CHAPTER 5

EVALUATING THE COST-EFFECTIVENESS OF BROWN-ROT CONTROL STRATEGIES

Development of a bio-economic model of brown-rot prevalence in the Dutch potato production chain

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Abstract. Quarantine diseases comprise a distinct class of plant diseases. In contrast to other plant diseases, direct losses through crop damage are often limited. Yet, quarantine diseases may have serious economic consequences for a country as they threaten the country's export of affected crops. In particular for this category of diseases, it is important to design a control strategy that is optimal from an epidemiological as well as an economic point of view. This chapter presents the development of a bio-economic model to evaluate control strategies in terms of their cost-effectiveness, specified for brown rot in the Dutch potato production chain.

The conceptual model consists of two modules: an epidemiological module, which is a stochastic, spatially explicit simulation model that simulates the spread of potato brown rot over all potato-growing farms and fields in the Netherlands, and an economic module, which calculates the total costs of brown-rot prevalence, based on the results of the epidemiological model.

The model is applied for two brown-rot policy scenarios, which differ in sampling frequency of harvested potato lots but are otherwise similar. The two scenarios are compared with respect to their effectiveness and efficiency. Concerning the costs of controlling brown rot, a low monitoring level appears to be more cost-efficient; however, when including expected export consequences, a high monitoring level may be preferable.

The model presented here strongly facilitates the development of an optimal control strategy as it provides insight into the effectiveness of brown-rot control strategies in relation to their costs. Moreover, the introduced modelling concept can be a useful tool in analysing the epidemiological and economic effects of other (quarantine) diseases.

Keywords: *Ralstonia solanacearum*; epidemiology; economics; quarantine disease; simulation model

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INTRODUCTION

Quarantine pests and diseases comprise a distinct class of plant diseases (Heesterbeek and Zadoks 1987). A quarantine status is assigned to diseases that are not yet present, or present but not yet established in a region and can potentially cause serious economic damage in this region (IPPC 1999). The emergence of a quarantine disease in a country involves the imposition of a national control policy, which aims at eradication of the disease and prevention of new introductions. Such policy often includes a set of measures that bring along high costs for both the government and the stakeholders of the production chain to which the measures apply, whereas the disease in itself may cause only limited or even no damage at all to the host crop. The costs of controlling the disease may thus far exceed the direct benefits of avoiding yield losses, whereas long-term benefits of the control policy are unclear.

An example of a quarantine disease with potentially high costs is brown rot in the Dutch potato production chain. The disease is caused by the bacterium species *Ralstonia solanacearum* race 3, biovar 2, which is pathogenic on, e.g., potato, tomato and several solanaceous weeds. In warm and humid growing areas, the disease can be very destructive. Outbreaks have been reported in many European countries, and, within the EU, brown rot has obtained a quarantine status (Elphinstone 2005). In the Netherlands, climatic conditions are less favourable for brown-rot population growth, and infections generally remain symptomless. Nevertheless, its presence may have serious economic consequences for the Dutch potato production chain. The risk of establishment of brown rot as an endemic disease threatens the Dutch market share of seed potatoes, which comprise an important export product of the Netherlands (Van Vaals and Rijkse 2001). To avoid economic losses resulting from reduced export, the government has imposed a costly control policy aimed at eradication of the disease from the chain.

The number of detected brown-rot infections has strongly decreased since the first outbreak in 1995. However, the intended eradication of the disease from the chain has not been achieved. The set of brown-rot measures that are currently in force are generally based on practical experiences with brown rot so far; theoretical evidence of the efficacy of a measure is often lacking. Whereas the major risk factors responsible for brown-rot prevalence dispersal are known, quantitative knowledge about the risk-reducing effects of control measures is still poor. Moreover, although the currently implied control policy seems to be effective in reducing the number of outbreaks, insight into its cost-effectiveness is lacking. In other words, possibly the same result could be achieved at reduced costs, or with a similar budget the effectiveness could be increased.

In this chapter, we present a bio-economic model to evaluate brown-rot control strategies in terms of their cost-effectiveness. The model quantifies the total costs of brown-rot prevalence, based on the simulation of brown-rot dynamics for a specific control scenario. It provides insight into the relative importance of risk factors and the efficacy of control measures in relation to their implementation costs. Thereby, the model facilitates the design of an optimal control policy. In the next section, the conceptual framework of the bio-economic model is explained. In the third section, the conceptual model is applied for the above-described case of brown-rot prevalence in the Dutch potato production chain. Finally, wider implications of this model and future perspectives are discussed.

CONCEPTUAL FRAMEWORK

The bio-economic model consists of an epidemiological module and an economic module. The epidemiological module is a stochastic, spatially explicit simulation model that simulates the spread of potato brown rot over all potato-growing farms and fields in the Netherlands over a chosen time frame. It can be run independently from the economic module to evaluate the effectiveness of control strategies. The economic module calculates the total costs of brown-rot prevalence based on the results of the epidemiological model.

Figure 1 shows a schematic representation of the bio-economic model. For a given control strategy and time frame, the epidemiological model is run to simulate brown-rot dynamics over the indicated period. As this model is stochastic, numerous replications should be run in order to obtain a representative picture of brown-rot incidence under a chosen control strategy, parameterization or set of conditions. The results of each replication are recorded in output files, which serve as input for the economic module. This module subsequently calculates the yearly costs related to brown-rot prevalence and control. The economic module does not contain any stochastic elements. However, the output of the epidemiological model contains results of all replications, so the costs can be calculated for each year in each replication, resulting in a distribution of yearly costs. In the following two subsections, the epidemiological and economic modules are explained in more detail.

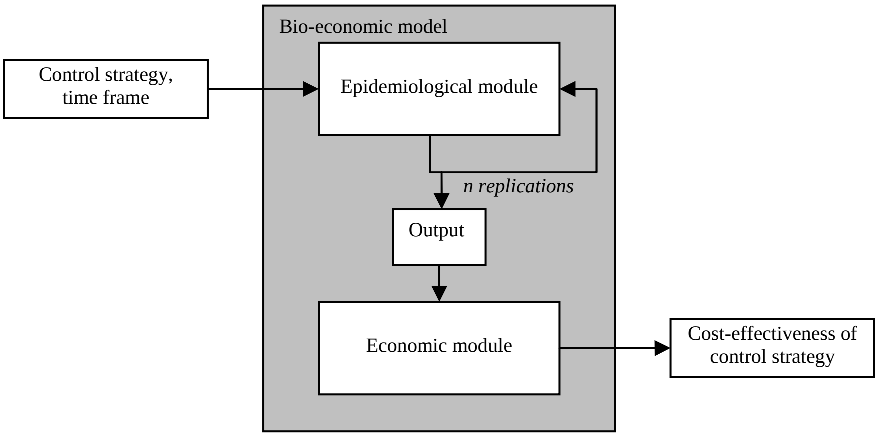

***Figure 1**. Conceptual framework of the bio-economic model*

Epidemiological module

Simulation of disease dynamics at the level of the plant production chain is still rather uncommon (Breukers et al. in press). As local circumstances of, and contacts between different infectious units are for a large part determined by human-driven processes, the epidemics of a disease are not solely determined by the pathogen's biological characteristics, and conventional epidemiological models are not appropriate anymore. In our attempt to simulate disease dynamics in the potato production chain, we used an individual-based modelling technique, which originates from the field of ecology. The essence of this technique is that it acknowledges and explicitly represents the principle that each individual is unique in its characteristics and interactions with other individuals. An individual-based model (IBM) traditionally defines the individual organism as the logical basic modelling unit instead of using aggregated-state variables to describe population dynamics (Huston et al. 1988; Grimm 1999). In our application, the modelled 'individual' is the potato lot, which is the commercial production entity of the potato production chain.

The modelled potato production chain starts with the multiplication of high-quality seed potatoes. After several years of multiplication, these seed potatoes are grown as ware or starch potatoes, which are eventually transported to retail or industry; this is where the modelled production chain ends. The production chain contains three possible pathways for brown-rot infection: primary infection, horizontal transmission and vertical transmission. Primary infection may occur as a consequence of irrigation of a potato lot with surface water; large parts of the Dutch surface water are contaminated with brown-rot bacteria as a result of the common presence of the wild host plant, woody nightshade (*Solanum dulcamara*). Horizontal transmission means infection of a healthy potato lot where the source is another infected lot, and can for instance be caused by poorly separated storage of potatoes or planting or harvesting a lot with contaminated machinery. Vertical transmission, also referred to as infection through clonal relationships, implies transmission of the disease from 'parent' to 'offspring', i.e. from one generation to the next.

The individual farms, fields and potato lots in the above-described system are represented in the model by so-called objects. Each object is described by a set of variables, or 'attributes'. The values of these attributes describe the state of each object and make each object unique. Examples of attributes are the size of a field object, the potato acreage of a farm object, and the detection status of a potato lot object. To include spatial explicitness, farm and field objects have attributes indicating their geographical location. Objects can be linked with other objects to represent certain relations between individuals. For example, an infected lot is linked to the field on which it is grown, and a farm is linked to the fields it has in use.

During a simulation run, the model separately keeps track of the dynamics of all objects included in the simulation, taking into account their unique properties and interactions. Each year of simulation consists of one production cycle, which in turn consists of a number of processes, such as planting, irrigation, testing and storage. These processes may go together with 'events', which affect the attribute values and thus the state of objects. Examples of events are ‘primary infection of a lot’ during irrigation, or ‘detection of a lot’ when an infected lot is tested for brown rot. The occurrence of an event is determined stochastically and depends on one or more parameters.

Information about the state of the system is recorded and stored in output files. At the end of a simulation, the output files contain detailed information about the number and characteristics of infected lots and the farms and fields on which they were grown. The results may strongly vary across years and replications, which is partly due to the stochasticity of most events related to infection and detection of potato lots. Another part of the variation is explained by the dynamic nature of brown rot; the number of infections in one year is partly determined by the incidence of infections in previous years. The output files of the epidemiological model serve as input for the economic module. As the output includes the variation in brown-rot prevalence, the total costs of brown rot can be presented by a frequency distribution, which allows for calculating both the average costs and the likelihood of extremely high or low costs.

The structure of an IBM is similar to the structure of an object-oriented program (Acock and Reddy 1997); therefore, the epidemiological model described here is implemented in the object-oriented programming language C++. A detailed description of the modelled system and conceptual epidemiological model is given in Breukers et al. (2005).

Economic module

The economic module calculates the total costs of brown rot for a given control policy. It distinguishes three categories: (1) structural costs, which are incurred yearly as a result of preventive measures; (2) incidental costs, which only occur in case of brown-rot detection and result from eradication measures; (3) export losses, which arise as a consequence of failure to reduce brown-rot incidence to an acceptable level. One could also discriminate between direct costs, which are clearly attributable to an outbreak, and indirect costs, which are independent of the brown-rot incidence and are incurred also by individuals that are not involved in an outbreak. Incidental costs correspond with direct costs, while structural costs and export losses can alternatively be referred to as indirect costs. Costs are incurred by stakeholders in the potato production chain, such as farmers and trading companies, as well as the governmental authorities. Possible economic consequences for other sectors, for instance the transport sector or crop protection companies, are not included in the analysis. Below, each category of costs is described in more detail and its method of calculation is explained. An overview of all cost items is given in Table 1.

Structural costs

Structural costs are incurred yearly and are more or less stable over time for a specific control strategy. They result from preventive measures against introduction and dispersal of brown rot, such as monitoring of potato lots and other potential brown-rot sources. Monitoring is done by the authorities, but growers are (partly) charged for the sampling costs of potato lots. Another preventive measure is the prohibition of surface-water use in areas where this water may contain brown-rot bacteria. The ban on the use of surface water causes losses for potato growers and trading companies due to yield reduction and quality disorders caused by common scab. These losses of brown rot only occur in areas where alternatives to surface water (e.g., groundwater) are not available.

The total structural costs are calculated by summing up all components of structural costs.

Incidental costs

Incidental costs are directly related to eradication measures following detection of an infected lot, such as destruction of a detected lot and tracing of lots that might have been in contact with this lot. Furthermore, lots that are not found to be infected in a test but nevertheless are highly suspected because of clonal or spatial relationships with an infected lot, are defined as ‘probably infected’ and downgraded. Such lots cannot be replanted and can be marketed only under strict conditions, often for low prices. The losses for a farm resulting from destruction and downgrading are considerable. Seed-potato growers multiplying their own seed potatoes for several successive years face even higher losses, as they have the costs of buying new planting material. Furthermore, affected growers may earn lower revenue per hectare for one or more years after detection as a result of restrictions on the crops that can be grown on the farm and field on which a detected lot was grown. Labour costs at farm level are not included; it is assumed that a farmer will not hire (extra) labour and that the opportunity costs of the farmer’s own labour are zero.

The incidental costs for affected potato growers are calculated by partial budgeting. This technique quantifies the economic consequences resulting from a change at the farm level (i.e. detection of an infected lot). Four components are accounted for: extra costs, returns forgone, reduced costs, and additional returns (Rushton et al. 1999; Dijkhuizen and Morris 1997). The tracing costs are determined by the number of extra samples that must be taken, which is given by the epidemiological model. All costs made at farm level and the costs of tracing are subsequently summed up to obtain the total incidental costs.

Export losses

As a result of inability to achieve a low and stable level of brown-rot incidence, the potato sector, or even the national economy, may experience negative consequences from the presence of brown rot. Prolonged presence of brown rot in the Dutch potato production chain will harm the image of the sector and its products in importing countries, which has a negative effect on export volume and consequently on the potato price. In particular, export of seed potatoes will be reduced, as these potatoes are replanted and thus comprise a high risk of introducing brown rot in the potato production chain of the importing country. Lower prices may in the long run result in a reduction in national potato production, as growers will replace part of their potato acreage by other, more profitable crops.

The relation between brown-rot incidence and the level of export consequences is difficult to quantify. Therefore, the losses due to export consequences are qualitatively assessed based on the yearly number of exported infected lots, which is an output of the epidemiological model.

***Table 1**. Overview of direct and indirect costs per category and underlying measure or causal factor. Stakeholders responsible for the costs are indicated by capitals: F = farmer; T = trading company, retail and industry; G = government; S = entire sector*

Measure or cause	**Costs**	**Payer(s)**
Structural costs		
sampling of potato lots for brown-rot prevalence	costs of sampling	F, G
sampling of other potential sources for brown-rot prevalence	costs of sampling	G
prohibition on use of surface water	yield and quality loss	F, T
Incidental costs		
destruction of detected potato lots	loss of revenue	F, T
	replacement of propagation material	F
	destruction costs	F
downgrading of probably infected potato lots	loss of revenue	F, T
	replacement of propagation material	F
tracing of potato lots related to detected lots	costs of sampling	G
increased sampling intensity on affected farms	costs of sampling	G
monitoring on affected farms	labour costs	G
prohibition of seed potato production for 1 or 2 years	production of less profitable crops / smaller acreage	F
quarantine status on field	cultivation of less profitable crops / rent of other field	F
Export losses		
loss of international market share	effects on (seed) potato price	S
	effects on (seed) potato acreage	S

APPLICATION OF THE BIO-ECONOMIC MODEL

In this section, simulation results are presented for two different brown-rot policy scenarios. The first scenario represents the policy applied in the Netherlands until 2004. This scenario includes an intensive monitoring strategy: all seed lots grown according to the standards of the Dutch General Inspection Service (Nederlandse Algemene Keuringsdienst, NAK) are sampled during or shortly after harvest at an intensity of 200 tubers per 25 tonnes. Ware and starch potatoes are sampled randomly at a frequency of approximately 7 % (one sample per lot). If a lot is found to be infected, it is destroyed, and quarantine measures are enforced on the farm that owned the lot and the field on which it was grown. All lots that are clonally related to the detected lot or may have been in contact with it are traced and tested for brown rot. Lots that are not found infected but that are nevertheless strongly suspected of being infected, as for example all other lots grown on the infected farm, are defined ‘probably infected’ and are downgraded to ware or starch potatoes, depending on their variety. The second scenario differs from the first in that only 10 % of all seed lots are randomly sampled, as compared to 100 % in the first scenario. The two scenarios will further be referred to as the ‘base’ and ‘reduced sampling’ scenario, respectively.

The system represented by the model comprises the Dutch potato production chain, including all potato-growing farms and arable fields in the Netherlands. Data on these farms and fields were obtained from the Dutch Agricultural Research Institute (Landbouw Economisch Instituut, LEI). Epidemiological and sector parameters required for the epidemiological model are derived from elicitation of experts (Breukers et al. in press). Economic data were provided by the PPO (Praktijkonderzoek Plant & Omgeving) research unit Arable Farming (Dekkers 2001), the brown-rot insurance company PotatoPol, and various stakeholders of the Dutch potato production chain. Results presented in this section are based on 100 replications for each scenario, each replication covering a period of 15 years. At this number of replications, the change in the running mean of the average yearly number of infections per simulation is less than 0.5 % and the computer time required for a simulation is still acceptable. The results are based on years 6-15 of the simulation runs to exclude initial transitory effects.

Brown rot dynamics

Figure 2 shows the normal and cumulative distribution of the yearly number of infected lots over all years of all replications (n=1500) for both policy scenarios. For the base scenario, the yearly number of infections varies between zero and approximately 80, but is equal to or lower than 10 in more than 50 % of the observations. This result corresponds with the typical irregular pattern of brown-rot dynamics observed in practice (Hendriks and Höfte 2004). Occasional outbreaks of brown rot can be caused by weather circumstances such as a conducive (i.e. warm and humid) summer, which is a stochastic model variable. Outbreaks may also occur when one or more infections in seed lots in a certain year are not detected; these seed lots are split in approximately 5 daughter lots on average, which are replanted in the following year.

Comparing the base scenario with the reduced-sampling scenario shows that reducing the sampling frequency mainly affects the median and variation in yearly number of infection, while leaving the mode (i.e. the most frequently observed number of infections per year), rather unaffected. Outbreaks of over 100 cases per year are occasionally observed, and the median almost doubles to 19 infections per year. The explanation for this difference is that, at a reduced sampling frequency, the detection efficiency of infected seed lots decreases. Consequently, infected seed lots have a higher probability of remaining in the production chain and being split into daughter lots for several years, occasionally leading to high numbers of infected lots.

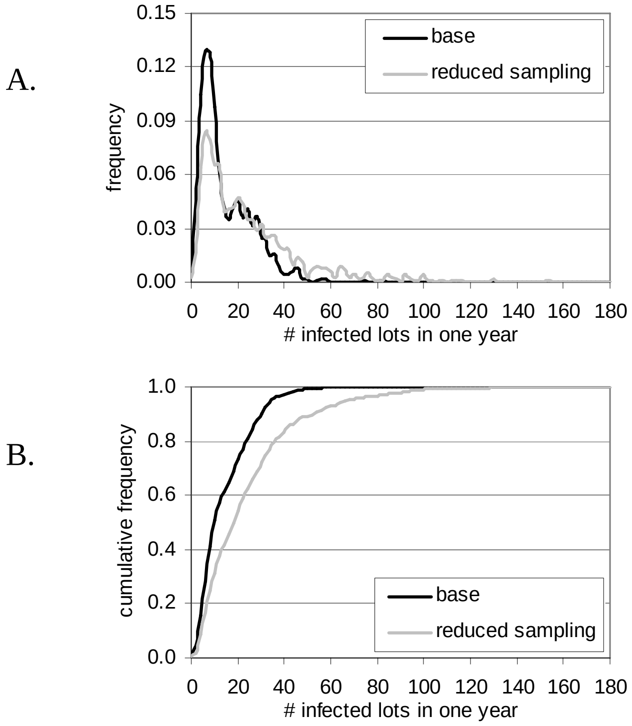

Figure 2*. Normal (a) and cumulative probability density diagram (b) of the observed yearly number of infections over 100 replications of 15 years*

Structural and incidental costs

The structural and incidental costs are presented at national level; no specification is given of the costs for different groups of stakeholders in the potato production chain. The only structural costs calculated in this chapter include the yearly sampling costs of potato lots. Other structural costs will be more or less the same for the two scenarios evaluated here. Structural costs are assumed constant over time and are calculated based on a fixed potato acreage and average lot size and yield per hectare. Incidental costs are calculated separately for each year in each simulation run and include all structural and incidental costs. The economic module that is currently available is preliminary and does not include the costs related to the quarantine status on fields yet, as these are still under investigation. The module assumes that, in case seed-potato production is prohibited on a farm, this farm will produce ware potatoes or starch potatoes instead.

The total production of seed potatoes in the Netherlands is approximately 1.4 mln tonnes on average. Under the base scenario, this quantity results in approximately 55,000 samples, whereas under the alternative scenario only 10 % of these samples are taken. The costs of sampling ware and starch lots are the same under both scenarios. In total, the yearly sampling costs comprise on average almost 4.5 million euros per year for the base scenario, and 0.7 million euros for the reduced-sampling scenario. The variation in sampling costs between years is negligible, as the total potato acreage planted – and thus the number of samples taken – remains stable over time.

In contrast to the structural costs, the incidental costs can vary strongly across years, as they are directly related to the number of detected lots in the current and previous year. Figure 3a shows the distribution of the incidental costs per year for both scenarios. For both scenarios, the incidental costs remain far below one million euros in most years. The median for the base scenario lies at 0.19 million euros per year, as compared to 0.11 million euros per year for the reduced-sampling scenario. Occasionally, the costs for the reduced-sampling scenario are much higher than for the base scenario. This result reflects the high variation in the number of brown-rot cases per year that was already observed from the epidemiological output of the reduced-sampling scenario (Figures 2A and 2B). The two incidental costs lines intersect; consequently, there is no first-order stochastic dominance, i.e. it is not possible to select one scenario which is always ‘better’ than the other. Risk-averse decision makers will in the first place try to minimize the risk of incurring extremely high costs, whereas risk-neutral decision makers attach most importance to average costs. The average yearly incidental costs of the base and reduced-sampling scenario are 0.31 and 0.41 million euros, respectively, so the base scenario will be preferred over the reduced-sampling scenario, irrespective of the risk attitude of the policy makers.

When summing up the structural and incidental costs (Figure 3B), it turns out that the reduced-sampling scenario is dominant over the base scenario to the first order; i.e. the curve of the reduced-sampling scenario is always preferred over the base scenario. Even in years with relatively high losses, the costs under the reduced-sampling scenario will generally be lower than the minimum costs incurred when applying the base scenario.

Export consequences

This section makes a qualitative assessment of the export consequences based on the results of the epidemiological model. The section focuses on consequences for potato export. Figure 4 shows the distribution of the yearly number of exported infected but undetected seed lots, for both scenarios. Under the base scenario, there is a probability of less than 15 % that one or more infected seed lots are unintentionally exported, and the observed number of seed lots exported almost never exceeds five per year. For the reduced-sampling scenario, the probability of exporting one or more infected lots is increased to more than 60 %. Moreover, there is a considerable probability that the number of exported infected seed lots exceeds five. Thus, under the reduced-sampling strategy, the likelihood for an importing country to receive an infected lot from the Netherlands is relatively high compared to the base scenario.

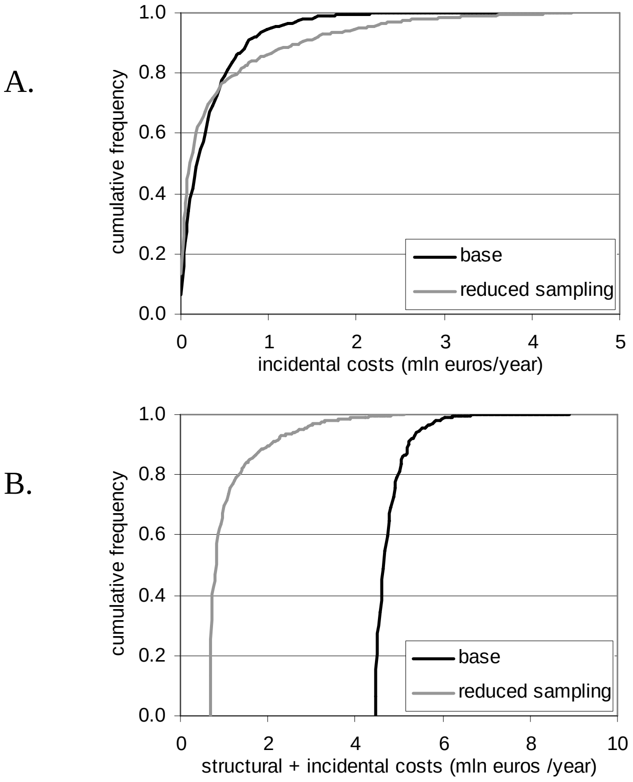

***Figure 3**. Cumulative frequency diagram of incidental costs (Figure 3A) and total short-term (=structural + incidental) costs (3B) per year, for the base scenario and the reduced-sampling scenario*

A large share of seed potatoes is exported to countries with a summer climate that is relatively conducive to brown rot (NAO 2004). It is likely that infected seed lots replanted in these countries will show visual symptoms of brown rot soon after they are replanted, resulting in detection. An incidental brown-rot detection in Dutch seed potatoes by another country will not immediately affect the export of Dutch seed potatoes. In contrast, at a level of infected exports as observed for the reduced-sampling strategy, the reliability of the disease-free status of Dutch seed potatoes may become at stake. Decreased confidence in the quality of Dutch seed potatoes will initially cause importing countries to require a more intensive testing policy in the Netherlands. Ultimately, it can result in a reduced export of this product. Since the elasticity of the domestic-demand curve for seed potatoes is rather low and the amount exported is about three times as high as the domestic demand, even a small reduction in export will have considerable consequences for the Dutch seed-potato price. As production of seed potatoes and ware and starch potatoes are strongly correlated, also the prices of ware and starch potato will be affected.

A decrease in potato prices will have economic consequences that are of a much higher magnitude than the short-term costs. For instance, lowering the seed-potato prices by 0.1 eurocent per kg already results in a loss over one million euros per year. Consequently, when taking into account the long-term consequences of the two scenarios described in this chapter, it is not so evident anymore that the reduced-sampling scenario is more cost-effective than the base scenario.

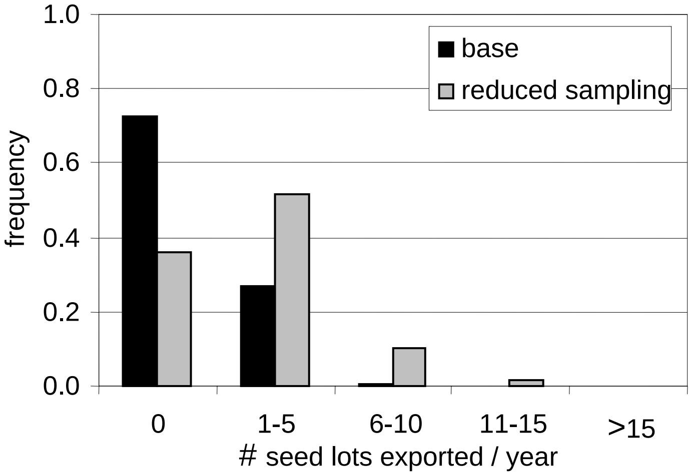

Figure 4. *Distribution of the number of infected seed lots exported from the Netherlands per year, for the base scenario and the reduced-sampling scenario*

OUTLOOK

In this chapter, we have introduced a new modelling concept for evaluating the cost-effectiveness of strategies for controlling brown rot in the plant production chain. Simulation results of brown-rot dynamics for the base scenario reflect the current knowledge of, and experience with brown rot in the Dutch potato production chain. As expected, reducing the sampling frequency of seed potatoes leads to an overall increase in brown-rot prevalence and, in particular, in the yearly variation in the number of brown-rot infections. The incidental costs of brown rot under reduced sampling are lower in most cases, but occasionally far exceed the incidental costs incurred under the base scenario. However, the yearly structural costs of the base scenario are more than six times higher than those of the reduced-sampling scenario, making the reduced-sampling scenario the more cost-efficient of the two scenarios in the short run. Yet, when including the export consequences in the model, this conclusion no longer holds. Although not quantified, it is very plausible that the reduced-sampling scenario leads to long-term losses as a consequence of reduced image of Dutch potatoes, which may more than cancel out its short-term economic benefits. In the near future, a method will be developed to analyse the export losses quantitatively.

An aspect that has not been discussed in this chapter is the issue of ‘who has to pay’. The distribution of the costs over the different categories of stakeholders involved, as well as the distribution of costs between individuals of the same category, can affect the effectiveness of a strategy. If the majority of the costs are incurred at one level of the production chain, it is likely that these stakeholders will not support a specific control strategy. The same holds if within one level of the production chain some individuals have a much higher share in the costs than equivalent individuals. Lack of support for an imposed control strategy decreases the collaboration in the implementation of that strategy and encourages undesirable or illegal behaviour, which decreases the effectiveness of that strategy. Such behaviour can be avoided through surveillance, which increases the costs of the strategy. Another way to decrease the likelihood of illegality is to create an opportunity for stakeholders to share the costs or decrease the risk of incurring extremely high individual costs. For instance, in the Netherlands, potato growers can insure their crop against brown rot (not included in the economic analysis). Insured growers affected by brown rot receive a compensation for most of the incidental costs they incur. This compensation is paid from the insurance premiums of all growers; the incidental costs are thus shared among all insured growers.

The modelling concept presented here has a number of features, which altogether distinguish it from existing bio-economic models. Firstly, it focuses on an entire plant production chain. This has consequences for the modelling approach to describe disease dynamics, as these are not purely dominated by the biological behaviour of the pathogen anymore. The populations of plants that comprise the units in these chains behave as aggregated individuals for which the concepts of individual-based modelling apply. Secondly, the model is stochastic, and simulation results do not only show the average brown-rot prevalence and economic consequences but also their variations from year to year. The results show that this variation between years plays an important role when evaluating the cost-effectiveness of control strategies. Moreover, export consequences are shown to be important. Quarantine disease often cause minimal damage to host crops, in which case control and eradication measures have hardly any direct benefits. Yet, when taking into account what might happen when controlling the disease to a much lower extent, there is a significant benefit of ‘avoiding even higher costs’. Finally, the model is spatially explicit, which increases the imaginative power of the model and allows for evaluating the effect of regional impositions of measures.

The model can be used, amongst others, to study the effect of measures concerning sampling strategy, farm management, or other factors that possibly affect brown-rot prevalence and dispersal. Thereby, it can be of great support to authorities and policy makers who are responsible for the implementation of effective and efficient control policies. With some adaptations, the model could be used to study control options for other ‘chain-related’ potato diseases, such as ring rot (*Clavibacter michiganensis* subsp. *sepedonicus*) and blackleg or soft rot (*Erwinia* *carotovora* subspecies). The conceptual framework presented in this paper is generally applicable to diseases in other production chains and other countries.

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