Using weather derivatives for the financial risk management of plant diseases

A study on Phytophthora infestans and Fusarium head blight

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Summary table

	Phytophthora infestans	*Fusarium head blight*
Crop	Potatoes	Wheat grain
Weather parameters	7.2°C – 25.5°C, 5 days	10°C – 32°C, 15 days
	>30 mm rainfall, 10 days	>80 mm, 30 days
Critical time	May – Sept	June
Probability for weather parameters	87 – 97%	0 – 2%
Correlation weather/disease	Yes, but not scalar	No
Weather derivatives a viable tool	No	No
Why?	- Premium would be too high	- Correlation weather with disease too low
	- Non-scalar predictor for disease	

1. Introduction

1.1 Problem statement

Agricultural practice is confronted with different risks. Barry *et al.* (1999) describe six different business risks for farmers: 1. Production and yield risks 2. Market and price risks 3. Losses from severe casualties and disasters 4. social and legal risks 5.human risks in the performance of labour 6. Risks of technological change and obsolescence. Berg *et al.* (2007) divide entrepreneurial risk into market risk, financial risk and operational risk. Within operational risk they define endogenous risks like technological risk, efficiency risk and exogenous risks such as weather risk and disasters. The outbreak of plant diseases can be regarded as an operational risk for the farmer.

Several plant diseases show a large correlation with weather conditions. Examples are *Phytophthora infestans* in potatoes that favours wet weather (Erwin, 1983) and *Fusarium head blight* in wheat grain that is related to relative warm and wet weather during germination (Schaafsma *et al.*, 2001). The weather conditions relating to a specific plant disease are called environmental parameters in literature (Norton and Turvey, 2008).

Different instruments are present to cope with the risks in agriculture. Berg and Schmitz (2008) group these instruments into 'on farm' instruments and 'market based' instruments. To the 'on farm' instruments belong risk prevention, diversification and holding of reserves, the 'market based' instruments are risk pooling and risk transfer (contracting). Within the risk transfer instruments, weather derivatives have emerged in the last ten years. Weather events can have a large influence on agricultural business performance (Hardaker *et al.*, 2004), weather derivatives provide a tool for insurance against these adverse weather conditions. Using a weather index such as cumulative rainfall as the basis for indemnity pay out, classic problems in insurance such as adverse selection, moral hazard and prohibitive administrative costs are limited (Turvey and Norton, 2007).

Although weather derivatives have come up in last years, their success is still limited. Literature discusses different reasons for the limited use of these new instruments; high level of basis risk (Woodard and Garcia, 2008a), remaining price uncertainty (Berg and Schmitz, 2008, Richards *et al.*, 2004, Turvey, 2001), diversification effects (Berg and Schmitz, 2008) and idiosyncratic risk (Woodard and Garcia, 2008b). Turvey and Norton (2007) argue that risks in agriculture are mostly 'joint'; which means that risks are often based on both temperature and rainfall. Current tools are mainly based on one element of weather, for instance temperature. By assessing the joint probabilities, weather derivatives can be connected to specific agricultural risks like plant diseases (Norton and Turvey, 2008).

In this study two plant diseases, *Phytophthora infestans* in potatoes and *Fusarium head blight* in wheat grains, will be analyzed in respect to a potential use of weather derivatives for the management of financial risks related to these plant diseases. The weather parameters related to the disease will be determined from literature in order to analyze the weather data. These data, together with incidence data of the diseases will be used to formulate a risk profile of the plant disease. The risk profile will be the input for discussion of the potential use of weather derivatives in risk management of the specific plant diseases.

1.2 Objectives of the study

In the context of risk management of plant diseases, the main objective of the study is to assess the potential use of weather derivatives for the risk management of the plant diseases *Phytophthora infestans* in potatoes and *Fusarium head blight* in wheat grains. The diseases *Phytophthora infestans* and *Fusarium head blight* were chosen due to their known correlation with weather conditions (Schaafsma *et al.*, 2001, Erwin, 1983), the vomitoxilogical properties of *Fusarium head blight* (Desjardins, 2006) and the economic impact of both *Phytophthora infestans* and *Fusarium head blight* (Agrios, 2004). The main objective can be divided into different sub-objectives:

(1) to define environmental parameters of plant diseases from literature;

(2) to assess the probability of the relevant disease parameters; and

(3) to define the applicability of weather derivatives for plant disease risk management.

1.3 Outline of the report

The first part of the report will provide a literature review on weather derivatives and discuss the two plant diseases that are the object of study in this report, being *Phytophthora infestans* in potatoes and *Fusarium head blight* in wheat grains. The second chapter will outline the weather derivatives and will discuss the economic losses incurred with the chosen plant diseases, the characteristics of the plant diseases and the relationship of the diseases with weather parameters. The third chapter of the report will discuss the data and methods used in the study. A conceptual model will be introduced and an outline will be presented of the weather parameters selected from plant literature, the weather data, the disease incidence data and the method of analysis used. The fourth chapter of the report will be devoted to the results of the data-analysis and will outline the statistical analyses. The last chapter of the report will discuss the applicability of weather derivatives for the risk management of the specific diseases based on findings from the statistical analysis.

2. Literature

This chapter will discuss the literature relevant for this research. The first paragraph will present a background on weather derivatives. The second paragraph introduces the plant science literature review that forms an essential element in this report. The third and fourth paragraph will describe the findings from plant science literature on *Phytophthora infestans* in potatoes and *Fusarium head blight* in wheat grains.

2.1 Weather derivatives

Weather derivatives were effectively introduced in the mid 1990's on the Chicago Mercantile Exchange. The first publicised deal concerned a risk sharing product between Enron and Koch electricity (Cao *et al.*, 2003). This transaction set the stage for the development of many different weather related finance products since then. Weather derivatives are a common name for multiple financial risk management products that have one shared characteristic, which is that they use an element of the weather (such as precipitation or temperature) as an objective proxy as basis for a financial product (Berg *et al.*, 2007, Turvey, 2008). Based on literature review of articles of Campbell and Diebold (2002), and Alaton *et al.* (2002), Muβhoff *et al.* (2005) describe in their article five differences between traditional risk management tools and weather derivatives:

1. Traditional insurances are based on risk management of catastrophic events (such as floods, hail and storms). Weather derivatives can also be used to manage less catastrophic events (such as insufficient rainfall).

2. In traditional insurance the insured need to prove their losses before he or she receives an indemnity. In weather derivatives the indemnities are based on an objective weather index.

3. Weather derivatives are not susceptible to traditional moral-hazard problems

4. A market for weather derivatives enables risk sharing between companies that have opposite positions towards a similar weather event. When a contract is set up between these companies, the risks can be effectively hedged.

5. Aftermarkets may arise for weather derivatives. Trading on these markets might become interesting for institutional investors because the weather related risks are relatively uncorrelated with traditional business risks.

In order to provide a structure to the different weather derivative products, two divisions can be made. Firstly between products that are generally traded and products that represent tailored contracts. The second distinction can be made related to the function of the contract. First we will discuss the difference between over-the-counter products (OTC) and exchange traded products. The OTC products are tailor made contracts between a writer and an underwriter that contractually describes the specific risks covered by the instrument and the terms and conditions of the contract. The over-the-counter products are often traded between an insurance company and an organisation needing risk mitigation (Woodard and Garcia, 2008b). The exchange traded products have a clear standard format, often resembling traditional financial options traded on the financial exchange markets (Berg *et al.*, 2007). Instead of using the price of a financial asset, it uses a weather index as a proxy. While the generally traded products mostly have the function of a call or put option, the OTC products can be varied in the function of the contract (Roth *et al.*, 2008). Apart from the call or put option function the over-the-counter products can also represent loans, mortgages or other financial products. These products are still called weather derivatives because they use an element of the weather as a basis to determine decision rules of the contract such as premiums and indemnities. In this report weather insurance will be analysed for the use of financial risk management of plant diseases.

As discussed in the introduction the potential for weather insurance in agricultural sector is large, but is not fully discovered so far. Literature describes different reasons for it not being an important risk management instrument yet. Most important issues in the field of weather insurance for agriculture lies in pricing issues (Richards *et al.*, 2004, Turvey, 2001), the problem of basis risk (Musshoff *et al.*, 2005, Woodard and Garcia, 2008b, Woodard and Garcia, 2008a) and the relation of weather insurance with current risk issues in agriculture (Norton and Turvey, 2008). This last issue will partly be covered in this thesis by looking to the possibility of a weather insurance contract for the weather related plant disease *Phytophthora infestans* in potatoes and *Fusarium head blight* in wheat grains.

2.2 Plant disease literature

The weather has a large influence on agricultural production (Hardaker *et al.*, 2004). Weather interferes with the production by the amount of water and sunshine that are present for the plants, but also influences yields trough certain extremes in the weather that can increase the chance of an outbreak of a certain disease. The weather conditions that are favoured by certain organisms that might harm a specific crop are called weather parameters (Norton and Turvey, 2008). In the following paragraphs an overview will be presented of the weather parameters influencing *Phytophthora infestans* in potatoes and *Fusarium head blight* in wheat grains.

The findings from the literature review were discussed with experts of the specific plant diseases, to be certain that the conditions found in literature represent the knowledge present in the field. The experts consulted are Mr. Schepers, potato and *Phytophthora infestans* specialist and Mr. Spits, *Fusarium head blight* specialist; both from Plant Science Group Wageningen University.

2.3 Phytophthora infestans in potatoes

The first person to analyze *Phytophthora infestans* was the plant scientist Anton de Bary in 1876. He introduced the name *Phytophthora infestans*, which literally means ‘plant destroyer’. Its potential to have devastating effects was seen in the Irish potato famine of which *Phytophthora infestans* was the cause. The disease does not only destroy complete potato fields, but it can also cause bacteria to invade infected tubers, resulting in the “meltdown” of stored tubers. Under severe infection, entire storages must be discarded (Fry and Goodwin, 1997). In the same article the authors describe the case of a potato grower in New York State that went bankrupt due to the outbreak of *Phytophthora infestans* in 1994. Duncan (1999) estimates the monetary costs of control efforts and lost production of *Phytophthora infestans* at more than 3 billion dollar per year in the US alone. Hooker (2002) states that *Phytophthora infestans* is the most important disease in potatoes.

Although described by De Bary as a fungus (De Bary, 1876), *Phytophthora infestans* is actually an oomycete plant pathogen, and is more related to brown algae and diatoms than true fungi and has been placed in a separate kingdom, the Stramenopiles (Gunderson *et al.*, 1987). *Phytophthora infestans* is widely analysed in research. Zentmeyer (1983) describes the reason for the intensive study to the unique morphological, genetic, and physiologic features, combined with the wide variety of diseases caused on a tremendous number of plants.

The spores or mycelium of *Phytophthora infestans* or potato late blight can survive in winter on remaining potato tubers. In a study of Zwankhuizen *et al.* (1998) the main infection source of *Phytophthora infestans* they identified are refuse piles adjacent to healthy potato fields, while infected seed tubers, volunteer plants and infested allotment gardens are of minor importance for a later development of potato late blight. In a more recent study of Evenhuis *et al.* (2008) they found latently infected potato tubers as the major source of late outbreaks of *Phytophthora infestans*.

Spores develop on the leaves, spreading through the crop when temperatures are above 10°C and humidity is over 75% for two days or more (Smith, 1956). Rain can wash spores into the soil where they affect young tubers. Spores can also be dispersed by air (Duniway, 1983). Late blight first appears as a few grayish specks on the plant's leaves, after which a cottony film appears. Under certain climatic conditions (high humidity and cool to warm temperatures), the disease can easily lead to the destruction of a whole field of potatoes. The disease also affects tubers, and can make the crop unfit for storage (International Potato Center, 2008). Infected tubers develop grey or dark patches that are reddish brown beneath the skin, and quickly decay to a foul-smelling mush caused by the infestation of secondary soft bacterial rots.

Following the recent insights in research (Grunwald and Flier, 2005) the *Phytophthora infestans* originates from the central Mexican Highlands .

The relationship of *Phytophthora infestans* with weather conditions was clear from the early studies of the disease by De Bary (1876). South-American potato farmers have linked the disease to the weather, without being aware of the existence of the organism *Phytophthora infestans* (International Potato Center, 2008). Within the field of *Phytophthora infestans* experts there is a common, general understanding to what *Phytophthora infestans* favourable days are. *Phytophthora infestans* favourable days are moderate to cool temperatures, high precipitation and relative humidity. Although there is consensus about the general conditions, each of the decision systems used to manage the disease use different parameters (Schepers, personal communication). In literature, different weather conditions are discussed that promote the development of *Phytophthora infestans*. The conditions are summed in the following table 1:

Table 1; Weather parameters related to *Phytophthora infestans*

Source	Temperature condition	Humidity condition
(Beaumont, 1947)	>10°C	>75%
(Smith, 1956)	>10°C	>90% for >11 hours
(Hyre, 1954)	>7.2°C – <25.5°C for last five days	Total rainfall >3cm for last 10 days
(Duniway, 1983)	>3°C - <26°C, longer than 8 hours	100% relative humidity for 8 hours

Looking to the weather parameters displayed in table 1, one sees that three of the parameters listed in table 1 use relative humidity as a measure. Relative humidity is widely used in plant sciences and it is used in most *Phytophthora infestans* management systems such as SimCast (Grunwald *et al.*, 2002). Relative humidity is difficult to use as a parameter in insurance derivative context because these values are not as widely available as rainfall data. The parameters formulated by Hyre do take rainfall as a measure and they are commonly used in plant science research (Fry, 2008). A restriction of the Hyre period is that is can only be used in relatively humid areas like the North-East region in the United states of America (Krause and Massie, 1975).

2.4 Fusarium head blight in wheat grains

The economic impact of *Fusarium head blight* is twofold. Firstly *Fusarium head blight* leads to lower yields because the fungus influences the production of grains in the ear of the wheat and directly influences the kernels. Secondly the disease can produce vomitoxins which can lead to a lower price of the grains, due to a lower classification of the grains. Milus and Parson (1994) state that scab infection in 1991 for Arkansas was the primary cause of average wheat yields dropping to 1.91 kl/ha compared to previous 5-year average of 3.73 kl/ha. In 1993 scab struck the border region of Minnesota, North Dakota, South Dakota and Manitoba. Yield and quality losses lead to an estimated financial loss in profit of $1 billion (Busch, 1995), making it one of the greatest losses due to any plant disease in North America in a single year (Mcmullen *et al.*, 1997). In an economic analysis of Nganje *et al.* (2001) over the years of 1998 to 2000, they calculated the combined direct and secondary economic losses of different crops affected by *Fusarium head blight* on $2.7 billion for nine different states in the USA.

Fusarium head blight is a filamentous fungus that can be present in wheat and other grains. It is either a disease of roots and crowns which can extend to the stubble, or it is a disease that affects the heads which in turn can harm individual grains, part of the head, or even the entire head. Root and crown rot, cause a scalding of the head and sometimes even a lack of grain development. If the disease affects the head, the disease leads to a lack of grain development and the scalding of the head can lead to a contamination of the seed, this can limit germination or reduce the quality of the grain by the production of mycotoxins (Cassini, 1981).

The *Fusarium head blight* varieties culmorum, graminearum and avenaceum can all produce the mycotoxin *deoxynivanol* (Schepers and Spits, 2005). This mycotoxin, belongs to the toxin group of the vomitoxins. Acute to subacute toxicity of deoxynivalenol is characterized by vomiting (vomiting is seen in pigs, whereas delayed gastric emptying has been observed in rats and mice), feed refusal, weight loss and diarrhea. After acute intoxication necrosis in various tissues such as the gastrointestinal tract, bone marrow and lymphoid tissues can also be observed (European Commission, 1999). Head blight is what the grower sees between flowering and maturity where groups of grains wither and take on a more or less pink colour (Cassini, 1981). There are different varieties that can lead to the production of mycotoxins, but according to Desjardins (Desjardins, 2006) the 'graminearum' species was the dominant *Fusarium head blight* species isolated from outbreak of swine feed refusal and estrogenic syndrome in central United States in the 1970's and 1980's. *Fusarium head blight* graminearum occurs worldwide on cereal grains, such as barley, maize, oats, rice, and wheat and can also occur on plants as diverse as Acacia species, coffee, legumes and potatoes (Desjardins, 2006). The *Fusarium graminearum* species are mostly soil-based but can also be passive air-borne (Burgess, 1981).

The relationship of *Fusarium head blight* with certain weather conditions was noticed in Japan by Urakura where the incidence of red mould-contaminated cereals was associated with heavy rains and cold weather (Joffe, 1986). Head blights require high humidity in order to multiply (Cook, 1981). An overview of weather parameters connected to *Fusarium head blight* is presented in table 2.

Table 1; Weather parameters related to *Fusarium head blight* graminearum

Source	Temperature range	Humidity range
(Pugh *et al.*, 1933)	25°C	Continuous wetness for 48 hours relates to 77% infection
(Cook and Christen, 1976)	20°C - 30°C	Substrate is moist
(Lacey *et al.*, 1999)	>9°C - <26°C	

Other literature sources use water activity as a primal parameter for the development of *Fusarium graminearum,* but are less useful in an insurance derivative context where these values cannot be an input for models. Hooker *et al.* (2002) have tried to relate the incidence of *Fusarium head blight* to the more common measured weather parameters, temperature and rainfall. With the help of multiple regression techniques they have found significant differences in weather parameters between different stages of the wheat. They used a four day moving window and determined whether (I) daily rainfall was above >5 mm (before heading) and >3 mm (after heading), (I) when minimum temperature was <10°C (III) when maximum temperature was >32°C and (IV) when relative humidity was >90% at noon. With three formulas representing three different periods during crop growth, they predict the level of deoxynivalenol, and thus the level of *Fusarium head blight* infection of the grain. Using the findings of this report, the following weather parameters are relevant:

1. Before heading

Temperature >10°C - <32°C, 4-7 days before heading

Precipitation >5 mm rain, 4-7 days before heading

2. After heading I

Temperature >10°C – 32°C, 3-6 days after heading

Precipitation >3 mm rain, 3-6 days after heading

3. After heading II

Temperature >10°C – 32°C, 7-10 days after heading

Precipitation >3 mm rain, 7-10 days after heading

Primary element in this analysis is the prediction of the heading of the crop. Since the date of seeding differs per field and year, it is virtually impossible to take one date of the start of the crop growing season. An analysis based on growth models is a possibility, but in discussion with *Fusarium head blight* expert Harro Spits the average heading period was determined from half of May to half of June in Western-Europe (Spits, personal communication). In a detailed report about different outbreaks of *Fusarium head blight* in the context of the United States, McMullen *et al.* (1997) they set the critical rainfall at >80 mm cumulative rainfall for the month of June. The temperature values as described by Hooker *et al.* (2002) and the rainfall criterion for June will be used in this report.

3. Materials and methods

This chapter will discuss the methods used in analyzing whether the financial risks related to *Phytophthora infestans* and *Fusarium head blight* can be managed with weather derivatives. In the first paragraph a conceptual model will be presented that draws the background for the analysis of weather data. In the second paragraph the weather parameters will be discussed that are chosen after review of plant science literature. The third paragraph will introduce the weather database that is used in this project. The fourth paragraph presents the incidence data of the specific diseases. In the fifth paragraph the method of analysis will be discussed, this paragraph will introduce the descriptive and regression analysis used in this report.

3.1 Conceptual model

The starting point for the conceptual model is the farmer. The farmer has to make a risk management decision prior to a growth season without knowing what the weather conditions will be. In order to limit asymmetric information the contract needs to be bought before the growing season starts. During the growth season either disease favourable or unfavourable weather conditions may emerge. Based on the weather he might decide to apply pesticide on the crop or to abandon from pesticide use. The probability that the farmer will use the pesticides, is assumed to be higher when disease favourable conditions are present compared to the situation when no such conditions are present. Due to the fact that the incidence of the disease is only partly related to the weather disease, the disease can either occur or not occur. The decision options that are confronted to the farmer during the growth season are outlined in the plant disease risk management decision tree in figure 1.

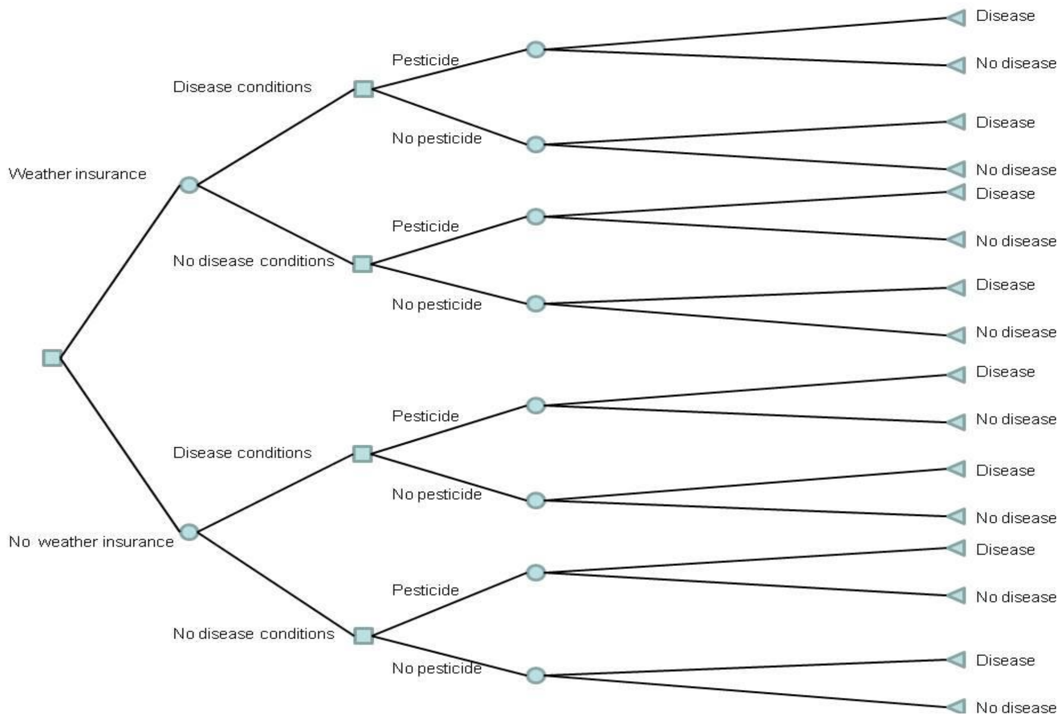

Figure 1; Plant disease risk management decision tree

In this paragraph an economic conceptual model will be outlined, based on the decision tree outlined in figure 1. The conceptual model is an adapted version of a model on the abandonment option of irrigation, developed by Turvey and Mafoua (2005). The option to abandon irrigation is similar to the option to abandon pesticides in the context of plant diseases.

The first variable that needs to be introduced is the variable of weather. Traditionally in weather insurance literature this is a single variable such as cumulative rainfall or growing degree days (GDD). Based on the plant disease literature analysed in this report, the first element related to the weather variable are a certain temperature interval (*T*). Diseases caused by fungi, bacteria and viruses favour a certain range of temperatures in which they are most successful. Secondly the weather variable is related to a certain rainfall parameter (*R*). Rainfall can either be represented by average rainfall or cumulative rainfall. The third element related to the weather variable, is the factor time (*t*). This factor can either be the same for both temperature and rainfall, or be separate as we have seen in the Hyre period that is connected to *Phytophthora infestans*. The variable can be expressed in the following formula 1:

$$1. \omega = f\left(\frac{T, R}{t}\right)$$

The weather variable ω is either disease favourable or disease unfavourable. It is assumed that the weather variable represents a constant function, and there exists a point ω^* which represents the weather conditions most unfavourable for the disease. For conceptual reasons this point is close to 0. All more favourable weather combinations lie above that point. There also exists a point ω^c for which the weather conditions change from disease unfavourable into disease favourable conditions. From this point pesticide becomes a viable instrument for disease risk management.

A second element that needs to be introduced, is the probability for the disease to break out. The development of the plant disease is sometimes largely, but not solemnly correlated to the weather conditions. The variable related to this probability is g_{ij}. The assumption that the pesticides reduce the probability for the disease, and disease unfavourable conditions relate to a lower probability than the disease favourable weather conditions.

A farmer has the choice to either use or not to use pesticides. The assumption made in the following function 2 is that the weather conditions are favourable for the disease, or $\omega_j \geq \omega^c$, where ω_j indicates the weather conditions in year *j*. To express the pesticide use, the variable p_i will be introduced. This depicts that the farmer either uses pesticides $i = 1$ or does not use pesticides $i = 2$. Under the given disease favourable weather conditions there exists an optimal pesticide use level p^*, resulting into a optimal y^*. The choice to use pesticides, or to abandon from it leads to different yield function, which can be depicted by the following function 2:

$$2. y_i = \begin{cases} f_i(h_i p_i g_{ij}), \forall p_i < p^* \\ y^*, \dots \forall\, p_i \geq p^* \end{cases} \quad i = 1,2$$

Function 2 represents the yield from a general production function that establishes a piece-wise non-linear relationship between crop yield and the pesticide variable p, with $i = 1$ representing pesticide use and $i = 2$ representing non pesticide use. Therefore the pesticide use of the non-pesticide using farmer will always be equal to 0. The symbol h_i represents the productive efficiency of the pesticide use.

The yield differential of pesticide use can be expressed by the following function 3:

$$3.\, y_1 - y_2 = \begin{cases} f_1\left(h_1 p_1 g_{ij}\right) - f_2\left(h_2 p_2 g_{ij}\right) \geq 0, \forall\ \omega_j \geq\ \omega^c \\ 0, \ldots \forall\ \omega_j\ \leq \omega^c \end{cases}$$

The assumption in the model is that when the weather conditions are favourable for the disease, that pesticide use is positively related to the yield. This can be expressed by function 4:

$$4. \frac{\partial f_1(p_1)}{\partial p_1} \geq 0$$

and function 5:

$$5. \frac{\partial^2 f_1(p_1)}{\partial^2 p_1} \leq 0$$

Function 5 shows that the assumption that the application of pesticides is positively related to the yield (following from function 4), but that this relation is convex. The positive relationship with the yield can also be explained by a lower disease probability g_{ij} when pesticides are used.

If the non-pesticide using farmer would choose to insure his crops against the plant disease his production function would look like the one outlined in function 6.

$$6.\, y_2 \begin{cases} z, \ldots \forall\ \omega_j\ \geq \omega_z \\ f_2, \forall \omega^* < \omega_j < \omega_z \\ y^*, \ldots \forall \omega_j\ \leq\ \omega^* \end{cases}$$

The rationale behind this function is that you can determine a strike level z which is related to a adversary financial risk for which the farmer would like to be insured. The assumption is that the strike level z is higher than the weather condition by which a pesticide using farmer would start to use pesticides ω^c. At the strike level ω^z the unsprayed yield is lower than the sprayed yield.

Although not further discussed in this report, it is possible to valuate such a derivative. The calculation should then be based on the monetary value of the yield differential of the non-pesticide using farmer.

3.2 Selected weather parameters

The different weather parameters extracted from literature were discussed in chapter two of the thesis. From this analysis it was seen that there are different parameters that use relative humidity as a measure. Since relative humidity data are not present at this moment in the used database, the decision rules based on this measurement cannot be used in this project. One set of parameters that uses precipitation as an element are the weather parameters introduced by Hyre (1954). The specific parameters of the Hyre period are temperature between 7.2° and 25°C over the last five days and cumulative rainfall higher than 3 cm over the last ten days.

As discussed in chapter two, the disease weather parameters of *Fusarium head blight* the parameters of two literature sources are merged. First source is the paper of Hooker *et al.* (2002) in which they have analysed the relationship of weather conditions before and after heading of the wheat grain to predict the *Fusarium head blight* infection. The research found significant higher levels if the temperature is between 10°C and 32°C. The rainfall parameter used in this analysis is the parameter proposed in the research of McMullen *et al.* (1997) in which they found a critical level of 80 mm or higher leading for the month of June to increased levels of *Fusarium head blight* infection and severity.

3.3 Weather data

For the analysis of the weather parameters the weatherwizard internet application is used (www.weatherwizard.us). This web based risk management tool was introduced by Turvey and Norton (2007). The system is designed to analyze different weather related risks on an historical basis for all states of the United States. The system uses four different weather indexes, being maximum, minimum and average daily temperature and rainfall. The system includes different user-oriented tools, for example a joint risk tool, and burn rate price calculation. The burn rate calculation uses the historic probabilities of events as a basis for insurance calculations (Musshoff *et al.*, 2005). The weather data in the weatherwizard database originate from the National Organisation and Atmospheric Administration (NOAA). The data represent roughly 500 million daily measurements from 25,000 weather stations from all 50 states of the United States. The weather station data in the database represent a vast number of years with the majority including years 1899 up to 2006.

For the weather data analysis of *Phytophthora infestans* two states were chosen. The states are Maine and North Dakota. For both of these states incidence data were present, and the state of Maine is an important potato producer. In both states two weather stations were chosen, based on their location and the number of years present in the database. The weather stations are Bottineau and Ashley in North Dakota, Madison and Presque Isle in Maine. *Phytophthora infestans* is not bounded to a specific growth stadium of the potato crop. Based on the reports that the Euroblight (www.euroblight.net) initiative is recording, the months May, June, July, August and September were taken for the analysis.

Four weather stations were chosen in North Dakota for *Fusarium head blight* analysis. North Dakota was chosen because incidence data were present for this state, and because of the relative importance of wheat grain production in the state. The specific weather stations were chosen based on the region in which they are located in North Dakota, and based on the large number of years recorded at these stations. The specific stations are Bottineau, Longdon Experimental Farm, Jamestown and Keene. Based on discussion with experts and literature review, the month of June was the main month for investigation.

3.4 Disease incidence data

Phytophthora infestans and *Fusarium head blight* are both diseases of high economic importance (Nganje *et al.*, 2001, Fry and Goodwin, 1997) and two diseases that are commonly studied in plant sciences (Agrios, 2004, Westerdijk and Schepers, 2006, Joffe, 1986). Looking at these two characteristics of the diseases one might expect that there is ample literature about the incidence of the disease. Although there are many different articles referring to notorious outbreaks it is in general hard to find sources that study the incidence of the disease over a longer time span including years with medium to low incidence.

Phytophthora infestans has been widely studied since the first publications on the disease in 1876. In the development of different disease management studies, the incidence of *Phytophthora infestans* has been studied to determine the weather conditions favourable for the disease, as was discussed in chapter two. The incidence data used in the analysis of this report were incidence data of Northern Maine (Hyre and Bonde, 1954) and data provided by the North Dakota *Phytophthora infestans* specialist Neil Gudmestad (Gudmestad, personal communication). Other literature such as provided by Fry *et al.* (1997) could not be used due to a limited number of incidence years presented or because the region could not be used to check for the Hyre period Henderson *et al.*(2007). Although the data from literature give some indication of incidence data, they are certainly not comprehensive in the exact statement of incidence, or non-incidence of late blight. Many plant researchers were asked to the existence of a central database with *Phytophthora infestans* incidence data. They all reported that no such exists so far in the United States. Some of the researchers indicated that potato farmers are careful in sharing these data. In order to come to a clear and sound analysis of the disease for insurance purposes, these data are important in determining the relation between the weather and the existence of the disease.

Fusarium head blight incidence is a fixed measurement of the yearly wheat survey conducted by the NDSU. The wheat survey includes all counties of North Dakota and measures the number of outbreaks per year and the intensity of the different outbreaks. The surveys were firstly conducted in 1998 and were held annually ever since. The data are available on the internet at http://www.ag.ndsu.nodak.edu/aginfo/ndipm/ . The maps available on the internet were transferred into numbers by counting the frequency of each of the severity classes defined by the NDSU. The severity classes were labeled with an ordinal scale, with one being the lowest severity percentage and 7 being the highest (>35%). The frequencies of each of the severity classes in each year were multiplied by the ordinal scale number. With this exercise each of the years received a specific ordinal based scab severity score.

3.5 Method of analysis

Muβhoff *et al.* (2005) describe five steps in the analysis needed to determine a weather derivative. The first step is to model a weather variable, the second step is estimation of correlation between weather event and yield, the third step is the design of a weather derivative, the fourth step is the determination of a market price for the weather derivative and the last step is to determine the risk profile with or without the weather derivative. In the analysis in this report we will limit ourselves to the first two steps of analyzing weather derivatives, the analysis will analyze the weather variables related to the disease, and the research project will look into the correlation between weather and yield.

The input of the analysis of weather data are the weather parameters determined from plant science literature review. These weather parameters will be used to analyse the weather data present in the weatherwizard database. Aim of the exercise is to define a 'decision' or 'chance' tree that describes the joint risk of favourable rainfall conditions, under the condition that temperature is favourable and analogously, the chance that the disease breaks out under the given conditions. The theory used for the analysis is the joint probability theory. The common joint probability assumptions will be applied, such as described by Duda *et al.* (1998) resulting in the following general formula:

$$P(x, y) = P_x\,(x)\,P_y(y)$$

For the analysis one can regard the x to be the chance that temperature is favourable and y the chance that the rain is favourable. For temperature one can see in plant literature that temperature often has to lie in a certain interval, which can be expressed in the following two forms:

$$P(x, y, z) = [P_x \;\cup\; P_z]\,P_y$$

When you want to calculate the probability that the weather parameters are not favourable for the disease, so for instance that minimum temperature is lower than value x (P_x), or maximum temperature is higher than value z (P_z), and rainfall does not exceed a given value y (P_y).

Analogously one can express the chance that the weather parameters do match the critical weather conditions and thus disease favourable conditions would occur, writing in a formula yields:

$$P(x, y, z) = [P_x \;\cap\; P_z]\,P_y$$

This chance tree can be called the decision tree of 'mother nature', because it represents instances that cannot be influenced by human beings. The figure is shown in figure 2:

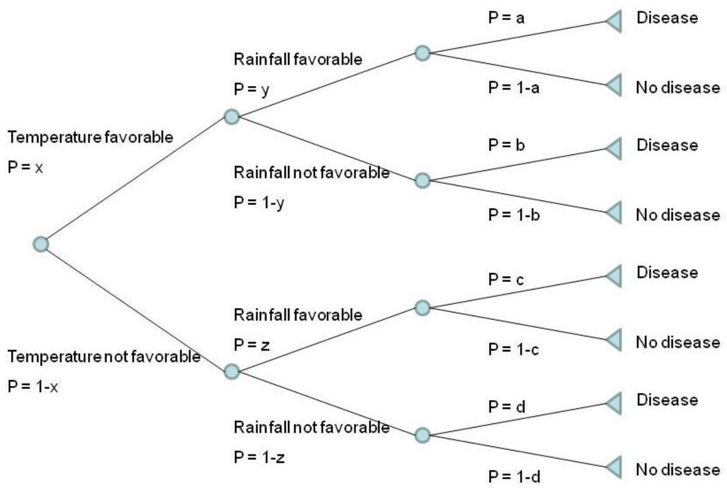

Figure 2; Decision tree 'mother nature'

The chances on the left side of the decision tree (x-y-z) will be calculated by translating the weather parameters from plant science literature and applying these to the weather station data present in the weatherwizard database. The probabilities on the right side of the decision tree (a-b-c-d) will be estimated with comparing the incidence data to the weather variables indicating disease favourable conditions. In the statistical analysis four steps will be set, each adding a part of the answer to the research objectives.

Step A. The first step in analysing the probabilities of a disease favourable weather conditions, will be to apply the weather parameter rules for the critical period using the same index used as is defined in plant science literature (cumulative rainfall and temperature range). The critical weather conditions need to last for a minimum time period before they can be connected to the development of the disease. Depending on the sensitivity of the plant during its growth stages this critical weather period need to lie in certain months in the year. In the statistical analysis these months are divided into a number of periods that are based on the minimum time period that a critical weather condition needs to be present. For each of the weather stations, per time period the probability is defined that a disease critical weather conditions occur. Since the weather conditions are based on both temperature as precipitation for each period two probabilities are calculated. These probabilities are multiplied to yield the joint probability. How these probabilities are used to determine the chance of disease favourable weather conditions occurs is different for the two diseases. The difference is based on the difference in the months that the disease favourable conditions can harm the plant. For *Phytophthora infestans* this is a period of five months, for *Fusarium head blight* this is a period of only one month.

Based on the reports that the Euroblight (www.euroblight.net) initiative is recording, the months May, June, July, August and September were used for the analysis. Each of the months were divided in three ten day periods for the precipitation analysis, and divided into six five day periods to check whether all daily average temperatures were between 7.2 and 25°C. The analysis resulted in a probability for each weather location that the specific precipitation or temperature event occurred for each of the five and ten day periods in May to September. The probability of the temperature events (temperature between 7.2 and 25°C for all five days) belonging to a 10 day period were averaged in order to calculate a joint probability of both precipitation and temperature being advantageous for *Phytophthora infestans*. Now that the probabilities of each of the 10 day events are known, the probability can be calculated of each of the combinations of the fifteen ten day periods between the first of May to the last day of September, with the extremes being either having all periods to be disease favourable or all non-favourable. These probabilities will be used as an input for a binary Bernoulli probability tree, where a 10 day period is either disease favourable or non-favourable. Assumption made in the analysis is that the chance of period *t+1* is independent of period *t*. This assumption does not hold if you look to a specific year. The probability that a cold period will emerge after a cold period is higher than that a heat period will follow, but since we look in this analysis over the years and not to a individual year this assumption is statistically correct. Apart from the analysis based on the decision tree a second method was used to look at the individual years. The second method assigned all ten day periods between the May to June with a binary value, being '1' if the ten day period met the rainfall parameter and at least one of the two five day periods met the temperature measurement.

For *Fusarium head blight* the literature provided the critical temperature interval, which needs to last for at least 14 days (by adding up the minimum number of days), since this is a minimum number of days two 15 day periods in June were examined so that the month can be divided into equal periods for examination on temperature range. For each of these stations an analysis was performed on whether the cumulative rainfall was above 80 mm for the month of June, as well as whether the maximum temperature was below 32°C and minimum temperature above 10°C for 15 consecutive days. If the rainfall conditions was met, and one or both 15 day periods in June met the temperature conditions the month was labelled as a disease favourable year.

Step B. Second step in the statistical analysis will be to try to express the absolute weather parameters from plant science literature into Degree Days. Degree day is a measure often used in the insurance context and most standardized temperature exchange products are based on a degree day index (Ellithorpe and Putnam, 2000). Main advantage of using degree days as a measure is that the risks can be traded with standard contracts on the weather risk transfer market such as the Chicago Mercantile Exchange. In this report we will use the Growing Degree Day measure in the calculations. The growing degree day is the result of a calculation with the average daily temperature. The calculation of the growing degree day in this analysis is as follows:

$$GDD = \frac{Tmax\ + Tmin}{2} - \ T_{base}$$

For the *Phytophthora infestans* analysis the base temperature used is 15.56°C as this is a base temperature often used in GDD calculations. For the *Fusarium head blight* the base temperature value of 10°C is used, because this represents the critical lower limit as found in plant science literature about *Fusarium head blight*. The growing degree day measure can have two interpretations depending on whether you adjust the base temperature if the minimum temperature is below the base temperature (Mcmaster and Wilhelm, 1997). In this analysis we will not adjust the base temperature if the minimum temperature falls below the base temperature.

In order to investigate whether growing degree days could be used as a replacement of the absolute temperature values for *Phytophthora infestans* the chances were calculated for each of the 5 day periods between May and September that the temperature was favourable for the development of *Phytophthora infestans*. These probabilities were plotted against the growing degree days for the same five day periods.

In the *Fusarium head blight* analysis two methods were used to investigate if growing degree days could be used as a substitute for absolute temperature values. First method that was tried was based on plant science literature that stated that temperature should either not exceed a maximum temperature of 32°C or minimum temperature should not fall below 10°C. One can check the probabilities that one of these two events occur in the distribution of maximum temperature and the distribution for the minimum temperature. These probabilities can be applied in the distribution of the growing degree day measure to find the absolute growing degree day cut off points. The second method was based on the assumption that with a heat or cold wave, one can expect that growing degree days either take a high or low value. A heat or cold wave was defined as a two day consecutive period that minimum temperature is below 10°C or maximum temperature is above 32°C. The number of heat and cold waves for the month of June were plotted against the growing degree days of the same month.

Different methods were tested for the diseases as a result of new insights during the research process.

Step C. The third step is to evaluate whether the incidence data are in line with the high risk years as defined in by the analysis of step A. Linear regression techniques were used to determine these relationships. The linear regression coefficients were calculated with the software programme SPSS 16.0.

For *Phytophthora infestans* the disease severity values from literature were ranging from '0' being no *Phytophthora infestans* detected in that year, up to level '3' depicting multiple severe *Phytophthora infestans* outbreaks detected for that year. These severity/incidence values were related to the number of Hyre period in that year. In order to relate the incidence data with the Hyre periods in each specific year, each of the 10 day (and belonging two five day periods) it was determined whether there were *Phytophthora infestans* positive or negative conditions present. If the rainfall was above 3 cm and one or two five day periods belonging to that ten day period were in the Hyre range, the specific period receives a '1' otherwise a '0'. The number of Hyre periods present in that year were added. The regression formula used is as such:

$$\text{Disease severity} = \beta_0 + \beta_{\text{No of Hyre periods}} X_{\text{No of Hyre periods}}$$

To enable the linear regression of *Fusarium head blight*, a severity number was assigned to each year in the study (1998-2004). Four counties were chosen in North Dakota related to the weather stations used in the analysis of step A. In order to cover all months in which weather can be of influence on the development of *Fusarium head blight* the regression includes the growing degree days and cumulative rain for the months May, June, July and each of the combinations of these months (May-June, June-July and May-June-July). If multiple weather stations were present in one county, the values were averaged in order to get the county average for each of the periods. The linear regression for *Fusarium head blight* will be calculated with as the dependent variables rainfall and temperature during the critical period and the severity of the disease outbreak as the independent variable as such:

$$\text{Disease severity} = \beta_0 + \beta_{\text{Rainfall index}} X_{\text{Rainfall index}} + \beta_{\text{Temperature index}} X_{\text{Temperature index}}$$

The difference in regression formulas used is related to the difference in statistics used in step A.

Step D. If the linear regression does not show clear results, the data will be additionally reviewed with the help of qualitative analysis. Aim of the qualitative analysis is to determine whether the weather parameters as defined in plant science literature can be traced in incidence data of the disease.

The qualitative analysis for *Phytophthora infestans* was aimed at finding a pattern in the number of Hyre periods related to the disease severity number related to the same year. The qualitative analysis used visual inspection as tool to do this.

For *Fusarium head blight* the qualitative analysis will be based on analyzing the underlying distributions of the weather indices for the specific weather stations. @Risk will be used as the tool to fit these historic data into the best fitting distribution. The BestFit function in @Risk automatically fits distribution functions to own data using maximum likelihood estimators (Thompson, 1999). The goodness-of-fit statistic based on chi-square will be minimized by choosing the distribution that yields the lowest chi-square value.

The difference in the qualitative analyses in step D was based on the results found in the previous steps and on reasoning what would be needed to make a relationship between the incidence data and the critical weather periods.

4. Results

This chapter will discuss the results of the statistical analyses of the weather data present in the weatherwizard database. The first paragraph will present the outcomes of the statistic analyses on the available data for *Phytophthora infestans*. In the second paragraph the *Fusarium head blight* results will be presented by describing the statistics related to weather data of *Fusarium head blight*. The third paragraph will conclude the statistical analyses of both diseases.

4.1 Statistic analysis Phytophthora infestans

Step A. For the weather data analysis of *Phytophthora infestans* two states were chosen. The states are Maine and North Dakota. The weather stations analysed are Bottineau and Ashley in North Dakota, Madison and Presque Isle in Maine. *Phytophthora infestans* is not bounded to a specific growth stadium of the potato crop. Based on the reports that the Euroblight (www.euroblight.net) initiative is recording, the months May, June, July, August and September were used for the analysis. Each of the months were divided in three ten day periods for the precipitation analysis and divided into six five day periods to check whether all daily average temperatures were between 7.2 and 25°C. The analysis resulted in a probability for each weather location that the specific precipitation or temperature event occurred for each of the five and ten day periods in May to September. The probability of the temperature events (temperature between 7.2 and 25°C for all five days) belonging to a 10 day period were averaged in order to be able to calculate a joint probability of both precipitation and temperature being advantageous for *Phytophthora infestans*. Now that the probabilities of each of the 10 day events are known the probability can be calculated of each of the combinations of the fifteen ten day periods between the first of May to the last day of September, with the extremes being either having all periods to be disease favourable or all non-favourable. These probabilities can be calculated by using the calculated probabilities and adding them to a binary Bernoulli probability tree, basis is that either the 10 day period is disease favourable or non-favourable. Assumption made in the analysis is that the chance of period $t+1$ is independent of period t.

In the literature related to the use of the Hyre period for the prediction of *Phytophthora infestans* they define that if one or more Hyre periods are present in a year then one can be certain with a 89,5% chance (Hyre and Bonde, 1954) that *Phytophthora infestans* will occur. This means that if any of the 10 day periods is disease favourable, *Phytophthora infestans* will occur with an 89.5% probability. From the statistical analysis, the probability of not having a Hyre period (Avg P=0,8 for Bottineau, ND) is much larger than the probability of having a Hyre period. Because of the 'exploding' character of the binary decision tree, it 'explodes' after 15 periods to 2^{15} instances. This means that only one of these instances represents the situation that no single Hyre period was present. For the stations reported, the probability that no single Hyre period was present in a year lies between 3 to 6 %. This percentage is obviously too low to base an insurance premium on. Using the widely used burn rate method this would relate to a 94% premium. In practice this would mean that a farmer that wants to have an indemnity of $ 1000 per hectare if the disease breaks out, needs to pay a premium of $ 940 per hectare. The second method assigned all ten day periods between the May to June with a binary value, being '1' if the ten day period met the rainfall parameter and at least one of the two five day periods met the temperature measurement. The results of this evaluation of three weather stations are reported in table 3.

Table 3; Probability and average number of Hyre periods for three weather stations

Station	Total no years	Total no of disease negative years	Probability for disease favourable	Average number of Hyre periods
Bottineau, ND	64	5	0.92	2.45
Madison, ME	57	3	0.95	2.65
Presque Isle, ME	79	10	0.87	2.37

Step B. In the analysis towards investigating whether growing degree days could be used as a substitute for absolute temperature values, we tried to find a relation between the probability that the temperature is within the set absolute border and the number of growing degree days for the same period. The graphs showing the relations found for the four weather stations can be found in appendix I. The basis temperature used in this growing degree day calculation is 15.56°C as this is the default in the weatherwizard database. The graphs show that there is a relation between the probabilities to a disease favourable period and the number of growing degree days, but that the relation differs greatly per weather station. This difference shows the main problem in translating absolute temperature intervals into general cut off points in growing degree days, being that every temperature measurement per station per time in the year can have a total different distribution making it impossible to apply a general rule to the data.

Step C. In the statistical analysis, described in step A, the disease probabilities are determined over all years per time period, per weather station. In order to relate the incidence data with the Hyre periods in each specific year, another investigation was needed. For each of the 10 day (and belonging two five day periods) it was determined whether there were *Phytophthora infestans* positive or negative conditions present. If the rainfall was above 3 cm and one or two five day periods belonging to that ten day period were in the Hyre range, the specific period receives a '1' otherwise a '0'. This analysis was done for all periods in the years present for the stations, and the Hyre periods were added into one value. Incidence data of *Phytophthora infestans* was reported on a four point scale with '0' being no blight and '3' days related to a high number of severe of outbreaks. The results of this exercise are outlined in table 4. A linear regression was executed on these data. The regression yielded a beta estimator value of 0.258, being non significant at a p-value of 0.1. The adjusted R^2 value is 0.024 which is a really low value. Based on this linear regression you have to conclude that from these data no clear relation can be found between the disease severity and the number of Hyre periods.

Table 4; Number of Hyre periods and disease severity for Presque Isle, Maine

Year	No of Hyre periods	Disease severity (0-3)
1927	3	3
1928	7	3
1929	4	1
1930	4	3
1931	3	3
1932	4	3
1933	3	0
1934	4	1
1935	2	1
1936	3	3
1937	3	2
1938	3	3
1939	0	1
1940	2	1
1941	3	3
1942	0	2
1943	3	3
1944	5	1
1945	2	3
1946	2	1
1947	2	3
1948	2	2
1949	0	1
1950	3	3

Step D. The linear regression did not show a clear relation between the number of Hyre periods and the disease severity. Though plant science literature reported a clear relation between a Hyre period being present and the incidence of *Phytophthora infestans*. Looking to table 4, one can find that there is a relation between the years with one or more Hyre periods and the incidence of *Phytophthora infestans*. This is in line with the direct reports from plant science literature, though one cannot say that the number of Hyre periods is a predictor of the disease incidence and severity.

The Hyre period used here is a useful tool for disease management systems that advise farmers whether or not to use pesticides. For the aim of pesticide management it is most important that the systems signals whether or not the disease would possibly emerge. For insurance goals though it is also important to be able to have a guiding rule in the severity of the late blight outbreaks. Without such a disease parameter, the insured would have to pay a very high premium because he can expect an indemnity almost every year.

4.2 Statistic analysis Fusarium head blight

Step A. From plant science literature a temperature range between 10-32°C and rainfall above 80 mm for the month of June were selected as critical values leading to an increased risk for *Fusarium head blight*. From the extensive study of Hooker *et al.* (2002) it was shown that the temperature conditions need to last for at least 14 days (by adding up the minimum number of days), since this is a minimum number of days, two 15 day periods in June were examined. In this way each month can be divided into two equal periods for examination of the temperature range. Four weather stations were chosen in North Dakota. The stations were chosen by the region in which they are located in North Dakota and because of to the large number of years recorded at these stations. The specific stations are Bottineau, Longdon Experimental Farm, Jamestown and Keene. For each of these stations an analysis was performed on whether the cumulative rainfall was above 80 mm for the month of June, as well as whether the maximum temperature was below 32°C and minimum temperature above 10°C for 15 consecutive days. The case that in a year both the rainfall conditions as well as that one or both 15 day periods met the temperature conditions was low, being 1%, 2%, 2% and 0% for the stations of Bottineau, Longdon Exp. Farm, Jamestown and Keene. When only the rainfall criterion was taken, the chances for rainfall to exceed 80mm are 36%, 26%, 36% and 39% for the respective stations.

When analysing the weather data for the month of June for the weather stations in North Dakota, the ambiguity in the plant science data became apparent. Questions like the following come up: If the maximum or minimum temperature in a 15 day consecutive period goes above 32°C, or falls below 10°C does this mean that this year is a low risk year or is it still a risk favourable year? This uncertainty makes it difficult to draw sharp conclusions.

Step B. Two methods were tested to see whether growing degree days can be used as substitute for absolute values. For the growing degree day calculation a base temperature of 10°C was chosen because this temperature represents the lower limit for *Fusarium head blight* as described in plant science literature. Aim of this investigation is to find a relation between the growing degree days and cumulative rainfall on one side and *Fusarium head blight* severity on the other side. Plant science literature showed that either very cool (<10°C minimum temperature) or heat (>32°C maximum temperature) are stopping the development of *Fusarium head blight*. The question of the growing degree day exercise is to find the correct cut-off points of the tails of the growing degree day distribution. The cut-off points of the GDD distribution could be calculated by fitting a distribution to the minimum and maximum temperatures of the weather station. In these specific distributions the chance can be calculated when the minimum temperature is below 10°C in the distribution of the minimum temperatures, and similarly the chance that the maximum temperature is above 32°C in the maximum temperature distribution. These chances (or integral of the cumulative distribution function) can then be entered in the distribution of the average temperatures in order to find the growing degree days belonging to the left and right hand surface under the distribution. Problem with the method is that with the exercise the error of the individual distributions is multipliticated which can lead to incorrect conclusions when looking to extreme values.

A second method used to link the absolute values with the growing degree days is based on the hypothesis that years with heat waves or cold waves should expectedly be related to the number of growing degree days for that period. In a year with a high number of growing degree days in the month of June you expect a higher probability of a heat wave occurring in that month than in a year with low number of degree days and vice versa. In order to try to find a relationship for each year, the total number of days were counted per year that noted a maximum temperature above 32°C or a minimum below temperature below 10°C. By plotting the data one can see that there is indeed a negative relationship between the cumulative growing degree days for June and the total number of days counted in June that are below 10°C as can be seen in figure 3. This relationship could also be seen in the calculation of the correlation between GDD and the number of days below 10°C which resulted a Pearson correlation coefficient of -0,419, significant at $P < 0.0001$. Although this correlation is present, it does not provide an answer to the cut-off points of the growing degree days relating to the absolute values as discussed in plant science literature. The correlation between the growing degree days and the cold and heat waves will be used in the qualitative analysis of the data.

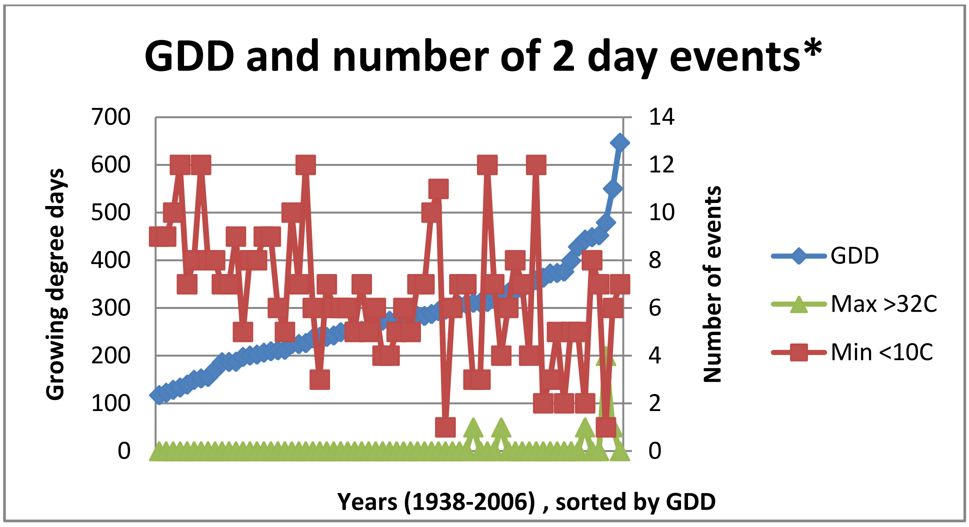

Figure 3; Graph of growing degree days and number of times that the maximum temperature is above 32°C or that the minimum temperature is below 10°C for two consecutive days. The years are sorted by the total number of GDD

Step C. The translation from plant science literature into a sound data-analysis raised questions on how to exactly interpret the plant science literature parameters. In the following analysis the incidence data collected by the NDSU will be used to determine the relation between temperature and rain expressed in growing degree days and cumulative rainfall on one side and the *Fusarium head blight* severity on the other side. Four different counties in North Dakota were chosen for this regression analysis, which relate to the weather stations used in step A. A *Fusarium head blight* severity number was assigned to each year in the study (1998-2004), with the method outlined in the materials and methods chapter. In order to cover all months in which weather can be of influence on the development of *Fusarium head blight* the regression includes the growing degree days and cumulative rain for the months May, June, July and each of the combinations of these months (May-June, June-July and May-June-July). If multiple weather stations were present in one county, the values were averaged in order to get the county average for each of the periods. The results of the analysis are shown in table 5. From the table one can see that the betas do not show a clear relation and that the adjusted R squares are relatively low and sometimes even negative. When looking to the significance levels of the betas a similar pattern was seen since none of the betas was significant below $P < 0.025$ or $P < 0.05$.

Table 5; Regression results *Fusarium head blight* North Dakota

County	May	June	July	May-June	June-July	May-June-July
Bottineau						
Adj R^2	0.267	(0.365)	(0.186)		0.340	0.400
β_{GDD}	0.795	(0.51)	0.256	0.313	0.055	0.645
β_{rain}	0.140	0.310	0.277	(0.066)	0.745	(0.108)
Cavalier						
Adj R^2	0.094	(0.427)	0.073		(0.329)	(0.322)
β_{GDD}	0.557	(0.130)	0.078	(0.150)	0.316	(0.021)
β_{rain}	0.448	0.251	(0.609)	0.838	(0.421)	0.338
Stutsman						
Adj R^2	0.517	0.277	0.198		0.236	0.683
β_{GDD}	0.540	0.757	0.684	0.408	0.713	0.196
β_{rain}	(0.476)	0.656	0.032	(0.543)	0.908	(0.762)
McKenzie						
Adj R^2		(0.149)	0.279	(0.014)	0.118	(0.104)
β_{GDD}	0.026	0.395	0.453	0.607	0.396	0.503
β_{rain}	(0.354)	0.422	0.632	(0.380)	0.513	0.017

Step D. In different previous studies (Musshoff *et al.*, 2005, Woodard and Garcia, 2008b, Woodard and Garcia, 2008a) it was shown that geographical basis risk is an essential element in the analysis of weather indices. The location of a weather station relative to the field is important in the extent to which we can draw a relation between the weather variables and the occurrence of a specific risk event, such as a crop disease. An analysis, apart from the regression analysis, was conducted that included this element. With the help of the built-in Google Earth application of weatherwizard it was possible to determine the geographical position of the weather stations in the different counties. This geographical position was then visually compared to the *Fusarium head blight* outbreak maps of the North Dakota State University.

By using weather stations as the object of analysis, the incidence data become significantly lower and the distinction between years is harder to make. A qualitative method was therefore used to look at the data. The first of two qualitative method applied was to fit the historical growing degree days into a proper distribution, using the fit to distribution function in @Risk. With the input data the quartiles were defined for growing degree days and cumulative rainfall. By doing this the weather data of the years are compared relatively to the historic levels and therefore a difference can be made between wet and dry years and analogously warm and cool years. The second method used was similar to the first method in that it also used the fitted distributions function. Instead of determining the quartiles, the 10% and 75% point of the cumulative input distribution were calculated. The 10-75 percentages were inferred by trial and error fitting of the distribution. For rainfall the cut-off point of 80 mm cumulative rainfall was used. The overview of the results of the qualitative analysis is shown in appendix II.

The data in appendix II show that, although there is still a relatively big error, there is a tendency in the data that wet and cool years seem to have a relationship with the incidence of *Fusarium head blight*. This tendency is in line with plant science literature. The reason behind the error can have different origins. Firstly the incidence data used in the study only cover seven years, which influences the significance levels of the inference parameters. Secondly the effect of disease management can have an influence on the outbreak or non-outbreak of the disease. The incidence data were not adjusted to this aspect as this can be region specific.

4.3 Conclusion of statistical analysis

Both diseases investigated in this report have a relationship to the weather, dependent on cool temperature and high rainfall. The statistical analysis based on the direct translation of plant science literature yielded probabilities in which the disease favourable conditions are found at the different stations. For *Fusarium head blight* this percentage is low enough to base a premium on, for *Phytophthora infestans* with a probability of 94% this is not in question. Like Norton and Turvey (2008) conclude in their paper on insuring plant diseases, the hardest element is not to find the probabilities that the disease favourable temperature conditions occur, but the hardest aspect is to find the right relation between the weather conditions and the true incidence of the disease. Although the incidence data present for this analysis were limited, for both diseases it was shown that a significant relation is hard to make. For *Phytophthora infestans* the relation is present, but the number of favourable weather periods does not relate to the severity of a possible outbreak, making it not useful for use in an insurance derivative context.

The main concept encountered in the analysis is the concept of type two error, or the error that you accept the null-hypothesis while you should actually reject it. Or phrased differently, based on the weather conditions you expect the disease to occur but it does not happen in the end. For disease management purposes type two error is not as severe as type one error. You better spray once when the disease apparently did not occur than to not spray while the disease does break out. For insurance purposes type two error is a serious issue because the lack of clear relationship between the weather and the true incidence and severity of the disease are essential in determining the indemnities and adhering premium.

6. Conclusion and discussion

In this last chapter the conclusions will be reported that were found during the thesis project. The chapter will also provide a discussion of these conclusions.

6.1 Conclusion

Weather derivatives have a potential to be used as a financial risk management tool in agriculture. Two plant diseases were analyzed that are cited in plant science literature to be highly correlated to weather conditions, being *Phytophthora infestans* in potatoes and *Fusarium head blight* in wheat grains. Main goal of the research was to define if weather derivatives might be a tool to manage the financial risks related to the specific plant diseases. Three goals were defined in order to answer the main goal.

The first sub-goal of the research was to define environmental parameters of plant diseases from plant science literature. Plant science literature provides various parameters related to the plant diseases chosen for the study. Two main conclusions can be drawn when looking to the weather parameters found in literature. First conclusion is that a lot of weather parameters in plant science literature are based on rather complex measurements such as relative humidity and soil humidity, which are not as commonly measured as temperature and rainfall. Second conclusion is that a lot of parameters are rather ambiguous. Temperature and rainfall are related to the disease, but when using these parameters, one cannot see how exceeding these limits relate to the exact development of a plant disease.

The second sub-goal of the research was to assess the probability of relevant disease parameters. For both plant diseases the probability for disease related weather parameters could be used in the analysis of weather data present in the database. For *Phytophthora infestans* the probability that disease favourable weather periods are present in a year are very high. For the four weather stations analysed, a 87 to 97% probability was calculated that at least one disease favourable period would emerge during a growth period. For *Fusarium head blight,* the probability of the disease favourable conditions to emerge varied between 0 to 2% for the four stations analysed in the *Fusarium head blight* analysis.

Weather derivatives are often based on the measure of growing degree days. Three methods were used to see whether growing degree days could be used as alternative for absolute temperature borders. None of the applied methods were useful in translating absolute temperature cut-off points into growing degree days cut-off points. Main problem with translating the absolute values are the differences in distributions underlying the temperature per weather station and specific period.

The third sub-goal of the research was to determine the applicability of weather derivatives for plant disease risk management. Apart from calculating the probability that disease favourable conditions emerge, the correlation was determined between the disease favourable conditions to emerge and the incidence of the disease. For both *Phytophthora infestans* and *Fusarium head blight,* regression techniques were applied to find a correlation between weather conditions and incidence. For both diseases no significant correlation was found related to the weather conditions. Because the incidence data for both diseases only covered a limited number of years and weather stations, an additional qualitative analysis was performed. From this qualitative analysis for *Phytophthora infestans* a relation could be drawn between the disease favourable conditions occurring at least once, and whether the disease occurred or not. This is in line with the literature, but it was expected that the number of disease favourable conditions would be related with the severity and incidence of the disease which was not found in the regression analysis. For *Fusarium head blight* the qualitative analysis showed a very weak pattern towards the parameters described in plant science literature. The weather parameters defined in plant science literature are mostly developed to use as an input in pesticide management systems. For these systems it is most important that the system always predicts that a disease would break out. It is more harmful in that context that a system does not correctly predicts the disease while it did break out, than the other way round. This type II error does create a problem in an insurance derivative context because when a disease was predicted but did not emerge, a farmer would receive an indemnity while he does not need to receive an indemnity from a farm income perspective. Based on these findings weather insurance would not be a suitable instrument for the management of financial risks related the described plant diseases. An option other than specific crop related weather insurance would be to introduce a more general farm income insurance as is proposed by Berg and Schmitz (2008) and Asseldonk *et al.* (2004).

6.2 Discussion

From the statistical analyses on both *Phytophthora infestans* and *Fusarium head blight*, it was concluded that a weather derivative like insurance would not be suitable for these diseases. For the diseases a relation was found, but for *Fusarium* the relation is too weak and for *Phytophthora* the predictor is not scalar, meaning that it does predict the disease but not the severity of the disease. The conclusion was surprising since plant science literature seems to be relatively certain in finding the correlations between weather parameters and the disease incidence. One of the explanations, the point of type II error, was discussed earlier in this report and will not be taken further. The following discussion goes into possible explanations from the research set up and the methods used.

First discussion topic are the weather parameters chosen from literature. The weather parameters chosen in this report are relatively basic, and do not include weather measurements like relative humidity. For *Fusarium head blight* two literature sources were combined and simplified for statistical analysis (a crop growth model was not used). The relative basic weather parameters were chosen, because if analysis would have found them to be useful, plant disease could easily be insured with available weather derivatives traded on the exchange. Although the weather parameters were relatively old and basic, discussion with plant disease experts ascertained that the weather parameters are widely used and proven to be useful in a plant science context. Using more complex weather parameters might be useful when analysing plant diseases in an insurance derivative context, although one can question how easily the diseases might be insured with a weather derivative if it is based on many different variables.

Second discussion topic are the incidence data used in the research. It was very difficult to find incidence data of consecutive years and for multiple regions. Many plant researchers were asked for extensive records of incidence and severity data, but only North Dakota State University had recent and elaborate disease incidence data for the diseases analysed in this study. The limited number of years available for the regression analysis might be a reason for the weak correlations found in the research. A second element might be related to the incidence data itself. Since it is possible to spray pesticides, the incidence data do not represent a situation without disease management which certainly influenced the relations found. The qualitative analyses of both diseases did indicate towards a relationship between the weather and the plant diseases. A collaborative study with plant scientist that incorporates the needs of economists for simple measurements and type II error-free data might therefore lead to a promising collaboration for the risk management of plant diseases that are of high financial importance to farmers.

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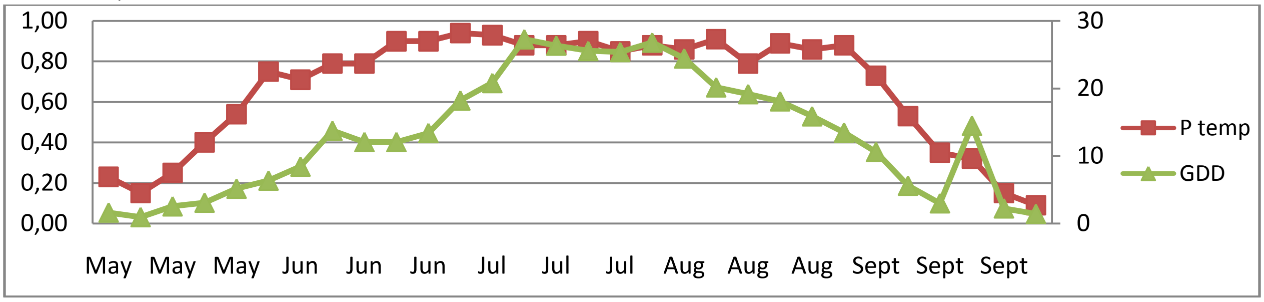
Appendix I

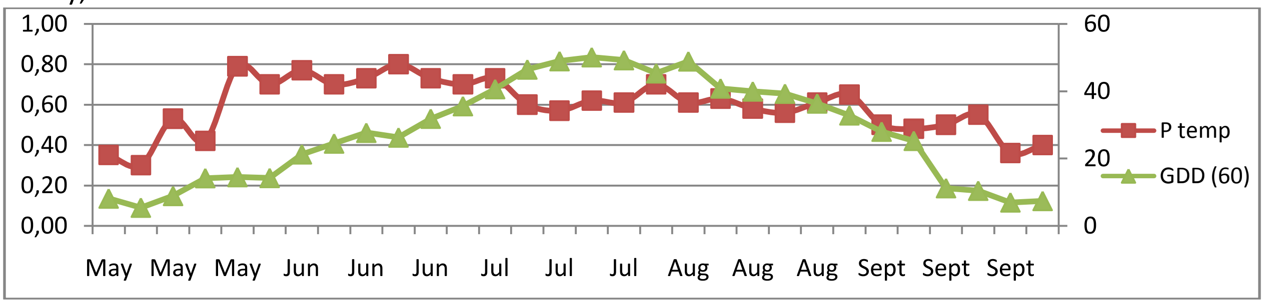
Growing degree days and probability for favourable temperature Phytophthora infestans

Left axis is probability for favourable temperature, right axis cumulative GDD

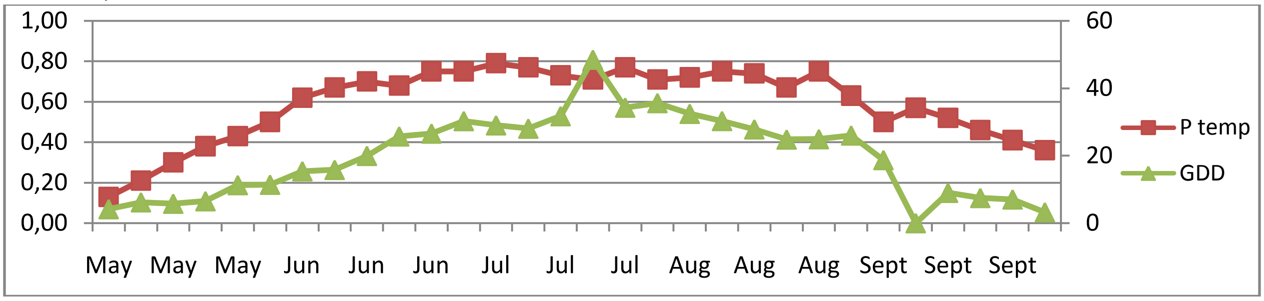
Bottineau, ND



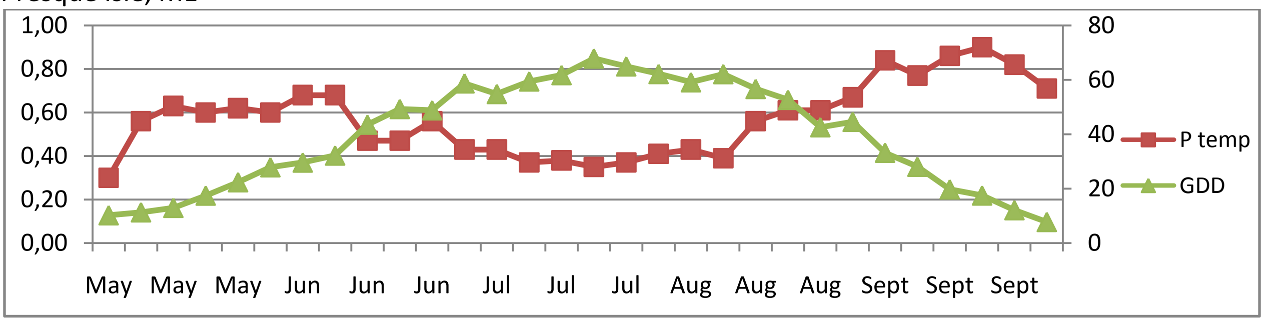
Ashley, ND



Madison, ME



Presque Isle, ME



Appendix II

Qualitative analysis Fusarium head blight data

Location specific decision rules

Station: **Bottineau, Bottineau county**

Year	Temperature	Rain	Severity
1998	cool	very wet	0
1999	cool	dry	0
2000	very cool	very wet	0
2001	cool	very wet	3
2002	warm	very wet	0
2003	cool	dry	0
2004	very cool	wet	0

Station: **Longdon exp. farm, Cavalier county**

Year	Temperature	Rain	Severity
1998	Very cool	very wet	4
1999	Very cool	wet	1
2000	Very cool	very wet	0
2001	Very cool	very wet	0
2002	Very cool	very wet	0
2003	Very cool	wet	0
2004	Very cool	very dry	0

Station: **Jamestown st. hospital, Stutsman county**

Year	Temperature	Rain	Severity
1998	cool	dry	2
1999	warm	dry	2
2000	warm	wet	0
2001	very cool	very wet	0
2002	very cool	very wet	0
2003	very cool	dry	0
2004	very cool	dry	0

Station: **Keene, McKenzie county**

Year	Temperature	Rain	Severity
1998	very cool	very wet	0
1999	warm	wet	0
2000	cool	wet	5
2001	cool	wet	3
2002	warm	wet	3
2003	cool	wet/dry	0
2004	cool	very dry/dry	0

'Absolute' decision rules

Station: **Bottineau, Bottineau county**

Year	Temperature	Rain	Severity
1998	normal	wet	0
1999	normal	dry	0
2000	cool	wet	0
2001	normal	wet	3
2002	normal	wet	0
2003	normal	dry	0
2004	cool/normal	wet	0

Station: **Longdon exp. farm, Cavalier county**

Year	Temperature	Rain	Severity
1998	normal	wet	4
1999	normal	dry+	1
2000	cool	wet	0
2001	cool/normal	wet	0
2002	normal	wet	0
2003	normal	dry	0
2004	cool	dry	0

Station: **Jamestown st. hospital, Stutsman county**

Year	Temperature	Rain	Severity
1998	normal	dry	2
1999	normal	dry	2
2000	normal	dry	0
2001	cool	wet	0
2002	cool	wet	0
2003	cool	dry	0
2004	cool	dry	0

Station: **Keene, McKenzie county**

Year	Temperature	Rain	Severity
1998	normal	wet	0
1999	normal	wet	0
2000	normal	wet	5
2001	normal	wet	3
2002	normal	wet	3
2003	normal	dry	0
2004	normal	dry	0

Station: **Crosby, Divide county**

Year	Temperature	Rain	Severity
1998	cool	very wet	2
1999	cool	very dry	3
2000	cool	wet	4
2001	cool	wet	3
2002	cool/warm	wet	0
2003	cool	very dry	0
2004	cool	wet	0

Station: **Crosby, Divide county**

Year	Temperature	Rain	Severity
1998	normal	wet	2
1999	normal	dry	3
2000	normal	wet	4
2001	normal	wet	3
2002	normal	dry	0
2003	normal	dry	0
2004	normal	dry	0

Station: **Garrison, McLean county**

Year	Temperature	Rain	Severity
1998	cool	wet	3
1999	warm	very wet	0
2000	very cool	wet	0
2001	warm	wet/very wet	4
2002	warm	very wet	0
2003	cool	dry	0
2004		very dry	0

Station: **Garrison, McLean county**

Year	Temperature	Rain	Severity
1998	normal	wet	3
1999	normal	wet	0
2000	normal	wet	0
2001	normal	wet	4
2002	normal	wet	0
2003	normal	dry	0
2004		dry	0