Climate change and plant health

Development of a conceptual framework for impact assessment

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Annemarie Breukers

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A. Breukers

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This report presents a conceptual framework for systematic assessment of direct economic impacts of climate change on pest and disease management at the crop level. The framework evaluates and aggregates the effects, and subsequently impacts, of climate change on selected pests and diseases and their control in a particular crop. Application of the framework reveals opportunities and threats in crop protection resulting from climate change, and can direct future adaptation efforts.

Dit rapport presenteert een conceptueel kader voor systematische analyse van directe economische impacts van klimaatverandering op ziekte- en plaagmanagement op gewasniveau. Het kader beoordeelt en aggregeert de effecten van klimaatverandering op geselecteerde ziekten en plagen en hun beheersing in een gewas, en de daaruit volgende impacts voor telers. Toepassing van het conceptueel kader biedt inzicht in kansen en bedreigingen van klimaatverandering voor plantgezondheid en kan richting geven aan adaptatie.

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Contents

Preface

Climate change is an actual issue, to which much research is currently devoted. Knowledge on climate change and its effects and impacts on agriculture is important as sustainable food production in the future is only secured if proper mitigation and adaptation strategies are implemented.

The research presented in this report contributes to this knowledge by improving insight into the impacts of climate change on pest and disease management. This aspect of agriculture has to date received relatively little attention in climate change research. Yet, pest (and disease) management comprises an important cost factor in crop production. Also at the national level, introduction and establishment of new pests and diseases - partly as a result of climate change - are of increasing concern.

The framework presented in this report can assist in valuing the consequences of climate change for agricultural production. It translates physical effects into economic impacts for farmers. Although applied within the domain of pest and disease management, the approach is essentially generic. Therefore, this research potentially serves a much wider public.

Special thanks go to Dr Anton Haverkort, who reviewed the case study on seed potatoes (Chapter 4), to Dr Johan Bremmer, who reviewed the methodological part of this study (Chapter 3), and to Dr Eefje den Belder and Ben Schaap for sharing their knowledge and ideas about this topic. Their contribution to this research is very much appreciated.

Prof.Dr R.B.M. Huirne
Managing Director LEI

Summary

S.1 Main results

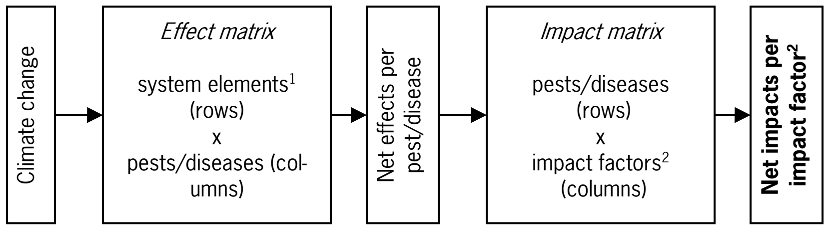
We developed a conceptual framework for systematic assessment of direct economic impacts of climate change on pest and disease management at the crop level (Figure S1)

The framework evaluates and aggregates the effects, and subsequently impacts, of climate change on selected pests and diseases and their control in a particular crop.

Impacts are categorised as costs of biological and chemical crop protection, and quantitative and qualitative losses. These impacts follow from effects on the pest or pathogen, host, environment, and human.

A pilot application of the framework provided proof of concept.

Figure S.1 Flow diagram of the conceptual framework



[1] System elements: pest/pathogen, host, environment, human.

[2] Impact factors: costs of biological and chemical crop protection, quantitative and qualitative losses.

S.2 Other results

Application of the conceptual framework can direct future adaptation efforts. It reveals opportunities and threats in crop protection, and provides an indication of the maximum acceptable costs of adaptation measures.

So far, the research focus was largely on fundamental knowledge generation. Practical interpretation of such knowledge is pending. This impedes assessment of the potential impacts of such effects for crop production.

Results of the pilot study stress the importance of an impact assessment at crop level, focusing on multiple aspects of climate change and multiple aspects of the system. In doing so, possible interactions are accounted for and impacts can be evaluated for their relative importance.

To put impacts of climate change on pest and disease management in perspective, the analysis should be integrated in a farm- or crop-wide impact assessment of climate change. A farm- or crop-wide approach can also provide insight into the robustness of farms or cropping systems to climate change. It is worth investigating whether the approach taken in this study is suitable for application at such level.

S.3 Method

We performed this research as part of the Knowledge Base programme 'climate change' (KB2), in order to enable better insight into possible impacts of climate change on pest and disease management in crop production. To achieve this, we started with a literature review and used the results to develop a conceptual framework. To evaluate the feasibility of the framework, we applied it to seed potato production in the Netherlands as a pilot study.

Samenvatting

S.1 Belangrijkste resultaten

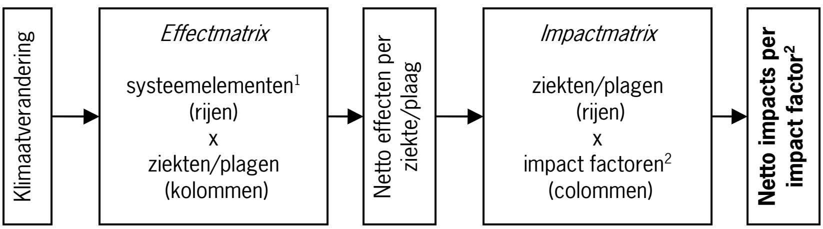
We hebben een conceptueel kader ontwikkeld voor systematische analyse van directe economische impacts van klimaatverandering op ziekte- en plaagmanagement op gewasniveau (figuur S1)

Het kader beoordeelt en aggregeert de effecten van klimaatverandering op geselecteerde ziekten en plagen en hun beheersing in een gewas, en de daaruit volgende impacts voor telers.

Impacts zijn ingedeeld in kosten van biologische en chemische gewasbescherming, en kwantitatieve en kwalitatieve opbrengstderving. Deze impacts volgen uit effecten op het pathogeen of plaag, de waardplant, omgeving, en mens.

Uit een pilottoepassing blijkt dat het kader goed functioneert.

Figuur S.1 **Stroomdiagram van het conceptueel kader**



[1] Systeemelementen: pathogeen/plaag, waardplant, omgeving, mens.

[2] Impact factors: kosten van biologische en chemische gewasbescherming, kwalitatieve en kwantitatieve opbrengstderving.

S.2 Andere resultaten

Toepassing van het conceptueel kader kan klimaatadaptatie sturen. Kansen en bedreigingen worden zichtbaar en de resultaten geven een indicatie van de maximaal aanvaardbare kosten van adaptatiemaatregelen.

Onderzoek heeft zich tot nu toe sterk beperkt tot fundamentele kennisontwikkeling; de praktische implementatie ervan ontbreekt vaak nog. Dit belemmert de analyse van impacts van dergelijke effecten voor plantaardige productie.

Resultaten van de pilotstudie benadrukken het belang van impact assessment op gewasniveau, waarin meerdere aspecten van klimaatverandering en het systeem meegenomen worden. Een dergelijke aanpak houdt rekening met mogelijke interacties en maakt onderlinge vergelijking van impacts mogelijk.

Om impacts op ziekte- en plaagbeheersing in perspectief te plaatsen is integratie van de analyse in een bedrijfs- of gewasbrede impact assessment wenselijk. Een aanpak op bedrijfs- of gewasniveau geeft ook inzicht in de robuustheid van bedrijven of productiesystemen in een veranderend klimaat. Het loont te inventariseren of het in dit rapport beschreven kader geschikt is voor toepassing op dit niveau.

S.3 Methoden

We hebben dit onderzoek uitgevoerd binnen het Kennisbasis programma 'klimaatverandering' (KB2), om beter inzicht te krijgen in mogelijke impacts van klimaatverandering op ziekte- en plaagbeheersing in plantaardige productie. Hiervoor hebben we eerst een literatuurstudie uitgevoerd. De resultaten daarvan hebben we gebruikt voor de ontwikkeling van een conceptueel kader. Om de functionaliteit van het kader te toetsen hebben we het toegepast op de teelt van pootaardappelen in Nederland als pilotstudie.

1 Introduction

1.1 Background

Changes in climatic factors such as temperature, rainfall, and CO_2 concentration in the atmosphere affect the incidence and dispersal of plant pests and diseases. Examples are changes in geographical range and epidemiological characteristics such as developmental and reproduction rate. Climate change can also indirectly affect the occurrence of pest and diseases, by altering the system in which they occur. For instance, natural enemies can increase or decline in population, host crops can become more or less susceptible, and the effectiveness of management practices may change. As a consequence, a shift in overall disease pressure as well as the relative importance of pests and diseases in crop production may occur.

Climate change in relation to plant health has remained unexplored until quite recently. Nowadays, the field is gaining more attention. Whereas it appears difficult to quantify relationships between climate change and shifts in pest and diseases, it is evident that climate change has an impact on plant disease management in crop production as well as the green space.

1.2 Problem definition

So far, research on climate change in relation to plant health has largely focused on the effect on single climate factors (e.g. temperature or rainfall) on individual pests or diseases. Additionally, studies have been performed on expansion of geographical ranges of occurrence of invasive alien species. Effects of climate change in general on management of a range of pests and diseases in agricultural crops have much less frequently been studied. For as far as they have been done, physical effects were not translated into the socio-economic and environmental impacts for directly or indirectly involved actors. Limited insight into possible impacts of climate change on pest and disease management in crop production complicates timely identification of future threats and opportunities in pest management, and impedes the search for effective adaptation strategies.

1.3 Objectives

The objective of this research is to (1) characterise the potential effects and subsequent impacts of climate change on plant pest and diseases and their management, and (2) to explore the feasibility of developing a conceptual framework for qualitative analysis of the potential impacts of climate change for pest and disease management in particular (field) crops. In doing so, the following steps are distinguished:

1. Exploration of effects and impacts of climate change on pests and diseases and their management (Chapter 2);
2. Development of a conceptual framework for structuring and aggregating the effects and impacts of climate change on pest and disease management in a particular crop (Chapter 3);
3. Application of a simplified version of the framework to one field crop as a pilot study (Chapter 4);
4. Evaluation of the feasibility of the conceptual framework, its major drawbacks and potential for further development (Chapter 5).

The research is restricted to field crops and has a strong focus on the primary sector. Also, it focuses purely on impacts following from the direct effects of climate change on pests and diseases and their control. Impacts following from (interactions with) other effects, such as more crop production due to higher growth rate or longer growing seasons, will not be considered.

2 Exploration of effects and impacts

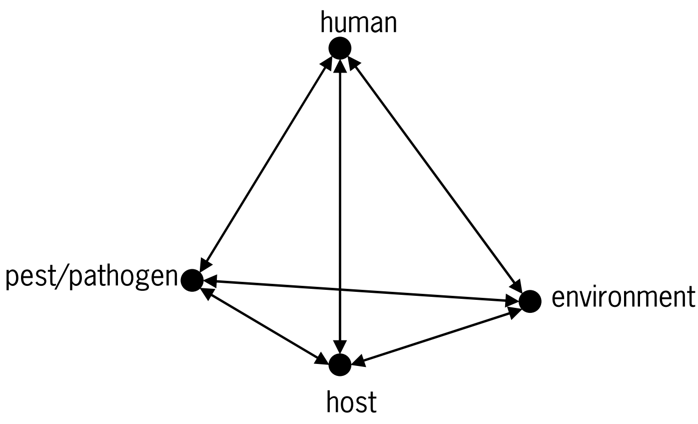
2.1 Effects

The relationship between climate, plant pests and diseases, and their control, can be explained by the so-called ‘disease triangle’. This concept was developed in the 1960s as a means to understand how epidemics might be predicted, limited or controlled (Scholthof, 2007). In the disease triangle considers plant disease development as an interplay between the host, the pathogen, and the environment, which represent the tree corners of the triangle.

The disease triangle was modified by Zadoks and Schein into a disease pyramid by adding man as a fourth factor (Zadoks and Schein, 1979). Since any commercial cropping system is to a certain extent managed by humans; they are at the top of the disease tetrahedron (Figure 2.1). Here, we extend the element 'pathogen' with pest to broaden the scope of the pyramid.

Below, each component of the disease tetrahedron is briefly described. A more elaborate discussion of their relation to climate change is provided in Appendix 1.

Figure 2.1 **The disease tetrahedron, illustrating the interactions between pathogen, host, environment, and human**



2.1.1 Pest or pathogen

The principal requirement for disease development is presence of the pathogen (or pest). The pathogen can be initially present on or in the plant, or it can be introduced during the growing season, by active movement or a vector. The eventual severity of the disease is determined by some additional factors, namely the virulence of the pathogen and the period over which the pathogen can be active (time) (Scholthof, 2007).

Pathogen - climate interactions

Temperature can affect critical stages in the life cycle of a pathogen, such as reproduction rate and survival between seasons (Garrett et al., 2006). For example, winter temperatures can be an important factor for survival of diseases that survive in debris or in vectors, as well as insects and nematodes. Summer temperatures affect the reproduction rate of many pests and diseases. For fungal and bacterial diseases, humidity during summer is also often an important factor. Elevated CO_2 seems to increase the fecundity of certain pathogens as well as the competition between weeds and crops. Finally, altered wind patterns can change the spread of both wind-borne pests and diseases.

2.1.2 Host

The host is represented by the crop that is threatened by a particular pathogen (or pest). Disease development depends on the susceptibility of the host to the pathogen (Hardwick, 2006). If the host plant is resistant, no interaction will take place between the host and the pathogen and no epidemic will occur. Susceptibility depends, apart from genetic composition, on a number of factors, including plant architecture, plant physiology, and structure of the plant canopy. These factors are related to life stage of the plant - and thus time.

Host - climate interactions

Changes in temperature and humidity can affect the susceptibility of plants as a result of stress. Also, high temperatures may induce changes in the plant that affect resistance. Elevated CO_2 levels can slow down pathogen invasion, but also increase plant density - and thereby leaf surface wetness, which makes infection by foliar pathogens more likely. CO_2 also affects the chemical composition - and thus nutritional value for insects - of the plant; yet, the net effects on insect abundance are uncertain.

2.1.3 Environment

It is generally assumed that the environment is the driving force for diseases (Hardwick, 2006). The environmental component covers both biotic and abiotic factors. Climate is considered part of the abiotic environment. Other examples of abiotic factors are soil type and geographical composition of the area. Among the biotic factors are biodiversity, soil microbial life, and presence of natural enemies or vectors. Some researchers even consider socio-economic circumstances as environmental factor (Scholthof, 2007).

Environment - climate interactions

Greater variability in temperature and precipitation might change the effectiveness of natural enemies (including biocontrol agents) in disease suppression. The synchrony between growth, development, and reproduction of natural enemies and their targets can be disrupted, or the balance between reproduction and predation of the pest can shift. Changes in temperature and/or humidity can affect the (size of) the range occupied by a pest or pathogen, leading to introduction of new pests, pathogens, or their vectors.

2.1.4 Humans

Management practices of humans include pest and disease management, e.g. choosing resistant varieties (interaction with host) or applying chemical, mechanical or biological crop protection (interaction with pathogen). But even management decisions that are not primarily aimed at disease control may affect disease development. Examples of these are the application of narrow crop rotations and growth of monocultures.

Human - climate interactions

Climatic changes affect the uptake, effectiveness and duration of crop protection chemicals, as well as the possibility to apply them (e.g. access to field). Biological control may be even more sensitive to climate change as biocontrol agent populations are vulnerable to environmental variation and environmental extremes. Climate change will also extend the possible growing seasons of crops - and thus the possible duration of epidemics.

2.2 Impacts

A change in pest or disease pressure or possibilities for control has consequences for the production of the host crop. More disease pressure can lead to more crop damage or a higher level of control. Likewise, a change in the possibilities for (or effectiveness of control) can affect disease control - and thereby crop damage. The changes in disease pressure and control have impacts for the farmer, but also for other stakeholders in the production chain as well as the whole society. We distinguish direct or indirect impacts. Direct impacts reflect the effects of a particular pest or disease on the host, and include amongst others changes in crop yield and quality and costs of control. Indirect impacts are the general effects that result from presence of a pest (not specific to pest-host dynamics). Examples are impacts on public health or ecosystem services, market effects (e.g. change in consumer preferences or market access), and impacts on tourism and other sectors of an economy (Bigsby and Whyte, 2001).

Impacts can be divided into three categories: economic, environmental, and social impacts. Below, each category is discussed. Figure 2.2 provides a schematic overview.

Adjustment of disease control is in fact an adaptive response to climate change. Yet, we want to keep impacts due to climate change separate from those resulting from adaptation. Adaptation practices refer to actual adjustments, or changes in decision environments, which might ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate (IPPC, 2007). Here, we exclude adaptation effects by assuming that the farmer does not introduce new or alternative control methods, but only substitutes between measures that are already included in his strategy.

2.2.1 Economic impacts

A change in disease pressure or disease control can affect the amount of quantitative or qualitative crop damage. Qualitative damage reduces the value of the harvested crop, e.g. through price discounts or changed destination. Quantitative damage is reflected in the amount of harvested product. Both types of damage affect the final crop revenue.

A change in level of disease control affects the production costs of a crop. It may include a change in amount of (chemical or biological) crop protection products used, but also a change in other inputs such as labour and energy.

If crop loss occurs at large scale, it can cause market shifts. For instance, qualitative loss may reduce consumer demand for the product, while quantitative loss can result in a reduced supply. A change in crop revenue or production costs can also cause a farmer to decide to grow other crops, which in turn affects the market as well.

2.2.2 Environmental impacts

Changes in disease control may imply an increase or decrease in use of crop protection chemicals, which may in turn affect leakage into the environment. Farmers who (partly) apply biological control methods may change their use of chemical control in response to climatic effects on biological control. The other way around is unlikely as this requires a change of strategy (i.e. adaptation).

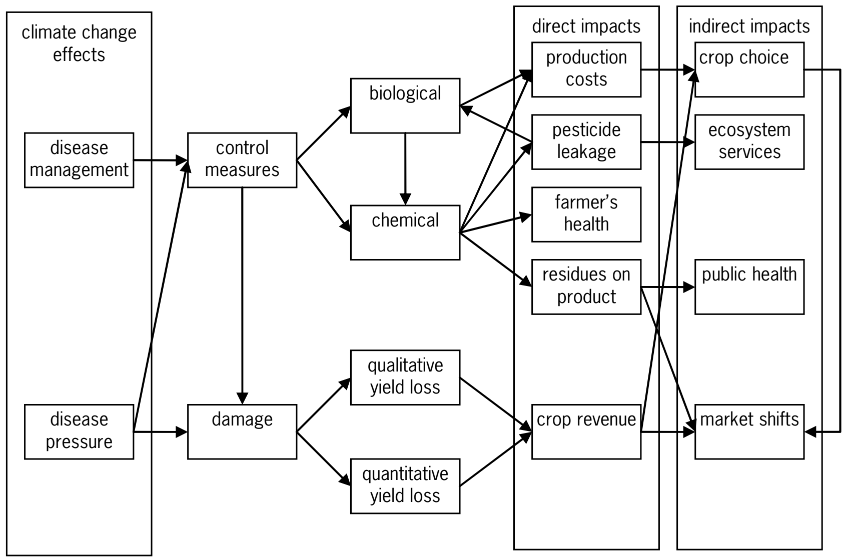
Chemical leakage can affect soil, groundwater, and surface water quality. Thereby, chemical control indirectly affects various types of ecosystem services. Crop protection chemicals can also affect beneficial organisms that may be used in biological control. Thus, a positive feedback loop exists in the use of crop protection chemicals.

2.2.3 Social impacts

The use of crop protection chemicals may cause a risk for the farmer if he gets in contact with the chemical. They may also remain present in or on the crop until after harvest, causing pesticide residues on the marketable product. This puts a risk on public health and may affect consumer demand, resulting in market shifts.

Although these social impacts are theoretically possible, they are very unlikely to occur in the Netherlands, as strict safety protocols apply to the choice and application of crop protection chemicals.

Figure 2.2 **Relationship between climate change effects, direct and indirect impacts**



3 Development of a conceptual framework

Cobon et al. (2009) describe a methodology for assessing the risk of climate change to the grazing industry in northern Australia. The methodology is qualitative, does not make use of computer programs or simulation models, and uses existing literature and expert judgment as input for assessing the overall risk. These characteristics make the approach suitable for application to other types of climate effects and study regions as well. Below, we describe the methodology and adjust it to the context of pest and disease control in the Netherlands.

3.1 Methodological approach

3.1.1 Original approach

To assess the risk of climate change to the grazing industry in northern Australia, Cobon et al. applied the following procedure:

1. Development of an impact matrix, in which the rows represent relevant variables of climate change and the columns represent key elements of the grazing industry (Table 3.1). For each cell in the matrix, the impact of the respective climate change variable on the respective key element was assessed. Per cell, the direction (decrease or increase) and extent of the impact ignoring all other influences was assessed, as well as whether the impact was desirable or not (positive or negative). For each key element, a statement on the overall impact of climate change was provided at the bottom row of the matrix. This statement was based on the aggregated impacts of all individual cells, while accounting for potential interactions.
2. Development of a risk scoring matrix, to determine the risk related to the identified impacts of climate change. This matrix consists of likelihood of an impact arising (rows) and its level of consequence (columns). Combinations of likelihood and level of consequence result in four impact risk levels: low, medium, high, and extreme. As the analysis of risk may also identify opportunity and gain (rather than just threat and loss), two risk scoring matrices

were defined, one for the positive and one for the negative impacts (Table 3.2).

3. Assignment of impact risk levels to each cell in the impact matrix, using the risk scoring matrices. Each cell was assigned one of the five levels of consequences and one of the five levels of likelihood. The combination of these two values determined the level of impact risk of that cell. This level was indicated by two colours (positive or negative) and different levels of shading (the darker the shading, the higher the level of impact risk).

The resulting matrix containing all possible impacts and corresponding levels of impact risk attached can be used to identify priorities for action. However, the matrix does not account yet for adaptive capacity of the system. The approach of Cobon et al. proceeds with a full vulnerability assessment, including the adaptive response of the system. We will not discuss this here, as adaptive capacity goes beyond the scope of this study.

Table 3.1 **Illustration of the impact matrix developed by Cobon et al. (2009)**

Climate change variable	**Key element 1**	**Key element 2**	**Key element 3**	**…**
variable 1	moderate increase …	severe reduction (references …)	Minor increase …	
variable 2	decrease due to …	increase because …	No significant effect …	
…				
overall estimate	*small decrease in key element 1*	*large reduction in key element 2*	*minor increase in key element 3*	

Table 3.2	**Impact risk matrices**					
Levels of negative impact risk						
		Negative consequences				
		Minor	Moderate	Major	Severe	Catastrophic
Likelihood	Rare	Low	Low	Low	Low	Low
	Unlikely	Low	Low	Medium	Medium	Medium
	Possible	Low	Medium	Medium	High	High
	Likely	Low	Medium	High	High	Extreme
	Almost certain	Low	Medium	High	Extreme	Extreme
Levels of positive impact risk (i.e. 'luck')						
		Positive consequences				
		Minor	Moderate	Major	Extreme	Phenomenal
Likelihood	Rare	Low	Low	Low	Low	Low
	Unlikely	Low	Low	Medium	Medium	Medium
	Possible	Low	Medium	Medium	High	High
	Likely	Low	Medium	High	High	Extreme
	Almost certain	Low	Medium	High	Extreme	Extreme

3.1.2 Adjustments

In the methodology described above, different climate change variables are directly related to impacts on key elements in the northern Australian grazing industry. In the field of pest and disease control, this step is not as straightforward, as it is often the combination of different climate variables that determine how the pest, crop, or system will respond. Moreover, information on effects of climate change on crop-disease systems is disease-specific, while the impact of these effects for affected farmers should be evaluated at the crop level. Therefore, the above-described method is adjusted to a two-step approach, in which first an effect matrix is compiled, and subsequently an impact matrix. The risk component will be included at a later stage and falls outside the scope of this project. We will return to this in the discussion (Chapter 5).

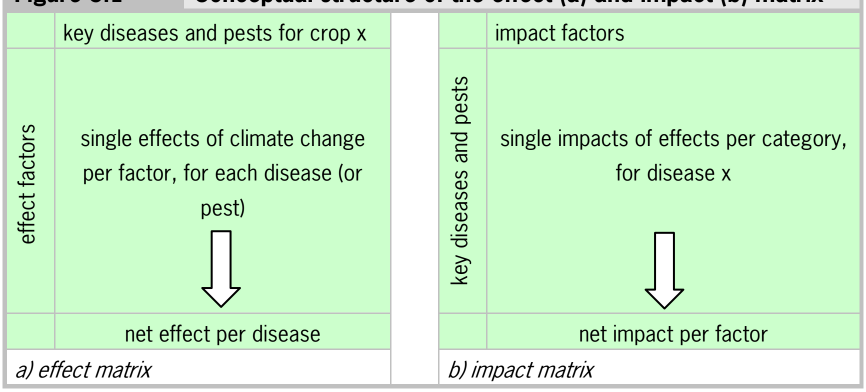
1. Development of an effect matrix. The effect matrix is similar to the above-mentioned impact matrix, but identifies the effects of climate change on crop-disease systems, rather than the impacts. No separate climate change variables are defined as the effects of climate change on the system are

generally dependent on interactions between these variables. Instead, the rows represent different key factors determining the overall effect on presence and control of pests and diseases. The columns contain the pests and diseases that are relevant for the crop that is under investigation. The effects of climate change on each of the four elements are qualitatively assessed for each disease, after which they are aggregated into an overall judgment of the effect per disease. This aggregation is done by summing the individual effects and correcting for interactions (i.e. the combined effect of two effects may be smaller or larger than the sum of the two individual effects).

2. Development of an impact matrix, in which the observed effects of climate change for each particular disease are translated into consequences for pest and disease management in the selected crop. The individual diseases are represented in the rows of the impact matrix. The columns comprise the different impact factors that can be affected. As with the effect matrix, the cells in the matrix are given qualitative impact scores which can be positive or negative. In the bottom row of the impact matrix, an overall assessment of each impact will be given, in which potential interactions between (control of) different diseases are accounted for.

Figure 3.1 shows the structure of both matrices. Since this study only intends to be an exploration, impact risk (or luck) is left out of consideration for the time being. This issue will, however, be addressed in the discussion (Chapter 5).

Figure 3.1 **Conceptual structure of the effect (a) and impact (b) matrix**



3.2 Characterisation of climate change, effects and impacts

3.2.1 Climate change

In order to determine potential effects, climate change has to be specified in terms of temperature shifts, change in frequency and intensity of rainfall, extreme weather circumstances, and so on. For the Netherlands, the KNMI has developed four scenarios for climate change in 2050 and 2100 as compared to the base year 1990 (KNMI, 2006). The scenarios have different underlying assumptions with respect to global warming (moderate vs. warm) and in changes in air circulation (none vs. changed pattern). Combinations of the two types of assumptions affect climate in different ways, which in turn can have different kinds of effects on pest management. Therefore, it is important to decide beforehand on which climate change scenario the analysis will be based.

3.2.2 Effects on disease control

We use the disease pyramid presented in Chapter 2 to capture all possible effects of climate change on disease control. Each component of the pyramid is included as a key factor determining the effect of climate change on disease control. To facilitate translation of effects into impacts, the human key element only represents disease control. Other relevant human activities, such as changes in length of the growing season of crops and changes in tillage, affect disease control via their effect on another key element, and are therefore included there. Table 3.3 presents the four key elements and, for illustration, a number of effects that can be thought of when evaluating each key element.

Table 3.3	Key effect factors, including examples of aspects captured by these elements
Category	**Relevant aspects**
Pest or disease pressure	initial inoculum and establishment; disease progress and spread; duration of epidemic
Host crop vulnerability	attractiveness (chemical and morphological), susceptibility (to infection), sensitivity (to damage)
Suitability of environment	abiotic circumstances (e.g. soil characteristics, potential geographic range), natural enemies, vectors, alternative hosts
Human control	applicability and (duration of) effectiveness of crop protection, biological control

3.2.3 Impact factors of disease control

For the time being, only the direct economic impacts, i.e. changes in production costs and crop revenue, are considered (but see Chapter 5). For transparency, changes in production costs and crop revenue are further specified according to their origin (Table 3.4). One reason for this is transparency; impacts of different origin that add up to zero (e.g. a switch from biological to chemical control against the same costs) remain visible. Moreover, when summarising the impacts over different diseases, their origin determines how costs add up to each other. For instance, quality of a crop is not a linear concept, and quality loss due to one disease may overrule quality losses due to other diseases. Also, certain crop protection measures may be beneficial for more than one disease, in which case the costs of controlling several diseases simultaneously are lower than the individual costs per disease.

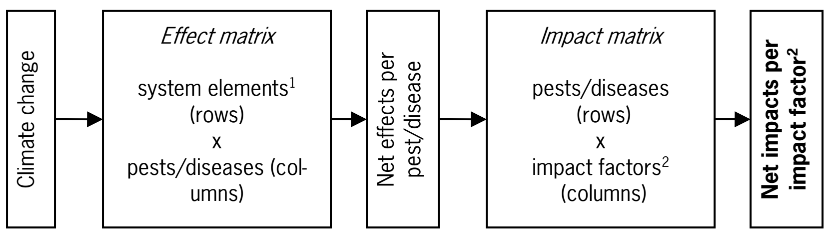
Table 3.4	Impact factors, including a description of the type of impact related to each factor
Impact factor	**Type of impact**
Biological crop protection	Change in production costs due to higher/lower costs of control
Chemical crop protection	Change in production costs due to higher/lower costs of control
Crop damage, quantitative	Change in revenue due to increase/decrease in yield
Crop damage, qualitative	Change in revenue due to increase/decrease in product price

3.3 Conceptual framework: overview

Figure 3.2 provides a flow diagram of the conceptual framework. In summary, the following steps need to be taken:

1. Characterisation of the system. Selection of climate change scenario, crop and relevant pests and diseases;
2. Construction of the effect matrix. Identification of effects of climate change for each of the selected pests and diseases:
   a. description of effects for each element of the disease pyramid (Table 3.3);
   b. aggregation over all elements per pest or disease;
3. Construction of the impact matrix. Assessment of the impacts resulting from the effects according to the different impact categories (Table 3.4):
   a. description of different impacts for each disease or pest;
   b. aggregation over all diseases or pests per impact category.

Figure 3.2 **Flow diagram of the conceptual framework**



[1]System elements: pathogen/pest, host, environment, and man.

[2]Impact factors: costs of biological and chemical crop protection, quantitative and qualitative crop loss.

4 Pilot study: seed potatoes

To test the applicability and suitability of the conceptual framework, it is applied to seed potato production as a case study. The analysis is structured according to the outline of the conceptual framework as presented in Section 3.3. The effect and impact matrix are presented in Table 4.1 (pages 35-36) and Table 4.2 (pages 41-42).

Note: this case study does not intend to provide a representative overview of climate change effects and impacts on disease management in seed potatoes! While trying to capture as much available information as possible, data may be coarse and incomplete, and have been verified only to a limited extent by experts. Therefore, results should be interpreted with care and should not be used as scientific reference.

4.1 System characterisation

4.1.1 Climate change

The KNMI considers all four scenarios equally likely. Each scenario has its own characteristics, and none of them can be considered as an 'average' scenario. Therefore, in this study we consider the climate scenario that predicts overall the largest changes (warm, changed air circulation pattern: W+). This brings along the possibility of overestimating impacts, but minimises the risk of missing important impacts that might occur within the next few decades and require urgent action. Furthermore, because uncertainty on climate change increases with the period over which predictions are made, we focus on the shortest time horizon (2050). Appendix 2 provides a summary of projected climate changes.

4.1.2 Selection of crop

As already mentioned, this case study focuses on seed potatoes. Seed potatoes comprise one of the most important cash crops in the Netherlands and have high quality demands. The production characteristics and quality demands of seed potatoes are principally different from those for ware potatoes, which makes generalisation to potato production not possible. The case study is further narrowed down to conventional seed potato production; organic seed potato production occurs at a very small scale and deals with pests and diseases in a very different way.

4.1.3 Selection of pests and diseases

Seed potato growers have to deal with a range of pests and diseases, some of which are more important than others. For this case study, five pests and diseases are selected on the basis of current and (potential) future importance and diversity in biological characteristics and type of damage. These are:

- Potato late blight;
- Bacterial diseases (black leg and aerial stem rot);
- Potato virus Y (PVY);
- *Meloidogyne chitwoodi;*
- Colorado beetle.

Late blight

Late blight, caused by the oomycete *Phytophthora infestans*, is the most important potato disease in the Netherlands. Farmers control late blight by means of chemical spraying. For seed potatoes, the average number of applications per growing season is ten, resulting in a cost of €500 per hectare (chemicals plus application). On average once in every 5 years, crop damage occurs despite chemical control, resulting in crop losses on an expected 10% of the total acreage due to forwarded sales and quality discounts. These losses apply mainly to ware potatoes, however (Boonekamp et al., 2008).

Bacterial diseases

Bacterial diseases (black leg and aerial stem rot) are caused by different bacterial pathogens, which were formerly classified as *Erwinia* spp. Nowadays, they are officially referred to as *Pectobacterium* species and *Dickeya* spp. Infection of seed potatoes with blackleg can lead to downgrading to a lower quality class or even to ware potatoes, depending on the severity of the infection. Besides a lower revenue, affected farmers often incur additional losses from the purchase of seed potatoes which they would have normally produced themselves. The losses from bacterial diseases vary strongly per year, depending on weather circumstances and potato prices. In the period 2003-2007, on average 16% of all seed lots were downgraded or rejected due to bacterial diseases. The corresponding losses for seed potato growers were €12m per year, or 1.0 ct per kg of seed potatoes, which equals 3.5% of the revenue.

Potato Virus Y

Of all virus diseases in seed potatoes, PVY causes most problems. As with bacterial diseases, PVY infections result in downgrading and rejection of seed potato lots. Viruses require a vector in order to be spread between plants. Potato virus Y (PVY) is spread by most effectively by the green peach aphid (*Myzus persicae*), but can also be spread by other aphid species. In order to minimise risk of PVY infection, each year a haulm destruction date is set at or before which all seed potato growers have to destroy haulm. Failing to do so will subject the crop to an obligatory post harvest PVY test (at costs). The haulm destruction date is determined regionally on the basis of observed PVY infections in fields and presence of aphids and on seed potato class (S, SE, E, A or C) and susceptibility group of the variety grown.

Meloidogyne chitwoodi

M. chitwoodi (also called the Columbia root knot nematode) is a nematode with a very wide host range. *M. chitwoodi* is a quarantine organism within the EU, which means that it is not widely distributed within the EU and can cause major economic damage. To prevent introduction and spread of the organism, planting material (e.g. seed potatoes) has to be free from the pest. In regions in the Netherlands where *M. chitwoodi* was recently found to be present, all seed potato lots (and other planting material) are tested after harvest for the presence of the nematode. In other areas, seed lots are randomly sampled. Seed potato lots in which the nematode is detected are downgraded to ware potatoes.

Due to its wide host range, *M. chitwoodi* can survive for many years in infested fields, so in theory, any field that becomes infested is from then on unsuitable for seed potato cultivation. However, monitoring of *M. chitwoodi* takes place at lot level, implying that seed potatoes can be grown on infested field for as long as they do not show symptoms. Although seed potato production on a field that is known to contain the nematode is very risky, it occasionally happens in practice.

Colorado beetle

The Colorado beetle (*Leptinotarsa decemlineata*) feeds on the foliage of potato plants. It can cause major damage, eliminating the entire crop and leaving only stems. The pest was introduced in the Netherlands in the 1950s and initially did not cause much damage. In recent years its presence and control are increasing. Obviously, it is one of the pests of which experts expect that it can considerably increase in importance in response to climate change.

Until 1996, a legal obligation to (chemically) control the beetle was in force. In practice, the damage caused by (first generation) larvae is rather low. Nevertheless, if not sufficiently controlled, large populations of adult summer beetles can emerge, causing serious crop damage. The actual yield loss depends on the reduction in foliage coverage caused by the beetle and the time in the season at which damage occurs.

Other diseases and pests

The predicted climate change is expected to have a negative effect on the presence of Phoma (*Phoma exigua*). Phoma is a storage disease, causing dry-rot of tubers after harvest. Phoma is favoured by cool or temperate climate and is low-pathogenic on potatoes. Nowadays, Phoma can well be controlled by available crop protection products and presently is of little economic importance.

Besides *M. chitwoodi*, seed potato production in the Netherlands is also threatened by the Potato Cyst Nematode (PCN). PCN has only one generation cycle per year, irrespective of climatic circumstances. It produces cysts to bridge the gap between two growing seasons. These cysts can survive for many years under extreme weather conditions. Thus, presence of PCN and the damage it can cause are not likely to be affected by climate change.

Higher temperatures allows a more rapid multiplication of brown rot bacteria (*Ralstonia solanacearum*). This disease has a quarantine status. Several outbreaks have occurred in the past, but currently the disease seems under control in the Netherlands. The disease is present in parts of the surface water where bittersweet (a host plant) grows along the waterways. Flooding of land with this surface water - and subsequent infection of the potato crop that grows on it - may become more likely in the future. However, this risk applies only to certain regions. Moreover, the potential consequences of such infections are already strongly reduced by legal preventive measures that are currently in force.

4.2 Identification of effects

4.2.1 Pests and diseases

Late blight

P. infestans prefers temperate temperatures and humid conditions. A moderate increase in summer temperature together with regular rainfall is expected to result in a more rapid and serious infestation of potato leaves and tubers during wet periods. However, if climate change results in more extremes (heat waves and incidental, but heavy showers), the infestation level is likely to reduce. In the W+ scenario, the latter is the case.

Late blight is expected to appear earlier in the season. In an analysis of late blight epidemics in Finland over the period 1933-2002, the observed more frequent early onsets of late blight epidemics over time were found to be climate-related (Hannukkala et al., 2007). Another Finnish study revealed that each degree of warming leads to a 4-7-day earlier late blight appearance (Kaukaranta, 1996, in Haverkort and Verhagen, 2008). Nevertheless, other (non-climatic) factors are responsible for earlier late blight appearance as well. The introduction of a new pathotype in the Netherlands about 30 years ago enabled survival of oospores in the soil, causing early infections in spring.

Bacterial diseases

In the past, the pathogens contributed equally to the occurrence of the bacterial diseases blackleg and aerial stem rot. However, the last five years, one particular species, Dickeya spp, is becoming more important than the others. This shift goes together with an increase in blackleg incidence. Dickeya spp. have a higher optimum temperature and can cause symptoms at lower densities than the other blackleg pathogens. Also within the Dickeya spp, a shift is observed towards a variant that has a higher temperature maximum than the prevailing species before 2000. This new variant is better capable of colonising plants and tubers. Although the evidence is still incomplete, it is hypothesised that above-mentioned changes are caused by a shift in climatic circumstances (Van der Wolf, personal communication).

Dickeya spp. are spread from infected tubers to neighbouring plants via free water in soil. Moreover, excess soil water causes larger populations of bacteria on infected tubers, resulting in more spread to other tubers as a result of smearing during and after mechanical harvesting. So, increased rainfall at the end of the growing season favours the spread of blackleg (Haverkort and Verhagen, 2008; Van der Wolf et al., 2008).

Potato virus Y

In order to spread, PVY is dependent on its vector, i.e. aphids. The vector is considered a component of the environment. No information is available on effects of climate change on the virus itself.

M. chitwoodi

Soil temperature determines the number of generations of nematodes per year. *M. chitwoodi* can start reproduction and infection at a minimum temperature of 5 °C (Van den Berg, 2009). The year 2007, which was characterised by extremely high temperatures, soil temperature at 20 cm below surface did not drop below this level until just before Christmas. Currently, *M. chitwoodi* can finish up to three generations per year. Climate change is likely to increase the number of generations to four. This results in higher population densities in the field, more infected tubers, and earlier symptom development.

Flooding can cause dispersal of nematodes such as Meloidogyne species, but may also reduce nematode populations because of anaerobic circumstances (inundation). However, in practice inundation is rarely 100% effective. Effects of flooding is not included in the analysis because it applies only to a small part of the Dutch seed potato production area.

Colorado beetle

The Colorado beetle is projected to expand its geographic range in Europe northward as a result of temperature rise. In the Netherlands, the beetle is already present, but climate change will considerably further increase the suitability for establishment (Baker et al., 2000).

After the winter season, Colorado beetles start laying eggs at a minimum temperature of 17 °C. The development rate of the Colorado beetle is also temperature-dependent. In a warm summer, the beetle can finish two generation cycles, as compared to one in an 'average' year. This was, for instance, the case in the relatively warm summer of 2006. The warmer winters also enable more beetles to survive the winter period as they experience less cold stress (Worner, 1988).

4.2.2 Host: seed potatoes

Less frost in winter results in a higher survival rate of tubers that remain in the soil after harvest, and thus in a higher number of volunteer plants emerging in spring. Volunteer plants are a potential source of overwintering for many diseases, such as late blight and PVY. Moreover, volunteer plants provide an initial inoculum source that allows pests and diseases to build up a population before or early in the actual growing season (Haverkort and Verhagen, 2008). Higher temperatures can prolong the growing season of potatoes. For seed potatoes however, the end of the growing season is determined by other factors (e.g. quality demands) than temperature restrictions. Any benefit should thus come from an earlier planting date, which is likely, provided that the soil is not too wet for access with machinery.

A number of other effects have been theorised, but not yet (empirically) validated. Different growing conditions (irradiation, CO_2) are suggested to cause changes in the anatomy and C/N ratio of the plants, which in turn changes the vulnerability to fungal and microbial diseases. The development of certain insects, amongst which the Colorado beetle, slows down. Yet, many insects compensate for the lower protein uptake by a strongly increased predation. Also, higher temperatures can have a negative effect on host plant resistance (Bouma, 2009). These effects are not included in the analysis as they are not (yet) supported by empirical evidence and dependent on other changes, such as potential shifts in the growing season.

4.2.3 Environment

We restrict the analysis of effects on the environment to changes in dynamics of aphids, the vector of PVY. Other relevant effects on the environment have not been reported of (yet).

The first day of flight of M. persicae occurs 14 days earlier per degree temperature rise (Bouma, 2009). Yet, planting dates are also expected to shift forward (Haverkort, personal communication), so the crop will be in the same stage by the time it is exposed to aphids. The temperature rise results in a higher number of aphid generations; this only affects seed potato production if the growing period is prolonged, i.e. if an earlier planting date does not forward harvest date. Since the haulm destruction date is based on virus pressure, harvest date is likely to be adapted.

A warmer climate is expected to go together with increased biodiversity. Moreover, aphids become less responsive to alarm pheromones at higher temperatures. Consequently, climate change may increase the vulnerability of aphids to natural enemies (Haverkort and Verhagen, 2008).

In recent years, an increase in percentage downgrading because of PVY has been observed. In a field study of the Dutch General Inspection Service for agricultural seeds and seed potatoes (NAK) over the period 2006-2008, no significant increase in aphid populations was observed, although large numbers of aphids were found early in the season compared to the 1980s (Verbeek et al., 2009). So far, there is no evidence for a relationship between PVY increase and climate change. Recent insights suggest that at least part of the increase in PVY can be explained by a change in cultural measures such as plant selection in field and increased field size (Van de Bovenkamp, personal communication).

4.2.4 Crop management

The curative and preventive effect of systemic crop protection chemicals is temperature-dependent. Also, uptake of the chemicals by the crop is favoured under optimal growth circumstances. Under the predicted climate change, both uptake and duration of effectiveness of systemic chemicals is expected to decline. Expected effects on contact fungicides and pesticides are lower, because these chemicals only need dry circumstances (Bouma, 2008).

An indirect effect of climate change on crop management is that the haulm destruction date, which marks the end of the growing period of the seed potato crop, is advanced over the years. The incentive for this is prevention of virus infection through aphids (see subsection 4.2.3). As a consequence, tubers have less matured at the time of harvest and are more vulnerable to damage - and thus to infection by pathogens during or shortly after harvest (Van der Wolf, personal communication). This effect is disputed by others, arguing that growers will not start harvesting until the tubers have maturated (Haverkort, personal communication).

It is expected that in the future, the amount of rainfall decreases, but more heavy showers and prolonged periods of rainfall will occur. Severe rainfall can reduce accessibility of fields. This impedes practices such as planting, spraying, and harvesting. Also, spraying under wet circumstances increases the chance of pathogen dispersal within the field through machinery (Schaap et al., 2009).

Table 4.1 **Effects of climate change on five seed potato pests and diseases, specified per effect factor and disease**

	P. infestans	Bacterial diseases	PVY	*M. chitwoodi*	Colorado beetle
pathogen / pest	- appearence earlier in growing season - lower infestation level	- more smearing due to higher mobility of bacteria under wet soil conditions - more symptom expression at higher temp	-	- more generations per growing season	- a second generation per growing season - earlier emergence of winter beetles
host	- more volunteer plants - increased leaf density		- more volunteer plants		- more volunteer plants
environment			- more aphid generations per growing season - earlier first day of flight of aphids - aphids more sensitive to natural enemies?		

Table 4.1 Effects of climate change on five seed potato pests and diseases, specified per effect factor and disease (continued)

	P. infestans	**Bacterial diseases**	**PVY**	***M. chitwoodi***	**Colorado beetle**
management	- fields become (incidentally) inaccessible - reduced effectiveness of crop protection chemicals?	- harvesting under wet conditions	- reduced effectiveness of crop protection chemicals? - earlier planting - earlier haulm destruction (and harvesting) date	- more soil displacement with (harvest) equipment?	
net effects	- ***earlier disease pressure*** - ***less effective crop protection***	- ***larger fraction of latently infected tubers*** - ***earlier disease expression in infected lots***	- ***earlier disease pressure*** - ***less effective crop protection***	- ***higher disease pressure in infested fields*** - ***earlier symptom development*** - ***more rapid spread to other fields***	- ***higher pest pressure***

4.3 Assessment of impacts

Little has been written on the impacts of above-described effects on pests and diseases for seed potato growers. Particularly quantitative information on the magnitude of impacts is lacking. Below, where possible a (rough) quantitative estimate of potential economic impact will be given on the basis of empirical data and expert judgments. However, the estimates are only indicative and should be not be taken as facts.

4.3.1 Biological crop protection

In conventional seed potato production, crop protection by means of biological products or natural enemies is uncommon. Concerning the five pests and diseases included in this case study, this probably will not change in the future.
A pest for which climate change might provide opportunities for more efficient use of natural enemies is aphids - and thus less use of pesticides. However, evidence is still lacking and biological aphid control in seed potato production seems not a realistic option in the short run. Research is ongoing regarding biological suppression of nematodes, e.g. by means of growing particular crops in rotation with (seed) potatoes. As this type of research is still largely in an experimental stage, it will not be further discussed here.

4.3.2 Chemical crop protection

Due to earlier disease pressure and reduced effectiveness of crop protection chemicals, crop protection chemicals may need to be applied over a longer period. Bouma (2008) states that under future climatic circumstances, on average seven additional chemical applications per growing season will be necessary to maintain effective control of current pests and diseases. Yet, this estimation is based on ware potatoes and on the assumption that late blight disease pressure during the season increases. Assuming an advanced harvest date and less severe climate change effect on late blight, the increase is probably lower. If the Colorado beetle becomes a threat in the future, applying pesticides against its larvae early in the growing season becomes more important again, in order to avoid escalation of damage caused by a second generation. Adult beetles are not susceptible to crop protection chemicals, and can lay numerous eggs for a second generation. Some of the crop protection products available for Colorado beetle control are also effective against aphids, so the net increase in pesticide use is lower than would be the case when controlling both pests individually.

Apart from increased crop protection directed at specific pests and diseases, volunteer plant control will also become more important in the future. While this brings along additional costs for growers, it is beneficial for pest and disease management in general. Moreover, effective volunteer plant control reduces disease or pest pressure, so to some extent there will be a trade-off between increased costs for volunteer plant control and pest and disease control.

The hypothetical reduction in effectiveness of crop protection chemicals may require seed potato growers to switch to more expensive systemic chemicals.

Quantitative estimation of impacts
Current yearly crop protection expenditure for seed potato production is approximately €800 per hectare (De Wolf and Van der Klooster, 2006). The increase in costs of crop protection under climate change is likely to remain within the range of €100-200 per hectare, or approximately €3.5-7m for the entire sector.

4.3.3 Quantitative crop loss

Currently, late blight causes yield losses, irrespective of crop protection, on average every five years. In the future, the incidental climatic circumstances that favour crop losses are likely to occur at a more frequent rate. So, it is likely that the crop losses that are sometimes incurred due to late blight will occur more often.

Quantitative estimation of impacts
Current average crop losses cost the sector on average €1m per year (36,000 ha in total, damage of €1,400 once in 5 years on 10% of the total acreage). Even if crop damage would increase twofold in the future, it is still a rather small impact compared to the total expenditure on crop protection chemicals against late blight.

4.3.4 Qualitative crop loss

Bacterial diseases, *M. chitwoodi* and PVY are expected to cause more qualitative crop loss in future. More seed lots will become infected and infections may become more serious, resulting in a higher detection rate and more downgraded or rejected lots. For bacterial diseases, the effect of a higher spread rate at harvest on detection has a delay of at least one year, because tubers that become infected at harvesting will remain symptomless for some time. Regarding PVY, more infections are expected to occur despite more frequent crop protection, particularly because in the future PVY is likely to emerge at an earlier, more vulnerable growing stage of the crop. Moreover, pesticides can never be 100% effective.

Quantitative estimation of impacts
According to an economic analysis of bacterial diseases in the Netherlands, in two years with serious problems, the acreage of seed lots that is downgraded or rejected reached 21%, as compared to 16% on average. Total losses from bacterial diseases for growers in the respective years varied from almost €12-24m, as a result of different market conditions. Using the average yearly loss of €12m over the period 2003-2007, an increase from 16 to 21% in the fraction rejected or downgraded seed lots would on average cause an additional yearly loss of almost €4m.

Virus diseases cause similar losses for affected growers but occur at a much lower rate; currently a yearly 3 to 4% of the acreage is downgraded or rejected.

Infections with *M. chitwoodi* are still found at an incidental base; between 6 and 25 per year over the period 1998-2005 (Janssens et al., 2008). Moreover, a future increase in detections over time comes largely at the account of changes in inspection policy. Nevertheless, the direct losses of detection for affected farmers are considerable. Detected lots are rejected and have to be sold as ware potatoes. The price difference between seed and ware potatoes is at least €0,10 per kg (De Wolf and Van der Klooster, 2006), resulting in a total revenue loss of at least €3,500 per hectare.

More downgrading or rejection of seed potatoes results in a lower net multiplication rate of seed potatoes declines. To maintain the same level of planting material for ware potato production (including export), requires that more high-quality seed potatoes are be available at the start of the production chain, i.e. more selection of class S tubers or production of minitubers. It is not possible to quantify this effect within the scope of this study.

4.3.5 Other economic consequences

Once a lot has been detected, all fields within a range of 1 km around the field on which the lot was grown are put into quarantine. From then on, for a period of at least three years, all planting material produced on these fields will be tested for (latent) infection with *M. chitwoodi*. Thus, detection of an infested seed lot in a region that was until then officially free from the disease strongly restricts future seed potato production in that region.

As a consequence of an increasing fraction downgraded or rejected seed potatoes, the total seed potato supply decreases. If this decrease is substantial, it will be reflected in a higher market price. The Netherlands is one of the largest seed potato producing countries in the world. A few percent decrease in Dutch supply can thus already cause a market shift. The increased price may compensate or partly compensate for the losses from rejection and downgrading. However, this is only likely to occur in years with low yields, as in normal years a surplus of seed potatoes is rather common.

Diseases causing qualitative crop loss often also can affect the image of the Dutch seed potato sector. Since seed potatoes are exported all over the world, infected seed lots are a source of dispersal to other countries. Detection of infections with bacterial diseases, viruses and *M. chitwoodi* is never 100%. So, an increase in the fraction downgraded or rejected seed potatoes also implies a higher risk of exporting infected seed lots. This can result in a lower demand for Dutch seed potatoes in the future.

Table 4.2 **Impacts of climate change on disease and pest control in seed potatoes, specified per disease and impact factor**

	biological crop protection	chemical crop protection	qualitative crop loss	quantitative crop loss	other economic consequences
Late blight		- more expensive fungicide sprayings per year? - more volunteer plant control required		- incidental crop loss occurs more often	
Bacterial diseases			- higher % of lots downgraded / rejected		
PVY	-(potential for use of natural enemies?)	- additional sprayings per year? - more volunteer plant control	- higher % of lots downgraded / rejected		
M. chitwoodi			- higher % of lots rejected		- less arable land available for seed potato production

Table 4.2	**Impacts of climate change on disease and pest control in seed potatoes, specified per disease and impact factor (continued)**				
Colorado beetle		- additional sprayings per year - more volunteer plant control		- slightly more often significant crop loss	
net impact	***-***	***more costs of chemicals (but net increase is less than the sum of all pests/diseases). estimated loss: €3.5-7m/year***	***more rejected or downgraded seed lots estimated loss: - €4m revenue loss/year - need for more minitubers***	***more frequent loss of revenue. estimated loss: €1-2m/year***	

4.4 Concluding remarks

The results of this case study suggest that, for seed potato production, the largest impacts of climate change comprise increased costs of chemical crop protection and increased quality losses. Total expected losses exceed €10m per year. Yet, this is the worst-case scenario, assuming that farmers and other stakeholders will not adapt. In practice, the sector will respond to the abovementioned changes to minimise negative impacts or even to benefit from climate change. For instance, the theoretical potential for higher leaf density can be compensated by reducing fertiliser (nitrogen) application, which actually saves costs. Also, soil displacement and tuber damage during harvest can be reduced by increased hygiene. Furthermore, the crop protection industry will likely develop chemicals that are effective under the changed climatic circumstances.

The fact that this case study is based on the (overall) most extreme climate change scenario does not necessarily mean that impacts are most extreme under this scenario as well. For instance, for late blight, the concentration of rainfall in fewer, but more severe showers results in a reduction of disease pressure, despite a relatively high increase in temperature. Another scenario, with less temperature increase and less heavy (but more evenly spread) showers will have the opposite effect.

The effect and impact matrices (tables 4.1 and 4.2) show the importance of including the whole system in an impact assessment. In the effect matrix, climate change is shown to increase the number of aphid generations, but also to advance haulm destruction date. The negative effect on the environment is thus compensated by a 'positive' change in management. The impact matrix shows that climate change possibly requires more spraying to control several diseases. Yet, as certain chemicals have a broad range of target species, the net increase in chemical crop protection is less than would be concluded on the basis of disease-specific assessments. As a result, impacts are probably less severe than suggested on the basis of literature review alone (see for instance Bouma, 2009). Nevertheless, in particular cases, the opposite - individual effects or impacts amplifying each other - may also be true.

5 Conclusion and recommendations

5.1 General conclusions

In the preceding chapters, we have explored the effects and subsequent impacts of climate change on pest and disease management in commercial crop production. Following this conceptualisation, we have presented a methodology for assessment of climate change impacts on pest and disease management. This methodology was subsequently applied to seed potato production as a pilot study.

5.1.1 Exploration of effects and impacts

From the exploration of effects and impacts, it appeared that much fundamental (theoretical) knowledge on the interactions between specific climatic variables and different categories of pests and pathogens has been gained over the past years. Empirical field studies supporting this theoretical knowledge are less common, as are studies that focus on the entire gamma of climate change variables. This makes it difficult to evaluate to which extent theoretically possible effects actually will occur in practice. Impact studies are still very limited; although a number of studies mentions impacts of climate change on disease development or control, these 'impacts' often refer to the magnitude of the effect, rather than what this effect actually 'means' to affected stakeholders.

5.1.2 Development of methodology for impact assessment

In developing a methodology for assessment of climate change impacts on pest and disease management, we have not started from scratch. The methodology is based on earlier research of Cobon et al. (Cobon et al., 2009). In adapting it to the field of disease control, we used the long existing concept of the disease pyramid developed by Zadoks and Schein (Zadoks and Schein, 1979). The characterisation of impacts was at least partly based on a typology of crop losses provided by the same authors, and on experiences in the field of Pest Risk Assessment (Baker et al., 2009).

Nevertheless, integration of these concepts and theories has resulted in a framework that can contribute to the knowledge gap in climate change research that was already identified before and supported by the exploration. It provides a systematic approach for evaluating the impact of climate change on pest and disease management at crop level, rather than individual diseases. In doing so, it considers not only the interactions between climate and diseases and pests, but also between climate and other system elements that play an important role in disease control. Furthermore, it translates the physical effects of climate change on the system into the economic, and possibly social and environmental, impacts for affected stakeholders and the ecosystem.

The results of impact assessments can be used to direct future adaptation efforts. They reveal the major weaknesses of the crop protection system with respect to climate change and reveals possibilities for the sector to cope with climate change impacts. Also, they provides a first indication of the maximum acceptable costs of (future) adaptation measures in order to be cost-effective.

5.1.3 Pilot study

The pilot study revealed that even for specific diseases, effects of climate change are often still uncertain. Nevertheless, insights are rapidly growing thanks to e.g. model studies and time series analyses. Restricted access to the results of such analyses appeared a limitation when performing the pilot study.

Much information on effects of climate change on diseases and their control is qualitative or even speculative. Moreover, it is often not clear how climate change effects on different system elements (e.g. host vs. pathogen) interact, i.e. what the net effect will be. Consequently, translation of effects into economic impacts was difficult and only rough indications could be given. Yet, even these indications can help in priority-setting and identifying potential future bottlenecks in pest and disease control.

5.1 Choices, limitations and drawbacks

5.2.1 Key effect factors

In a previous study on measuring effect of climate change on plant diseases, Boland et al. (2004) used the different stages of disease development as indicators for changes in disease severity. They distinguished primary inoculum (or disease establishment), rate of disease progress, and potential duration of the epidemic. This categorisation results in a more detailed and specified overview of effects of climate change on the disease itself. However, it does not explicitly account for the role of the host crop and the environment in disease development (although these factors are implicitly taken into consideration). Moreover, the focuses on disease development, rather than disease control. Therefore, we consider the use of the elements of the disease pyramid more appropriate for this study.

5.2.2 Key impact factors

As discussed in Chapter 2, effects can have economic, social, and environmental impacts, which can direct or indirect. Environmental and social impacts related to disease control are to a large extent avoided due to national legislation, and of less importance to agricultural producers. Moreover, in our pilot study of seed potatoes, biological control (or natural enemies) plays a minor role. Nevertheless, there are examples of cropping systems where potential environmental (and social) impacts are of much more importance. An example comprises organic crop production, which is to a large extent dependent on natural enemies and suppressiveness of the cropping system.

Indirect impacts follow from direct impacts. However, they are dependent on a number of other factors as well and therefore often not solely attributable to effects of climate change on disease control. For example, potential market shifts due to lower supply caused by crop losses are also dependent on simultaneous impacts of climate change on crop losses in other, competing countries. Such interactions are difficult to predict and go beyond the scope of this project.

5.2.3 Interaction with other effects on crop production

Climate change does affect crop production in various ways, of which disease control is only one aspect. Examples of other issues are crop yield (qualitative and quantitative), availability and suitability of agricultural land, and market position (competition with other countries). The impacts on these issues may amplify or (partly) compensate the impacts on disease control.

Several of these other aspects have already been studies to a more or lesser extent. However, examples of studies that combine multiple aspects of climate change impact are rare, so an overall insight into the risk of climate change for agriculture is lacking. This makes it difficult to set priorities in research and policy regarding adaptation to future climate conditions.

Ideally, an integral approach should be developed that enables inclusion and comparison of different types of climate change impacts on crop production. It is worth exploring whether the approach described in this report may be suitable for extension to - for instance - a farm- or crop-wide assessment tool.

5.3 From impact to risk to adaptation

The conceptual framework as illustrated in Chapter 4 provides an overview of all potential impacts. It does not weigh these impacts according to their likelihood of occurring. The combined magnitude and likelihood of an impact presents the *risk* (or *chance*, in neutral terms). The framework presented by Cobon et al. accounts for the concept of risk, which is integrated in the impact matrix. Integration of risk in our conceptual framework is somewhat more complicated. The likelihood of an impact follows from the likelihood of a particular change in the climate and the likelihood of the effect that follows from it. Likelihood is thus embedded in the effect matrix. The impacts, on the other hand, determine how 'good' or 'bad' a particular effect is in terms of pest management, given its occurrence. In order to translate likelihood to the impact matrix, the likelihoods of different effects would have to be somehow aggregated.

If impacts can be weighed according to their likelihood, the framework becomes suitable for identifying potential future threats and opportunities. Thereby, it provides a basis for setting priorities for action, i.e. for determining which possible impacts need urgent adaptation in order to avoid catastrophic consequences or take maximum benefit from climate change. The systematic, stepwise approach used in the framework enables tracing impacts back to the causal effect, which facilitates an efficient search for adaptation strategies.

Moving one step further, the framework could also be elaborated towards a full vulnerability assessment, as was done in Cobon et al. Vulnerability adds another component to impact risk: the adaptive capacity of the system. To a certain extent, the adaptive capacity is already implicitly accounted for in the impact matrix. For instance, if disease pressure increases, it is assumed that the farmer tries to avoid (more) crop damage by applying more intensive crop protection. This is a more or less intrinsic adaptation to climate change, which does not require a structural adaptation strategy. The higher the adaptive capacity of the system towards a particular change, the lower the urgency for development of new adaptation strategies.

5.4 Directions for future research

The results presented in this report offer several directions for further research. Below, an overview is given.

Recommendations related to this study:

- Extension of the impact assessment with environmental and social impacts. This is important as the responsibilities of agricultural production with respect to issues such as human health and ecosystem preservation are gaining more and more attention. Inclusion of indirect impacts would further complete the assessment; however, this will be difficult due to the complexity and interdependencies of such impacts.
- Inclusion of risk in the framework for assessment of climate change impacts on disease control. This will provide insight in the potential consequences of climate change for disease control, as well as their likelihood. An indication of the level of risk associated with consequences is necessary in order to set priorities for adaptation.
- Elaboration into a framework for vulnerability assessment. This would be the next step after incorporating risk. Accounting for the intrinsic adaptive capacity of the system would result in a more accurate risk statement of the observed system by distinguishing between risks that will be tackled by autonomous processes and risks that need joint effort in order to cope with.

Recommendations with respect to climate research in general:

- In studying climate change in relation to agriculture, its effect on (management of) pest and diseases is still lagging behind. Yet, pest (and disease) management comprises an important cost factor in crop production. Information on the relation between climate change and pests and diseases is also important at a national level, as their introduction and the failure of their control in a country or region increasingly leads to trade restrictions and costly regulations. Climate change may play a role in this trend.
- The study presented here offers a framework to enable transparent and structural impact assessment. Yet, the information required to fill in the framework is still very incomplete and mostly theoretical. Future research on climate change in relation to pest and disease control should take a more integrated approach, capturing several aspects of climate change simultaneously. Moreover, the empirical relevance of theoretical effects should be evaluated. For instance, there are numerous reports of effects on host plant

physiology and morphology, which theoretically affect its susceptibility to certain pests and diseases. Yet, empirical studies that support or reject these hypotheses are lacking.

- To put impacts of climate change on pest and disease control in perspective, the analysis should be integrated in a farm- or crop-wide impact assessment. Such an assessment covers climate change impacts on a range of aspects important in farm management or crop production, thereby enabling comparison of different types of impacts for their relative importance. A farm- or crop-wide approach can also provide insight into the robustness of farms or cropping systems to climate change. It is worth investigating whether the approach taken in this study is suitable for application at such level.

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Appendix 1

Effects of climate change on pest and disease control

Host

Temperature and drought

Heat (or cold) and drought are causes of abiotic stress in plants. During colder parts of the year, warming may relieve plant stress, whereas during hotter parts of the year it may increase stress. Heat stress causes changes in plants that affect susceptibility to pathogens, both positively and negatively (Chakraborty et al., 2000; Garrett et al., 2006). Drought stress and disease stress may have additive effects on plants.

Plants sometimes physiologically or morphologically adapt to high temperatures. For instance, elevated temperature may cause the breakdown of temperature-sensitive resistance, as is for instance the case with oat stem rust resistance of certain cultivars. Conversely, some forage species show increased lignification at higher temperatures, which enhances the level of host resistance to pathogens (Chakraborty et al., 1998).

CO_2 and ozone

A higher CO_2 concentration affects crop physiology and morphology. For instance, it increases photosynthesis rate, which has been reported to slow down pathogen invasion (Chakraborty et al., 2000; Pangga et al., 2004). On the other hand, a higher CO_2 concentration increases plant density - and thereby leaf surface wetness, which makes infection by foliar pathogens more likely (Garrett et al., 2006). CO_2 also affects the chemical composition of the plant, and thereby its nutritional value for insects. Yet, it is unclear whether the net effects on insect abundance are positive or negative (Fuhrer, 2003).

Ozone induces stress reactions in plants, which may result in either enhanced tolerance or susceptibility to a second stressor, e.g. a pathogen (Chakraborty et al., 1998). Elevated ozone concentrations cause changes in leaf structure, thereby influencing the ability of pathogens to attach to leaf surfaces and infect. Ozone exposure has been proposed to enhance attacks on plants by necrotrophic fungi, root-rot fungi, and bark beetles. Furthermore, increasing ozone concentrations will negatively impact plant production, possibly increasing exposure to pest damage (Tubiello et al., 2007).

Pathogen

Temperature and drought

Temperature can affect critical stages in the life cycle of a pathogen, such as reproduction rate and survival between seasons (Garrett et al., 2006). For example, winter temperatures can be an important factor for survival of diseases that survive in debris or in (insect) vectors. Milder winters are generally thought to favor insect survival, although it has also been stated that they reduce insect survival because their metabolism increases, which saves less energy for spring. For nematodes, summer temperatures can determine the number of reproductions per year. Also, their egg viability may be reduced in mild winters (Boland et al., 2004).

Dry conditions will slow down the infection rate of foliar pathogens and bacteria. In contrast, prolonged or repeated high moisture conditions facilitate epidemics (Boland et al., 2004).

Temperature increases are often predicted to lead to the geographic expansion of pathogen and vector distributions, bringing pathogens into contact with more potential hosts and providing new opportunities for pathogen hybridization (Chakraborty et al., 2000; Garrett et al., 2006).

Longer seasons that result from higher temperatures, and larger pathogen populations caused by increased overwintering and oversummering rates, will allow more time for pathogen evolution. This may increase the probability of more damaging pathotypes evolving more rapidly. Additionally, climate change may influence whether pathogen populations reproduce sexually or asexually (Garrett et al., 2006).

CO_2

Elevated CO_2 has both positive and negative reported effects on disease severity. Studies have shown an extended latent period of pathogens, but faster growth after establishment. Fecundity of both biotrophic and necrotrophic pathogens studied so far has increased under elevated CO_2 (Chakraborty et al., 1998; Pangga et al., 2004). Increased fecundity also contributes to infection severity and accelerates pathogen evolution, which is considered the biggest threat to the durability of host resistance (Chakraborty et al., 2000; Garrett et al., 2006).

CO_2 affects the competitive position of weeds relative to crops. The direction varies among weed-crop combinations; in temperate regions, however, it seems that the change is often in favor of the crop (Fuhrer, 2003).

Wind
Altered wind patterns can change the spread of both wind-borne pests and of the bacteria and fungi that are the agents of crop disease (Olesen and Bindi, 2002).

Environment

Natural enemies
Greater variability in temperature and precipitation might disrupt the synchrony between growth, development, and reproduction of natural enemies (including biocontrol agents) and their targets (Cannon, 1998). Even without disruption of synchrony, the effectiveness of natural enemies may change as a result of a balance shift between reproduction and predation of the pest (Harrington et al., 2001). Climate change might also have an effect on disease suppressive soils; however, predictions are difficult to make because of the great variation in interactions among microbial species (Garrett et al., 2006).

Pest distribution
Change in temperature and/or humidity can affect the (size of) the range occupied by a pest or pathogen, leading to introduction of new pests or pathogens (Cannon, 1998). The same applies to organisms that can act as a vector, whose introduction or change in presence (e.g. overwintering and oversummering) may have important effects on pathogen survival, movement, and reproduction (Garrett et al., 2006).

Man

Crop protection practices
Changes in leaf surface characteristics due to CO_2 effects may interfere with the uptake, translocation, and metabolism of systemic fungicides. Besides, climatic conditions (e.g. temperature, precipitation, wind and air humidity) affect the effectiveness and duration of chemical protection (Coakley et al., 1999; Olesen and Bindi, 2002). Biological control may be even more threatened as biocontrol agent populations are vulnerable to environmental variation and environmental extremes (Garrett et al., 2006) (see also under Environment). Alternative strategies such as delaying planting to avoid a pathogen may become less reliable (Garrett et al., 2006). Nevertheless, since climate change will modify host-

pathogen interaction, the greatest impact of climate change will be on management strategies that utilise host resistance (Chakraborty et al., 2000).

Production practices

Climate change will extend the possible growing seasons of crops. For some crops, this will imply higher yield, which is an economic stimulus for growers to apply earlier sowing dates. Yet, this increases plant exposure to pathogens, especially to those that have expanded ranges for overwintering and oversummering as a result of changing climate. (Garrett et al., 2006). This causes potentially more economic damage from diseases, and higher crop protection costs due to more chemical applications.

Increased drought stress of plants will result in more severe symptoms of certain diseases, such as vascular wilts, root rots, and nematode infections (Boland et al., 2004).

Crop breeding

Climate change can cause a shift in preferred crop characteristics, and thus a different focus in crop breeding. A concern is whether farmers will be able to identify and acquire crop genotypes that are adapted to their changing climates (Garrett et al., 2006). Also, the 'realised' (i.e. non-inherent) durability of resistance of a crop against a disease may change as a result of changed pathogen characteristics or increased evolution rate. This brings new challenges in resistance breeding.

Appendix 2

KNMI Climate change projections

The KNMI climate scenarios distinguish four categories: temperature, rainfall, wind and storm, and sea level. Here, sea level is omitted as it does not play a role in pest management. Per category, the variables considered most relevant for pest and disease control are summarised below.

Table A2.1	**Comparison of climate change characteristics in the current situation (baseline scenario) and 2050, assuming the W+ (most extreme) scenario**	
Climate change variable	**Baseline scenario**	**W+ scenario 2050**
Temperature		
1. Warmer summers, with higher and more frequent temperature extremes	Mean temperature: 16.8°C Number of warm days[1]: 80 Number of summer days[2]: 24 Number of tropical days[3]: 4 Warmest day per year: 31.8°C	Mean temperature +2.8°C Number of warm days: +46 Number of summer days +26 Number of tropical days: +11 Warmest day per year: +3.8°C
2. Warmer winters, with higher (less cold) and less frequent temperature extremes	Mean temperature: 3.2°C Number of frost days[4]: 59 Number of ice days[5]: 9 Coldest day per year: -13.3°C	Mean temperature: +2.3°C Number of frost days: -32 Number of ice days: -6 Coldest day per year: +3.9°C
Rainfall		
3. Less summer precipitation, but with (slightly) heavier showers	Summer rainfall sum: 218 mm Number of wet days[6]: 42	Summer rainfall sum: -19% Number of wet days: -19% Mean prec. on wet day: +0.3% Median prec. on wet day: -12.4% Daily precipitation sum exceeded once in 10 years: +10%

Table A2.1	**Comparison of climate change characteristics in the current situation (baseline scenario) and 2050, assuming the W+ (most extreme) scenario (continued)**	
Climate change variable	**Baseline scenario**	**W+ scenario 2050**
4. More winter precipitation, with more severe wet periods	Winter rainfall sum: 220 mm Number of wet days: 50	Winter rainfall sum: +14.2% Number of wet days: +1.9% Mean prec. on wet day: +12.1% Median prec. on wet day: +14.7% 10-day precipitation sum exceeded once in 10 years: +12%
5. Increase in drought	Average maximum precipitation deficit[7]: 144 mm Yearly probability of prec. deficit as in 2003: 10%	Average maximum precipitation deficit: +76 mm Yearly probability of prec. deficit as in 2003: 50% Potential evaporation[8]: +15%
Wind and storm		
6. Increase in likelihood of storm	Maximum average daily wind speed per year: 11 m/s (1990) Average wind speed per year: 4.0-6.0 m/s	Maximum average daily wind speed per year: +4% Average wind speed per year: + 5%

[1]Warm day: maximum temperature ≥20 °C; [2]Summer day: maximum temperature ≥25 °C; [3]Tropical day: maximum temperature ≥30 °C; [4]Frost day: minimum temperature <0 °C; [5]Ice day: maximum temperature <0 °C; [6]Wet day: total rainfall ≥0.1 mm; [7]Precipitation deficit: potential evaporation minus precipitation summed over the period from 1 April to 30 September; [8]Potential evaporation: maximum evaporation rate that can be supported by the atmospheric demand, assuming no feedback by atmospheric humidification (i.e. maximum evaporation of a well-watered reference crop).

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