, 1990), aiming to maximize social welfare. Existing decision analyses studies directed toward forest biosecurity, for instance, estimated the costs and benefits of specific control strategies (Gatto et al., 2009), evaluated the trade-offs between eradication and slow-the-spread programs (Sharov and Liebhold, 1998; Brockerhoff et al., 2010) or analyzed the cost-effectiveness of surveillance programs (Epanchin-Niell et al., 2014) and control strategies targeted toward particular life stages of an invader (Buhle et al., 2005). Techniques to value the economic costs and benefits are in line with those described in the previous sections.

It is important to note that the management of invading pest incurs various economic consequences. The main effects relate to the extent the implemented management measures slow down the spread of the invading pest. By slowing down the spread, damage to the susceptible hosts is prevented and thus the overall economic impact is reduced. However, implementation of management measures also directly results in control costs (e.g. costs to bio-control releases or removal of hazard trees) and in opportunity costs due to the occurrence of potential profits foregone (e.g. from advancing or delaying harvest or due to movement restrictions out of a demarcated zone). Indirectly, it might also influence trade opportunities of other commodities or services (e.g. due to movement restrictions, increased inspections, cargo treatments) resulting in additional consequential losses (opportunity costs).

Cost-benefit analysis provides an approach for structuring the information on the various types of effects to aid decisions about control management design, by evaluating whether the advantages (benefits) of an invasion mitigation strategy outweigh its disadvantages (costs) (Boardman et al., 2006; Kehlenbeck et al, 2012). By expressing the advantages and disadvantages in monetary terms, the different effects become comparable and can be used to determine whether the evaluated management strategy increases total welfare or not.

5 Case studies: pine wood nematode (*B. xylophilus*) and *X. fastidiosa*

To illustrate the application of an economic impact assessment using partial budgeting and partial equilibrium models, two case studies on pest organisms currently threatening Europe are presented in more detail. The first case study describes the insights obtained from the impact assessment evaluating the consequences of the establishment of pine wood nematode (*B. xylophilus*) in Europe. As pine wood nematode affects forestry stock and future production

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volume, indirect impacts on the European market lag the moment of actual damage. The second case presents the economic impact assessment of an uncontrolled infestation by *X. fastidiosa* vectored by xylem-feeding spittlebug nymphs (*Philaenus spumarius*) affecting the European olive production. Presented results highlight the distribution of impacts among various European countries and market participants.

5.1 Case study 1: pine wood nematode

PWN (*B. xylophilus*) is recognized worldwide as a major forest pest. The nematode can multiply rapidly at persistently high temperatures (>20°C for at least 8 weeks), creating large populations that disrupt water transport in the infected tree, causing pine wilt disease. Ultimately, pine wilt disease results in the death of the infested trees. PWN is vectored from diseased to healthy trees by bark beetles in the genus *Monochamus*. Pines (*Pinus* spp.) are favored hosts but other genera of conifers are also attacked (Evans et al., 1996).

Since its introduction to Portugal in 2008, PWN has been a serious threat to the European forestry industry. The presented case study is based on Soliman et al. (2012b) who analyzed the risk of PWN in the EU by estimating the decline in forest resources available for wood supply and its resulting impact on the downstream roundwood market over a time span of 22 years (2008–30). Spatial analysis was used to integrate the required information on climate suitability, host distribution, pest spread and value of assets. Information on spread was derived from the output of the process-based PWN spread model of Robinet et al. (2011) indicating the spread potential from the initial infested sites in Portugal to the rest of Europe. Direct economic impacts resulting from wood loss were computed using partial budgeting at the regional scale, while market impacts on the round wood market were computed using partial equilibrium modeling at an EU scale.

Under the assumption of no regulatory control measures, the value of lost forestry stock cumulated over the evaluated period of 22 years was estimated at €22 bn. Substantial direct impacts were expected in Portugal, Spain, Southern France and North-West Italy (Fig. 3). The greatest yearly loss of stock was expected to occur in the period 2014–9, with a peak of €3 bn in 2016, after which it stabilized at 300–800 M€/year (Soliman et al., 2012b).

The results of the PE analysis showed that the reduction in the domestic supply of industrial round wood caused by the PWN invasion led to an increase in the EU market price and a decrease in EU demand. Annual net total welfare (= total impact on affected, non-affected producers and consumers) after 22 years of spread (inducing a shift in wood supply due to an accumulated loss in forestry stock) was reduced by M€ 218 (Table 2). The shortage in EU supply (the gap between supply and demand) was covered by an increase in imports and/or

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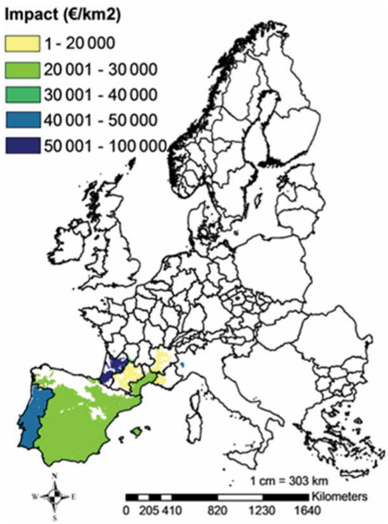

	Infested area (%)	Direct impact (M€)
Portugal	82.4	5164
Spain	67.5	14 649
France	13.2	2532
Italy	0.2	30
Total	10.6	22 375

Figure 3 Cumulative direct impact over 22 years of uncontrolled PWN spread in the EU (estimated by partial budgeting).

Table 2 Annual impact of a PWN invasion in the EU after 22 years of uncontrolled spread (estimated by partial equilibrium modeling)

	Absolute change	% change
Supply (Mm^3)	−1.89	−0.8
Demand (Mm^3)	−0.77	−0.3
Price (€/m^3)	1.44	2.8
Net trade (Mm^3)	−1	−14.6
Consumer surplus (M€)	−357	−2.5
Producer surplus (M€)	139	2.0
Total welfare (M€)	−218	−1.0

decrease in exports (i.e. change in net trade between the EU and the world market), triggering an increase in the world price for round wood. The increase in market prices caused an increase in supply leading to a new equilibrium in the industrial round wood market. Due to the higher prices, consumers suffered a reduction in their surplus of M€357. Non-affected producers experienced a positive net impact as they benefited from the higher market price in the new equilibrium situation without suffering losses in the stock. Affected producers experienced a loss as the reduction in production volume was not fully compensated by the price increase. Overall, the total producer surplus increased by M€139.

Figure 3 and Table 2 indicate a large difference in the magnitude of the estimated direct and indirect impacts. This is because the direct impacts

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represent the reduction in the value of standing forestry stock (future production potential), while the indirect impacts refer to the changes in the yearly flow of wood to the round wood market. These flows represented only 2% of the standing stock. Therefore, losses in wood flow accumulated slowly and over a long period of time after the standing stock was lost due to PWD. This means that if the spread of PWD had stopped, the annual direct loss would have disappeared, while the effect on the market would have continued to increase until mitigation efforts became effective (i.e. replanted [resistant] trees flow into the round wood market).

5.2 Case study 2: X. fastidiosa

X. fastidiosa is one of the most dangerous plant pathogenic bacteria worldwide causing a variety of diseases, with huge economic impact on agriculture, public gardens and the environment (EFSA, 2018). Multiplication of the bacteria within susceptible host plants results in clogging of the vascular system, decreasing water and nutrient flows. Consequently, large parts of the crown or foliage dry out and die off. Yields start to decline and fruit quality is reduced, and eventually the host plant dies. The bacterium is naturally transmitted by insect vectors (spittlebug nymphs), which feed on the xylem of host plants.

Since 2013, *X. fastidiosa* has been reported to have infected several hosts in different areas of Europe. To date, most damage has been inflicted on the olive orchards of southern Apulia (Italy), where infection with *X. fastidiosa* subspecies *pauca* has led to the death of millions of trees. To reduce the spread of the pathogen and the associated olive quick decline syndrome (OQDS), various control measures have been implemented, including containment measures such as tree felling and vector control and the establishment of demarcated areas. Unfortunately, the size of the area affected and the hidden reservoir of symptomless, but infectious, host plants have hindered disease eradication (Morelli et al., 2021). Worse, the dense network of olive groves in Apulia (Italy) might serve as a European reservoir of *X. fastidiosa* subspecies *pauca* (Strona et al., 2017).

This second economic impact case study is based on the research of Schneider et al. (2020; 2021) who evaluated the potential economic impact of *X. fastidiosa* on olives in the EU. Via a combination of a climatic suitability map to delineate the area of potential spread, a radial range expansion model (Robinet et al., 2012) to estimate the spread and an economic impact assessment module, a bio-economic model was developed to simulate the annual EU olive production area at risk within a time horizon of 50 years, under the assumptions of an uncontrolled infestation and the Apulia region as a point of entry (Fig. 4). The production area at risk was represented by the

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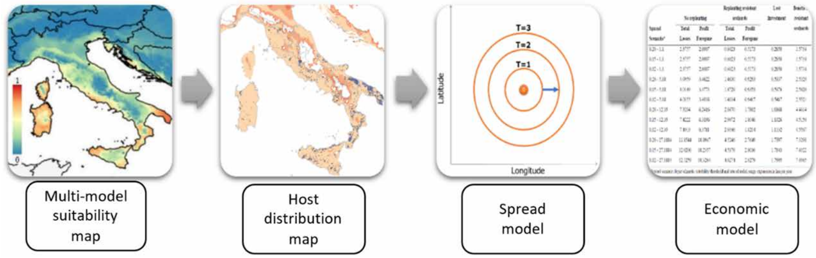

Figure 4 Illustration of bio-economic modeling framework to estimate the economic impact of *X. fastidiosa* in European olive orchards.

olive production sites of Italy, Greece and Spain, accounting for around 95% of European olive oil production.

The net profit flows of the following scenarios were evaluated using the modeling framework:

1) A reference situation in which production is not affected by *X. fastidiosa* to estimate the unaffected profits and replanting investments during the modeled planning horizon.
2) A situation in which infected hectares remain out of production after host death by *X. fastidiosa* for the remainder of the planning horizon (resulting in long-term yield and investment losses).
3) A situation in which infested hectares are replanted after host death by *X. fastidiosa*-resistant varieties, which – once full grown – produce the same yield and quality as susceptible equivalents (resulting in short/midterm yield and investment losses).

The comparison of situations 1 and 2 provides insights into the range of potential economic impacts from a *X. fastidiosa* epidemic, while the comparison of situations 2 and 3 provides insight into the effectiveness of replanting with resistant varieties as an adaptation measure. To account for the uncertainty and data scarcity on *X. fastidiosa* spread, scenario analyses were conducted by utilizing the 5th, 50th and 95th percentiles of the EFSA elicited range distribution to project the epidemic beyond Apulia, the area of entry (Bragard et al., 2019). These settings corresponded to radial dispersal rates varying between 1.10 km/year and 12.35 km/year, with 5.18 km/year as the median value (Fig. 5).

An economic module computed the direct impact by accounting for discounted foregone profits (e.g. yield losses) and losses in investments (e.g. tree dieback) on the olive orchard level using a partial budgeting approach (Schneider et al., 2020).

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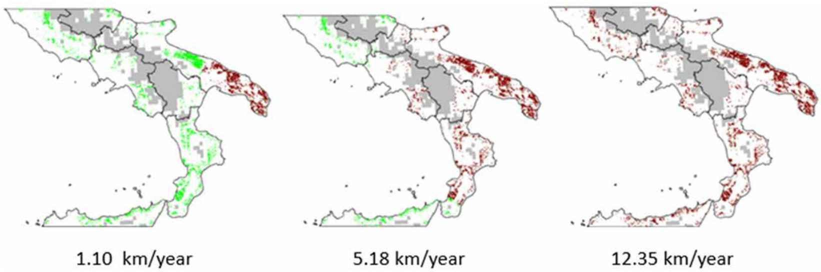

Figure 5 Sensitivity of proportion of invaded olive production area after 50 years to the rate of radial expansion (19–88% of the Italian area of production invaded at *t* = 50 years). Unsuitable area in gray, not infested olive cells in green, infested olive cells in red.

Table 3 Estimated direct economic impact due to *X. fastidiosa* in olives over 50 years

Radial dispersal rate (km/year)	Direct economic impact (€ bn)		
	No replanting (situation 1-2)	Resistant replanting (situation 1-3)	Benefit replanting (situation 3-2)
1.10	2.38	0.80	1.58
5.18	4.02	1.47	2.55
12.35	7.42	2.91	4.51

Across the evaluated rates of radial range expansion, the potential direct impact over a 50-year period ranged from €2.38 bn to €7.42 bn if replanting with resistant cultivars was not feasible (Table 3). If replanting with resistant cultivars was feasible, the impact ranged from €0.80 bn to €2.91 bn. Moreover, results indicate that, depending on whether replanting was feasible, €0.67–€1.63 bn could be saved over the course of 50 years if the spread was reduced from 5.18 km to 1.1 km per year (50th and 5th percentiles of the elicited spread rate distribution). Based on these results, it was concluded that, irrespective of the uncertainty in the rate of dispersal, the direct impacts over a 50-year planning horizon were sizable and hence warranted actions from regulators and the public. Moreover, results indicated clear economic savings that could be secured if resistant varieties are breed and/or the spread rate is reduced.

For the evaluation of the indirect impacts, a partial equilibrium model was defined on the European olive oil market to estimate changes to consumer and producer welfare from the reduction in supply and the associated increase in price. Within the defined model, Italy, Greece, Spain and the rest of EU (RoEU) and the rest of the world (ROW) were included as separate markets. Spread simulations were used to compute the newly infected share of the production areas in the four included EU countries (Table 4); their outcomes were used to

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Table 4 Shares of olive production areas affected after 50 years of uncontrolled spread in dependence on the rate of radial range expansion

Radial dispersal rate (km/year)	Italy (%)	Greece (%)	Spain[a](%)
1.10	19	0	0
5.18	52	5	0
12.35	88	53	0

[a]Independent of the dispersal rate, Spain remained unaffected during the simulated time horizon.

predict the change in supply due to reduced yields and changes in operational costs.

Prices across countries were assumed to be coupled to the world market price but differed in trade costs/tariffs by a constant wedge, which was calibrated on historical market data. Changes in price due to reduced supply were determined by country-specific elasticities of supply and demand. The total indirect impact was computed as the sum of total discounted future welfare losses due to the spread of the disease and associated changes in the equilibrium price and quantity (for more model details, see Schneider et al., 2021).

Table 5 depicts the indirect economic impact for all countries computed by aggregating the difference in welfare between the baseline scenario without *X. fastidiosa* and the different spread rate scenarios over the time horizon of 50 years. Negative values indicate economic losses, while positive values depict gains. Impacts on total welfare (TW) arise through changes in the consumer surplus (CS) and total producer surplus (PS), where the latter consists of changes in the producer surplus for non-affected farmers (PSn) and affected farmers (PSa).

Over the course of 50 years, the median rate of radial expansion of 5.18 km/year resulted in an indirect impact of −€9.91 bn in Italy. This outcome was mostly driven by negative changes in the producer surplus (€8.95 bn) but also due to a decrease in the Italian consumer surplus (€2.71 bn). For Greece, the net result suggested economic benefits due to the epidemic of around €0.50 bn over the course of 50 years. This outcome was driven by a higher producer surplus in Greece (€1.31 bn) due to the increase in prices over the time horizon. Greek consumers were adversely affected by this price increase with their surplus decreasing by around €0.86 bn. Similarly, Spain experienced economic benefits of around €4.70 bn over the course of 50 years through a sizable increase in producer surplus (€7.74 bn) which outweighed the adverse effects on consumers (€3.04 bn). However, Europe-wide the total welfare loss following a median rate of radial range expansion of the epidemic was €5.26 bn. This loss was driven by the aforementioned adverse impacts on consumers (€7.78 bn), which outweighed the benefits that arise to producers due to higher prices (€2.52 bn).

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Table 5 Indirect economic impact over 50 years for all countries in € bn given the evaluated spread rate scenarios (RoEU = rest of EU)

Country	CS	PS	PSn	PSa	TS
Radial expansion rate 1.10 km/year					
Italy	−1.54	−4.07	−4.94	0.87	−5.61
Greece	−0.49	0.84	0.84	0.00	0.35
Spain	−1.73	4.34	4.34	0.00	2.61
RoEU	−0.67	0.35	0.35	0.00	−0.31
EU total	**−4.43**	**1.47**	**0.60**	**0.87**	**−2.96**
Radial expansion rate 5.18 km/year					
Italy	−2.71	−7.20	−8.95	1.75	−9.91
Greece	−0.86	1.35	1.31	0.05	0.50
Spain	−3.04	7.74	7.74	0.00	4.70
RoEU	−1.18	0.63	0.63	0.00	−0.55
EU total	**−7.78**	**2.52**	**0.73**	**1.80**	**−5.26**
Radial expansion rate 12.35 km/year					
Italy	−5.35	−12.66	−15.76	3.10	−18.01
Greece	−1.67	0.97	0.31	0.66	−0.70
Spain	−6.06	16.01	16.01	0.00	9.95
RoEU	−2.38	1.33	1.33	0.00	−1.05
EU total	**−15.46**	**5.65**	**1.89**	**3.76**	**−9.81**

The tendencies described earlier were also found for the other two spread rates (i.e. the 1.10 km/year and 15.35 km/year). In general, all European consumers and producers in Italy were adversely affected, whereas Greek, Spanish and other European producers benefited from the reduction in supply and the associated increase in prices. As high rates of radial range expansion resulted in larger reductions in supply, the magnitude of impact increases depending on the rate of radial range expansion.

Around €2.3 bn in welfare could be saved if the spread was reduced from 5.18 km to 1.1 km per year. A reduction of the rate of radial range expansion from 12.35 km to 5.18 km per year would save around €4.55 bn in welfare. The indirect benefits consumers derived from this reduction in the spread were even larger than the aforementioned net benefits. Around €3.35 bn and €7.68 bn in consumer surplus could be saved by reducing the rate of radial range expansion from 5.18 km/year to 1.10 km/year and from 12.35 km/year to 5.18 km/year, respectively.

The analysis of indirect economic impacts extends the insights obtained from the direct impact assessment by highlighting the distribution of impacts among countries and market participants. Results indicated that most of the indirect economic impacts is suffered by Italian producers and consumers.

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While consumers in other EU countries also incurred sizable indirect economic impacts due to higher prices for olive oil, producers in non-affected EU territories were expected to benefit from the reduced supply in the EU market and the associated increase in prices. The results showed that spread reduction of *X. fastidiosa* not only benefited Italian producers but more so the European consumers. Utilizing public funds to enact regulatory measures or provide economic incentives to reduce the rate of spread should find general approval by regulators and the public given the sizable economic welfare that can be saved for the European consumers/taxpayers.

6 Conclusion and future trends

Economic research on invasive pests has expanded rapidly in recent decades, focusing on impact assessments to determine whether the introduction of a pest results in unacceptable economic consequences and – in case they are judged to be unacceptable – to identify cost-effective prevention and control measures. Hence, economic impact assessments have been essential in developing and prioritizing mitigation options.

On conducting an economic impact assessment, risk analysts must make choices regarding the most appropriate technique to apply. Depending on the objective of the study (scope, scale, timeline), the appropriate technique needs to provide an acceptable estimate of the economic impacts, while minimizing uncertainty with respect to conclusion. In addition, the technique should use the minimum possible resources in terms of data, skills and time.

Partial budgeting is often considered the default method of choice. This technique estimates the producer-level impacts with low uncertainty and requires modest number of resources. However, its economic scope is limited and does not include indirect effects of pest damage that follow from changes in market prices, supply and demand. In those cases where a significant change in social welfare is expected due to the occurrence of indirect effects, partial equilibrium modeling is the method of choice. Resource requirements for partial equilibrium modeling are, however, higher than requirements for partial budgeting. The I-O and CGE modeling techniques are rarely used in pest impact assessments; they are resource-intensive and their scope usually exceeds what is required for an impact assessment.

Independent of the method applied, a critical limitation in economic assessment modeling remains the ability to model feedback mechanisms between the biological and economic systems. Behavioral responses (adaptation) of stakeholders with respect to the spread of the pest and the political and institutional environment of the endangered area can influence the degree of social acceptability and technical feasibility of disease control measures, which strongly determines the course of the invasion (Fenichel

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et al., 2011). These inherent feedback mechanisms, therefore, require further research attention (Pacilly et al., 2016).

As invasive plant pests are expanding their ranges due to climate change, new challenges are created with respect to invasive pest management. Early detection could tackle some early invasions, but limited resources make it impossible to monitor every range-shifting pest species. Prioritizing range-shifting invasive pests provides a unique opportunity for early detection and rapid tackling of future problems of pest species before they can establish and spread. Economic impact assessments will be indispensable in establishing these targeted priority pest monitoring lists.

7 Where to look for further information

7.1 Further reading

- A good review on the concepts of economic impact assessments is provided by Epanchin-Niell (2017), Soliman et al. (2015) and Welsh et al. (2021).
- The book New Approaches to the Economics of Plant Health by Oude Lansink (2007) focuses on a number of scientific developments regarding the economic analysis of the impacts of invading pest organisms.
- International standards for conducting a pest risk assessment, including an economic analysis, are defined by ISPM11 'Pest risk analysis for quarantine pests' and ISPM21 'Pest risk analysis for regulated non quarantine pests', which can be inspected by: https://www.ippc.int/en/core-activities/standards-setting/ispms/.

7.2 Key journals

- Journals covering economic impact assessments related to pest invasions include Crop protection, Ecological Economics and Journal of Environmental Management.

7.3 Major international research projects

- PRATIQUE (enhancements of Pest Risk Analysis TechniQUEs), focusing on the development of methods to assess pest risk and analyze management options, https://secure.fera.defra.gov.uk/pratique/.
- POnTE (pest organisms threatening Europe) focusing on the biology, epidemiology, vector ecology and economic impacts of three main pathosystems that threaten strategic crops and natural landscapes in the EU, www.ponteproject.eu/.

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- HOMED (holistic management of emerging forest pest and diseases), aiming at the development of a full panel of scientific knowledge and practical solutions for the management of emerging native and non-native pests threatening European forests, www.homed-project.eu/.

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