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Review

Economic impact assessment in pest risk analysis

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ABSTRACT

According to international treaties, phytosanitary measures against introduction and spread of invasive plant pests must be justified by a science-based pest risk analysis (PRA). Part of the PRA consists of an assessment of potential economic consequences. This paper evaluates the main available techniques for quantitative economic impact assessment: partial budgeting, partial equilibrium analysis, input output analysis, and computable general equilibrium analysis. These techniques differ in width of scope with respect to market mechanisms (relationships between supply, demand, and prices), and linkages between agriculture and other sectors of the economy. As a consequence, techniques differ in their ability to assess direct and indirect (e.g. economy-wide) effects of pest introduction. We provide an overview of traits of the available methods to support the selection of the most appropriate technique for conducting a PRA. Techniques with a wider scope require more elaborate data, and greater effort to conduct the analysis. Uncertainties are compounded as methods with greater scope are used. We propose that partial budgeting should be conducted in any risk assessment, while more sophisticated techniques should be employed if the expected gains in insight outweigh the costs and compounded uncertainties.

1. Introduction

The worldwide increase of trade in plant material, the introduction of new crops and the continued expansion of trade blocks (e.g. the EU) result in increased threats of introduction of new plant pests. According to the International Plant Protection Convention (IPPC) and the World Trade Organisation Agreement on the Application of Sanitary and Phytosanitary Measures (WTO SPS Agreement) (WTO, 2009), any measure against the introduction and spread of new pests must be justified by a science-based pest risk analysis (PRA). As a result, PRAs are an essential component of plant health policy, allowing trade to flow as freely as possible, while minimizing to a reasonable and justifiable extent the risk of introduction of plant pests.

FAO (2007a) defines a PRA as "*the process of evaluating biological or other scientific and economic evidence to determine whether an organism is a pest, whether it should be regulated, and the strength of any phytosanitary measures to be taken against it*". As part of a PRA, an "*evaluation of the probability of the introduction and spread of a pest and the magnitude of the associated potential economic consequences*" is conducted. Estimation of the potential economic consequences of pest invasions is thus a fundamental component of every PRA. If the risk of introduction and spread is judged to be unacceptable, phytosanitary measures can be imposed to reduce the risk to an acceptable level (FAO, 2004). Two International Standards on Phytosanitary Measures (ISPMs), ISPM No. 2 (FAO, 2007b), "Guidelines for Pest Risk Analysis" and ISPM No. 11 (FAO, 2004) "Pest Risk Analysis for quarantine pests" set out the procedures for conducting PRAs for quarantine pests (IPPC, 2009). Standard No. 2 focuses on the initiation stage of a PRA while the emphasis in standard No.11 is on the pest risk assessment and risk management components of a PRA. In ISPM No.11, a distinction is made between qualitative and quantitative approaches for economic analysis. Qualitative approaches use expert judgment measured in non-metric terms (e.g. Likert scale), while quantitative approaches focus on information expressed in metric terms (FAO, 2007a).

In practice, the economic assessment within most PRAs, including those undertaken in Europe follow the PRA scheme and are based mostly on a qualitative approach, i.e. expert judgment (Sansford, 2002; Brunel et al., 2009). Expert judgment has enormous advantages in terms of low cost and efficient use of qualitative expert knowledge, but it may suffer from important drawbacks as lack of transparency and repeatability (Sansford, 2002). Qualitative approaches may be (ab)used for political or protectionist goals. To guard against this, many plant protection agencies in the

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world, including the European Plant Protection Organization (EPPO) have developed explicit decision schemes for making PRAs. The scheme provides detailed instructions for the successive stages of PRA, providing a framework for organizing biological and other scientific and economic information, and assessing risk. This leads to the identification of management options to reduce risk to an acceptable level (Anonymous, 1997; Brunel et al., 2009). Such a structured procedure makes a qualitative approach explicit and transparent, but the underpinning of a decision during application of the scheme may still be subjective, even if it is explicit. The need for quantitative and more objective approaches is therefore keenly felt (Baker et al., 2009).

ISPM No.11 mentions in particular three techniques for quantitative economic assessment: partial budgeting, partial equilibrium analysis and computable general equilibrium analysis. Partial budgeting is a method that addresses the additional costs and lost revenues that are incurred at the producer level when a pest invades. This method takes into account the area attacked by the pest, the loss per unit area, and the price of the product, but it does not include relationships between production volume and prices, or interlinkages between markets. Partial equilibrium modeling does take into account the price effects of changes in production volume in addition to those factors already taken into account by partial budgeting. Partial equilibrium modeling techniques also address linkages to other agricultural markets, e.g. due to substitution of one product by another. Computable general equilibrium modeling techniques are the most comprehensive and complex tools to look at effects of pest invasion on the whole economy. The techniques thus differ markedly in scope, i.e. the extent to which the impacts for the economy at wide are addressed. As a result they differ in data requirements, the level of expertise needed to conduct the analysis, and the time investment required to complete an analysis. Partial budgeting is the easiest and fastest to conduct, and computable general equilibrium modeling the most difficult and time consuming. No guidance is given in ISPM No.11 as to the pros and cons of different techniques for conducting economic impact assessment.

The limited use of quantitative economic techniques, and advanced economic techniques in particular, may be due to limited familiarity with these techniques in the professional field of regulatory plant protection. More generally, it is not clear whether the greater scope of more advanced techniques justifies the extra effort required in terms of data collection and human resources (Vose, 2001; Sansford, 2002). Also, it is felt that advanced techniques may require data that are impossible to obtain or characterize with sufficient certainty. It is felt that the more comprehensive techniques may introduce more uncertainty in the results than is justified by the extra insights they may provide (Vose, 2001; Sansford, 2002). The key question is: what added value does an advanced quantitative method for assessing economic impacts bring to the PRA, and does this extra value justify the costs in terms of data and resources?

In this paper we review the main quantitative methods that may be used for estimating the economic impact of pest invasions. We evaluate characteristics of these methods in terms of goals, founding principles, scope, and data requirements, and provide criteria that may be used in selecting the most appropriate technique for conducting a PRA.

2. Quantitative economic techniques

2.1. Partial budgeting (PB)

PB is a basic method designed to evaluate the economic consequences of minor adjustments in a farming business. The method is based on the principle that a small change in the organization of a farm business will reduce some costs and revenues, but at the same time add others. The net economic effect of a change will be the sum of the positive economic effects minus the sum of the negative effects (Table 1). Due to the marginal approach, PB is not designed to show the profit or the loss of a farm as a whole, but the net increase or decrease in farm income. With respect to plant production, various PB applications are known, primarily assessing the profitability of management options such as irrigation, pesticide use and fertilizer use (e.g. Arpaia et al., 1996; Donovan et al., 1999; Pemsl et al., 2004). Partial budgeting is also a suitable tool for assessing the economic impact of pests (Macleod et al., 2003; FAO, 2004).

The strength of PB in conducting a pest risk assessment is its simplicity and transparency. PB has a low complexity level with respect to resource needs as it requires a limited amount of data, skills, and time investment (Holland, 2007). Although the method is designed to evaluate the direct impact at the producer level, PB can also be used at the national or continental level by scaling up the budgetary impacts of the individual farms (Rich et al., 2005). Macleod et al. (2003) and Breukers et al. (2008) used PB to assess economic consequences of invasion of a quarantine pest or disease at the national level. However, PB is not suited to measure long-term effects or impacts in other sectors of the economy due to its reliance on fixed budgets with predetermined coefficients (i.e. price) to describe an isolated activity. Any change in production caused by a pest invasion could have a long-term effect on total market supply and prices, thereby affecting other producers and other sectors of the economy such as transport and the processing industry (Macleod et al., 2003). Aggregation of PB results from a representative farm to reflect costs at a higher scale will therefore only be representative if price effects and interlinkages with other sectors are weak. These shortcomings of PB can be counterbalanced by a complementary use of techniques that are described below.

2.2. Partial equilibrium modeling (PE)

PE is a powerful tool to evaluate the welfare effects on participants in a market which is affected by a shock like a policy intervention or an introduction of a pest. The approach is based on defining functional relationships for supply and demand for the commodity of interest to determine the market equilibrium or, in other words, the combination of prices and quantities that maximizes social welfare (Mas-Colell et al., 1995). Maximum social welfare is realized when consumers and producers – in aggregated terms – maximize their utilities and profits as illustrated in Fig. 1A. This figure shows a downward-sloping demand curve, reflecting diminishing marginal utility as consumption increases, and an upward-sloping supply curve, reflecting increasing marginal costs

Table 1
Partial budgeting layout.

Partial budget: Comparison current situation (no pest) versus alternate situation (pest invasion)	
Costs	Benefits
A) Additional costs: costs under the alternate situation that are not required under the current situation	**C)** Additional revenues: revenues under the alternate situation that are not received under the current situation
B) Reduced revenues: revenues under the current situation that will not be received under the alternate situation	**D)** Reduced costs: costs under the current situation that will be avoided under the alternate situation
Total costs: A + B	**Total benefits: C + D**
Net change in profit: C+D−A−B	

Box 1. : An illustrative example on partial budgeting

The case study of *Potato Spindle Tuber Viroid* (PSTVd) in the EU

This example uses PB to evaluate the direct economic consequences (viz. yield and/or quality losses and additional protection costs) of a PSTVd invasion in the EU. Initiation steps within the evaluation consist of 1) identification of the endangered along with 2) estimation of the potential for spread and 3) determination of the economic value of susceptible assets within the endangered area. Regarding the second step, we assume for simplicity, that PSTVd will invade the whole endangered area (worst case scenario). When considering only the main host crop, i.e. potatoes, the total endangered area within the EU is approximately 500,000 ha, yielding 14 M tons potatoes/year at a value of € 1890 M based on an average price of 140 €/ton. Based on the assumption of an average yield loss of 30% by PSTVd, revenues are expected to reduce € 567 M/year (30% × € 1890 M). Additional crop protection cost can be quantified by multiplying the current protection cost (€118 M/year) with the expected increase. Experts expect that in case of a PSTVd invasion, farmers will double their protection efforts, resulting in € 118 M/year extra costs. The total negative impact of a PSTVd invasion is the sum of yield loss and additional protection cost, which equals € 685 M/year.
Results (in M€) of partial budgeting analysis for potato spindle tuber viroid (PSTVd).

Costs		Benefits	
Additional costs		Additional revenues	
Control costs	118		0
Reduced revenues		Reduced costs	
Yield loss	567		0
Total costs	685	**Total benefits**	0
Net change in profit		**−685**	

of production. The market equilibrium (E_0), where quantity supplied equals quantity demanded, occurs at an equilibrium price of P_0 and quantity Q_0. The difference between P_0 and the demand curve represents how much consumers benefit by being able to purchase the product for a price that is less (P_0) than they would be willing to pay. This total benefit derived by the consumers, or consumer surplus, is represented by the triangle labeled 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_0) times quantity (Q_0), 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. Social welfare is defined as the sum of consumer surplus and producer surplus.

By PE analysis, the aggregate impact of a shock is determined by measuring the differences in equilibrium price and quantity, and change in welfare before and after the shock. A shock, like a pest invasion, may lead to a loss in yield and an increase in production costs, resulting in an upward shift in the supply curve (Fig. 1). This shift in the supply curve alters the equilibrium point (Fig. 1B), implying a decrease in quantity supplied (from Q_0 to Q_1) and an increase in market price (from P_0 to P_1). Producer losses, or the reduction in producer welfare, that result from the new equilibrium point can be calculated by comparing PS before and after invasion. In the same way, changes in consumer welfare can be calculated. The change in social welfare is determined by the aggregated impact of the changes in producer welfare and consumer welfare (Just et al., 1982).

For the purpose of illustration, the demand curve in Fig. 1B is assumed to be unaffected by the shock. In reality, demand can also be affected; for instance, the presence of a pest might affect consumer preferences, thereby shifting the demand curve down, resulting a lower price and quantity at equilibrium.

Partial equilibrium modeling has been widely applied to the analysis of agricultural policy, international trade and environmental issues (e.g. Qaim and Traxler, 2005; Elobeld and Beghin, 2006; Cook, 2008; Kaye-Blake et al., 2008; Schmitz et al., 2008). Examples of recent applications on pest risk assessment are the analyses performed by Arthur (2006), Breukers et al. (2008) and Surkov et al. (2009). Arthur (2006) used PE to evaluate the impact on net social welfare of liberalizing the Australian apple market for imports from New Zealand, accounting for the risk of entry of *fire blight* disease in Australia. The benefits were presented in terms of consumer welfare gain, resulting from lower apple prices due to an increased supply from abroad, while the costs were derived from the reduction in producer welfare as a consequence of losses in production and expenditures to control the pest. Measuring the

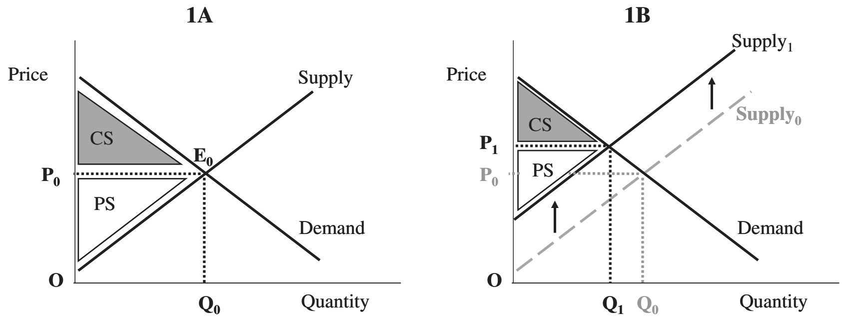

Fig. 1. Impact of shock on market equilibrium.

Box 2. : An illustrative example on partial equilibrium

The case of *Potato Spindle Tuber Viroid* (PSTVd) in the EU – continued

The indirect economic consequences of a PSTVd invasion (viz. price and economic welfare effects in the potato market) are estimated using PE modeling.

Before the invasion, the potato market is in equilibrium, which means that supply (S) equals demand (D). Supply of potatoes (i) is given by the function, $S_i = \beta_i P_i^{\theta_i}$, where P_i is producer price, β_i a parameter, and θ_i the supply elaisticity, representing the percentage change in the quantity supplied after a 1% change in the price. Demand for potatoes is given by $D_i = \chi_i P_i^{-\eta_i}$, where η_i is the demand elasticity and χ_i a parameter.

After the PSTVd invasion, the total potato area is divided in an affected and a non-affected area. In the affected area, the supply of potato growers is determined by the change in the price of potatoes (P_i), yield loss (h_i), additional crop protection costs (v_i) and the size of the area affected (z_i). Thus the supply of affected producers is represented by $SA_i = (1 - h_i)\beta_i(v_i P_i)^{\theta_i} z_i$. In the non-affected area, producer supply is affected only by the change in the price of potato and is given by $SN_i = \beta_i P_i^{\theta_i}(1 - z_i)$. With M_i representing import volume, the difference between total supply $S_i = SA_i + SN_i + M_i$ and domestic demand (D_i) reflects export volume (X_i) Therefore, total demand (i.e. $D_i + X_i$) is equal to total supply (i.e. S_i). The net export is given by $X_i = \phi_i WP_i^{\omega_i}$, where ω_i equals export elasticity, ϕ_i a parameter and WP_i the world market price which is connected to the domestic price through a price margin ($P_i = WP_i + \mu_i$) (Surkov et al., 2009).

Results of a partial equilibrium model are presented in terms of changes in quantity supplied and demanded, price and economic welfare for producers and consumers. Based on input assumptions of a production level of 58.9 M ton/year, a consumption level of 57.5 M ton/year, exports of 2.7 M ton/year, imports of 1.3 M ton/year and demand and supply elasticities of −0.48 and 3.2 respectively, the PE results demonstrate that – as a consequence of a PSTVd invasion - production and consumption decrease by 0.41% and 0.4% respectively, exports decrease by 0.44%, domestic and world prices increase by 0.73% and 0.84% respectively, producer welfare increases by 0.02% and consumer surplus decreases by 0.43%. Supply by affected producers decreases, which explains the increase in the price of potatoes. The price increase leads to an increase in total producer welfare (of producers in the affected and non-affected area). In this example, the direct negative impacts (i.e. yield loss and additional control cost) are transferred from producers to consumers. In this case the PE analysis adds a valuable insight by showing *how* the negative impact of the PSTVd invasion is distributed between producers and consumers and by showing what the underlying causes for the indirect impacts are.

change in net social welfare, Arthur concluded that Australia would be better off by $90 million even if fire blight became established across all areas. Breukers et al. (2008) modelled the impacts of repeated brown rot outbreaks on supply and (national and export) demand of seed potatoes. They found that the indirect effects as a consequence of reduced export demand are far bigger than the direct effects (yield losses). Surkov et al. (2009) determined the optimal phytosanitary inspection policy in the Netherlands given the estimated costs of introduction of pests through trade pathways. In this study the PE approach was used to account for the potential price effects due to a pest introduction .

The use of PE within a pest risk assessment is appropriate when the pest impacts are expected to change prices or social welfare significantly. PE analyses can be conducted with respect to one sector (single-sector model) or multiple sectors (multi-market model). Multi-market models link related markets and are, therefore, able to capture spillover effects between main markets as, for example, the impact of a pest affecting wheat supply on supply and demand of potential substitute crops like corn. The calculation of producer and consumer surplus in multiple markets involves sequentially computing the effects in each of the affected markets.

Within each PE model main assumptions needs to be made to define the structure of the affected market(s) (e.g. perfect 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; Rich et al., 2005; Baker et al., 2009) as data are needed to reflect the affected markets, including data on prices, quantities, and price elasticities of both supply and demand.

Despite its suitability for the evaluation of effects on markets of agricultural commodities, PE is limited in its ability to account for economy-wide effects. PRA by PE is, therefore, only appropriate when the indirect impact of the pest is not expected to significantly affect other non-agricultural markets or to generate measurable macroeconomic changes (e.g. changes in income and employment). For applications that require an economy-wide scope Input–Output analyses or Computable General Equilibrium modeling approaches may be needed.

2.3. Input–Output analysis (I–O)

The technique of I–O analysis focuses on the interdependencies of sectors in an economy (regional or national), making it suitable to predict an economy-wide impact of changes within a particular sector (Leontief, 1986). Central to an I–O analysis is the specification of an I–O table to describe the monetary flows of inputs and outputs among the productive sectors of an economy (Miller and Blair, 1985). In an I–O table, economic sectors are aggregated into representative groups. Each sector-group is represented by a row and a column. The rows of the table specify the distribution of total output of a specific sector sold to other sectors (i.e. to intermediate demand) or to final demand (e.g. to final consumption, investments and exports). The columns refer to the production side of a given sector, by denoting the value of inputs of each sector required to produce output.

Table 2 represents a hypothetical I–O table with 3 productive sectors, viz. agriculture, industry and transport. In this example, the

Table 2
Hypothetical I–O table indicating monetary flows of an economy in a specific time period.

		Purchasing sectors			Final demand	Total output
		Agriculture	Industry	Transport		
Selling sectors	Agriculture	80	300	30	60	470
	Industry	120	500	150	350	1120
	Transport	40	200	10	10	260
Value-added		25	120	15	100	260
Total Input		265	1120	205	520	2110

agricultural sector sells a value of 80 of output within agriculture, 300 of output to industry and 30 of output to transport, whereas a value of 60 is intended for the final demand. As denoted by the column accounts, the industrial sector purchases for its production a value of 300 in intermediate products from the agricultural sector, 500 of input within industry and 200 of input from transport, leading to a value added of 120. The value added cell includes payments to employees, holders of capital, and governments (e.g. wages and salaries, interest, dividends, and taxes) and represents the value that a sector adds to the inputs it uses to produce output. The value added row measures each sector's contribution to wealth accumulation.

Any change in final demand for the products of a sector generates direct as well as indirect effects on the economy as a whole. Changes create large primary "ripples" by causing a *direct* change in the purchasing patterns of the affected sector. The suppliers of the affected sector must alter their purchasing patterns to meet the demands placed upon them by the sector originally affected by the change in final demand, thereby creating a smaller secondary "ripple". In turn, those who meet the needs of the suppliers must change their purchasing patterns to meet the demands placed upon them by the suppliers of the original 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 as a result 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 agricultural sector according to the expected shock to demand (e.g. reduction in exports), multiplied by the multiplier matrix. Examples of recent applications to pest risk assessment are the analyses performed by Elliston et al. (2005) and Juliá et al. (2007). Elliston et al. (2005) used I–O analysis to investigate the regional economic impact of a potential incursion of *Karnal bunt* in wheat in Queensland. As *Karnal bunt* is considered a quarantine disease in Australia's most important wheat export markets, an incursion in Australia would lead to a significant loss of export markets. In the scenario of a widespread incursion the direct effect in the wheat and other grains industries was estimated as an $89 million decline in output over a fifteen year planning horizon and a loss of 400 full time jobs. The indirect effects of the incursion in all other industries were estimated as a decline of $38 million in output and a decline in employment of 200 full time jobs.

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

The strength of the I–O approach is its ability to capture spillover effects between economic sectors. The accuracy of this 'capture' depends on the level of sector aggregation in the I–O tables. If the level of aggregation is too high, indirect impacts of a shock will be overestimated. Lower levels of aggregation are, however, associated with substantial increases in data requirements.

In addition to its high data requirement, the potential use of I–O analysis is restricted by two fundamental assumptions. First, I–O models only account for changes in the economy due to shifts in demand; supply is assumed to be perfectly elastic. Since supply constraints are often present in agriculture, I–O models may miss important effects of a pest introduction. Second, due to the use of fixed coefficients, I–O models 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. However, this static assumption can be justified if the I–O technique is used to analyze only short-term impacts.

To conclude, the I–O approach provides the opportunity to measure short-term, spillover impacts across broad sectors of the economy given plant health incidents that affect the demand side only. For applications that require the economy-wide scope of I–O models as well as the economic realism of PE models, a Computable General Equilibrium Modeling approach would be more appropriate.

2.4. Computable general equilibrium modeling (CGE)

The CGE approach combines the strengths of I–O analyses and PE models to answer a wide range of questions. It uses I–O tables to represent the entire economy with the inclusion of functional relationships between actors in this economy as in a PE model. The basic structure of a CGE model can be described in terms of "blocks" of equations that specify demand relationships, production technologies, relationships between domestic and imported goods, prices, household income and numerous equilibrium conditions. Such a framework enables CGE models to address questions concerning impacts across sectors and employment groups as well as price changes and longer-run impacts. This capacity, however, makes CGE models highly complex, imposing high costs in the development of such a model as well as in the interpretation of its results (Sadoulet and de Janvry, 1995; Dixon and Parmenter, 1996).

By nature CGE models are highly aggregated, making it difficult to analyze a change in a sub sector of the economy. Many CGE models are disaggregated into only two agricultural sub-sectors, such as tradable and non-tradable crops, or food crops and cash crops (Bourguignon and Pereira da Silva, 2003). Applications of CGE models are, therefore, only appropriate to address large-scale problems which are most likely to generate measurable macroeconomic impacts. Pest invasion problems rarely generate such major effects as changes in aggregate employment, income or inflation rate. As a consequence, there are few applications of CGE applications in pest risk assessments. Recent applications are those of Wittwer et al. (2005, 2006). In Wittwer et al. (2005) a CGE model was used in order to quantify the impact of a hypothetical outbreak of the *Tilletia indica* fungus (the causal agent of *K. bunt*) on the wheat crop in west Australia. In their analysis, the effects on output, income, employment, wages, capital stocks and exports were estimated. In a second paper, Wittwer et al. (2006) investigated by the use of CGE the economic consequences of introducing *Pierce's disease* of grapevine in South Australia. Special attention was given to the adjustment in the labour market as a result of the disease outbreak.

3. Synthesis and implications

Plant import regulation is an indispensible tool for protecting agriculture and the environment against pest invasions, but overly strict import restrictions can unnecessarily limit trade and reduce welfare. Science-based pest risk assessment is needed to ensure that import regulations are commensurate with the risks they mitigate (WTO, 2009). Quantitative economic impact assessment is a pivotal element of science-based pest risk assessment, and this paper has addressed the four most important techniques that may be used for such assessments.

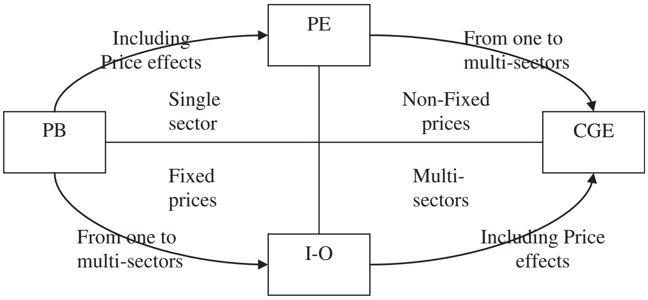

Fig. 2. Relationships between the evaluated quantitative economic techniques.

Techniques based on linear or dynamic programming were excluded from the overview as these optimization methods are more suitable for risk management evaluations than risk assessment analyses. With respect to plant health economics few applications are known of which the majority focuses on the determination of an optimal pest control management scheme (Hal and Hastings, 2007; Chalak-Haghighi et al., 2008).

The four evaluated economic risk assessment techniques differ markedly in their scope and contents (Fig. 2). While PB is a basic and easily understood technique for assessing direct impacts, its scope is limited, and does not include indirect effects of pest damage as a result of effects on market prices, supply, and demand, nor does it address spillover effects to other sectors of the economy. PE or CGE modeling techniques widen the scope to include those price effects, in the first case for the affected commodity only, and in the latter case for the whole economy. A technique intermediate between general equilibrium modeling and partial budgeting is I–O analysis. This technique allows calculation of spillover effects of a reduction in production of an agricultural commodity to other sectors in the economy, but does not address changes in prices. The techniques are thus very different in scope, level of sophistication, data requirements, and time needed to complete an analysis (Holland, 2007; Mas-Colell et al., 1995; Miller and Blair, 1985; Dixon and Parmenter, 1996). Table 3 summarizes these differences.

The question is; what is the method of choice, given the purpose of the analysis and the available data and resources. We suggest that, despite its limitations, the default method of choice for basic economic analysis is PB. This technique provides insight in the immediate impacts of the pest, while it is easily understood and explained. The required data can often be obtained at a reasonable level of accuracy, and the human resources needed to apply the method are modest. Moreover, results of PB evaluations provide necessary input for the remainder techniques. If the objective goes beyond a first assessment of the costs of pest introduction, more sophisticated techniques warrant consideration. Partial equilibrium modeling is worthwhile if the changes in production volumes are very large, indicating the possibility of price effects. As a general rule, a pest invasion reduces supply of crops. However, with the occurrence of price effects, part of these invasion costs is transferred from producers to consumers who pay a higher price. As a result, the negative effect of pest invasion on welfare is shared between producers and consumers. A more broad-based economic technique like I–O analysis or CGE modeling may be considered if large spillover effects to other sectors of the economy are expected, or even elimination of an entire industry, along with its suppliers. In exceptional cases CGE modeling has indeed been used (Wittwer et al., 2005). I–O and CGE techniques are fundamentally feasible to calculate pest impacts, but they have been very little used in impact assessments, and are probably over the optimum level of scope needed for a proper science-based impact assessment that is fit for purpose. The ability of I–O analysis and CGE analysis to capture indirect impacts to the entire economy is rarely needed in PRA since few pests have a wide economy impact. In most cases, a combination of partial budgeting and partial equilibrium modeling can provide a sufficient scope where both direct and indirect impacts occur (Rich et al., 2005).

An ironic aspect of the choice of method is that it is difficult to know *ex ante* whether a more advanced technique is needed without actually applying the method in the first place. The results of a partial budgeting exercise are not sufficient to judge whether a partial equilibrium modeling technique would yield different results. This can only be assessed when information on price elasticities of supply and demand has been gathered, i.e. when a first exploration in the domain of partial equilibrium is attempted. There is a need for case studies in which the outcomes of different techniques is contrasted, so these can act as "case in point" and "reference cases" when choosing between techniques.

Table 3
Resource requirements, scope and scale of the evaluated economic methods.

	Data	Time	Skills	Software	Scope
PB	– Production volumes – % Yield loss – Production prices – % Increase in control costs	+/++	Basic accounting	Excel	Direct impact; impacts on yield and crop protection
PE	– Product prices – Product quantities – Price elasticities of supply and demand – % Yield loss – % Increase in control costs – Export and import data	++/+++	Basic partial equilibrium modeling and micro-econometric estimation techniques	To solve non-linear equations; Excel, Stata, E-views, SAS, GAMS	Indirect impact; single-sector effects on price, trade and social welfare
I–O	– Detailed input-output table – Income and employment data – Expected reduction in demand due to pest incursion	++/+++	Basic macro economic theory and mathematical skills (e.g. matrix algebra)	To perform matrix algebra; GUASS, GAMS, MATLAB	Indirect impact; multiple-sector effects on output, income and employment
CGE	– Social accounting matrix – Elasticities – % Yield loss – % Increase in control cost	+++/++++	Advanced economic and statistical background.	To perform matrix algebra; GUASS, GAMS and MATLAB	Indirect impact; whole economy effects on income, employment, social welfare

Based on Holland, 2007; Mas-Colell et al., 1995; Miller and Blair, 1985; Dixon and Parmenter, 1996.

It is also important to take into account the possibilities of adaptations. Adaptation is defined as ex-ante efforts aimed at reducing the severity of a pest invasion. Adaptation differs from mitigation, which comprises ex-ante efforts to reduce the probability of pest invasion. A direct negative impact on a producer could be countered by a substitution effect with a switch to other crops that are not vulnerable to the pest. If producers can adapt by growing less vulnerable crops, the total overall impact for all producers could be less severe than that indicated if only direct impacts are evaluated. Another factor that needs to be taken into account is management. Normally, if a pest invades, producers take measures to limit pest damage. It is unrealistic to calculate pest damages, assuming that producer practices will remain unchanged. Producers are profit maximizers and hence will adapt. Including issues of adaptation and management into PRA to avoid overestimation of pest impacts, requires a high level of expertise of the PR-analyst. In order to avoid subjectivity, the PRA analyst should explicitly report the extent to which adaptation and management have been accounted for.

Finally, uncertainty about model outcomes and model parameters is an important issue. What matters in the end is not whether the impact assessment was accurate in its quantitative outcome, but merely if the action justified by the assessment was correct. In other words, the mathematical problem is not so much one of estimation, but of selection (Binns et al., 2000). Thus analysis of the performance of impact assessments should not focus so much on the quantitative outcomes, but on the error rates (e.g. Nyrop et al., 1999). Two types of errors are relevant: type I errors, i.e. rejecting the null hypothesis (of no action needed) while it is true, and type II errors, i.e. accepting the null hypothesis while it is false. Type I errors occur if the impact assessment tool suggests the economic risks justify phytosanitary measures where in reality the risks are too low to warrant measures. Type II errors occur when the tool does not correctly detect risks where the actual size of the risks would warrant phytosanitary measures. Uncertainty in PRA may lead to an overestimation of the economic impacts, particularly if the precautionary principle (which is allowed under ISPM No.11) is applied, and will therefore increase the occurrence of Type I errors. Use of the precautionary principle will, on the other hand decrease the occurrence of Type II errors. The occurrence of Type I and Type II errors may be reduced by using more advanced economic impact assessment techniques such as PE, I–O and CGE, since these techniques capture a wider range of potential economic impacts. However, the extent of this reduction will be hard to quantify. Receiving Operating Characteristics (ROC) analysis could provide some insights in these error rates by providing tools to select the optimal set of techniques and to discard suboptimal ones by indicating all possible combinations of the relative frequencies of the various kinds of correct and incorrect decisions given a defined threshold (Brown and Davis, 2006). Such an analysis would require a retrospective evaluation of a sufficient large number of performed PRAs to obtain any information on the relative distributions of the correctness of the decisions made.

Uncertainty about model parameters affects the reliability of outcomes of economic impact assessment techniques in different ways. We think that the degree of belief in economic models should decrease with level of sophistication, because the greater sophistication entails making assumptions about processes that may work quite differently from how they are modelled. Thus, PB has a greater potential of giving credible results, while confidence is bolstered as anybody can check the assumptions and calculations using a basic spread sheet. PE and CGE techniques give already more uncertain results, because mathematical statements are made on the relationships between prices, and supply and demand of agricultural produce that may work out quite differently in practice than they are modelled mathematically. This is not to say that the model is wrong. The models are theoretically correct, but they are simplifications of economic reality, and it is very difficult to know the parameters that apply to the producer and consumer behaviour in the future. Therefore, such models should be interpreted as plausible trends, inferred from past behaviour, and should be used to complement the results of a PB rather than replace them. Results of PE modeling should be interpreted with caution as to the absolute magnitude of the effects. The same applies to I–O and CGE modeling techniques. The parameters for these models are usually based on historic data, augmented with theoretical arguments, and each of these methods may not provide those parameter values that correctly model future economic behaviour of producers and consumers.

Monte Carlo techniques or sensitivity analysis may help to assess uncertainty bounds for model outcomes, but it should be remembered that these bounds are derived *within* the chosen model framework and domain of data collection. Future behaviour needs not stay in the confines of those bounds (e.g. Gilligan and van den Bosch, 2008). Although impact assessments should as much as possible be supported and enriched by objective analyses, we believe that there is no substitute for expertise, experience, caution and wisdom in the domain of regulatory plant protection. The greatest strength can be found in the combination of qualitative and quantitative approaches.

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