EXPLORE POSSIBLE WAYS TO INCREASE YIELD OF CONSUMPTION POTATOES

July 2018, Wageningen

Limiting factors assessment, recommendations and a future outlook for the Netherlands

Authors

Couwenberg, Twan
Francisco, David
Jonkergouw, Harm
Joshi, Toyanath
Puccetti, Guido
Smid, Wietse
van Vilsteren, Sjoerd

EPLORE POSSIBLE WAYS TO INCREASE YIELD OF CONSUMPTION POTATOES

Limiting factors assessment, recommendations and a future outlook for the Netherlands

Academic Consultancy Training

Project code:	2116		
Status:	Final report		
Commissioner:	Aleid Dik	aleiddik@xs4all.nl	
Coach:	Martine Nieboer	Martine.Nieboer@wur.nl	
Academic advisor :	Willemien Lommen	Willemien.Lommen@wur.nl	
Project team:			
Franscisco David Ruiz Zuniga	MPS – Greenhouse horticulture		Member
Guido Puccetti	MPS – Plant Pathology and Entomology		Member
Harm Jonkergouw	MPS – Crop Science		Controller
Sjoerd van Vilsteren	MPS – Natural Resource Management		Secretary
Toyonath Joshi	MOA – Agroecology		Member
Twan Couwenberg	MPS – Crop Science		Member
Wietse Smid	MAB – Robotics and system identification		Manager

Wageningen, July 2018.

Summary

Brancheorganisatie Akkerbouw (Branch organisation Arable Farming, BOA) raised the question 'why has the yield in consumer potatoes not been increasing for the last 30 years? The goal for this project was therefore to find the limiting factors that cause this stagnation, establish an advice and further determine the possibilities and threats caused by climate change in the future for potato growers. To get to the answer, first of all the yield potential of potato in the Netherlands was determined through literature research. This turned out to be somewhere between 72.6 and 90 tons per hectare. Furthermore, interviews were done with several potato growers and experts of Wageningen University to find the first limiting factors. Additionally an extended literature review and a model sensitivity analysis was done to find other limiting factors. The model that is used is called LINTUL-POTATO-DSS and is developed by the Plant Research Department of Wageningen University. Regarding the outlook on climate change and its effect on growing potatoes, the model was used for this chapter too.

In this research, it turned out that the limiting factors in current potato production are: water, nitrogen fertilizers, tuberization conditions, planting depth and season length. The model especially showed that planting depth and the length of the growing season have a big impact on the yield. However, according to the interviews, irrigation is in respect to farm practices, the main area of improvement. Furthermore, plant diseases, breeding and genetics indirectly have an impact on the yield. After finding these factors that currently limit the yield in consumer potatoes, climate change scenarios were analysed. Based on this analysis, ways to overcome threats and ways to benefit from these opportunities were determined. In the best scenario, growers already can achieve a 14% higher yield in 2019. Furthermore, in the future the yield potential of consumer potatoes is raised to about 115 tons per hectare, as the LINTUL-POTATOE-DSS simulations showed.

Based on these findings and the limiting factors, an advice has been written. The advice is a combination of adaptations methods to current challenges. Especially, ways to take benefit of the increasing length of the growing season. Furthermore, there are a few opportunities; applying more fertilizer by drip irrigation and reduced tillage, are promising. However, since the actual numbers on how beneficial these opportunities are, are not clear, further research in this area is advised. Regarding pests, the advice consists of making the advisory systems more easy to adapt for growers. Furthermore, an extension of crop rotation is desired. There are also opportunities for resistant cultivars to prevent crop damage by diseases, but this requires some support from multiple stakeholders in the production chain, such as retailers and supermarkets. Finally, breeding can help to overcome some of these challenges as well. Regarding future climate change challenges, more resilience in the crop is desired.

Table of content

Introduction

The potato is an important crop in Dutch agriculture. It takes up roughly one quarter of Dutch arable land, and contributes to almost half of the total volume of production from the arable farms. In the Netherlands, total land occupied for potato farming is ca. 160,000 ha and nearly 9000 growers are involved in the seed and consumer potato production. For consumption purposes, 85% of the total production is sold to processing companies while 15% is sold for direct consumption (CBS, 2018). The Dutch potato sector is worldwide known for its high quality and quantity production and aspires to continue to do so in future. Thus, potato production in the Netherlands is closely associated with international market signifying the importance of potato farming in the country. Despite the importance of the crop and the favorable changes within the production and quality, for the past 30 years, yields in the Netherlands have not increased (FAO, 2016). This yield stagnation has implications on the Dutch potato sector. The Netherlands could lose its important position in the global market as other countries continue to develop as well. As climate changes, Dutch agriculture needs to cope with an increasing pressure from society due to the environmental impacts of production. An increased yield with the same input means a more efficient way of production.

Potato tuber yield is determined by several factors. BrancheOrganisatie Akkerbouw (Branch Organisation Arable Farming, BOA), a central interest organization within Dutch agriculture raises the question why the yield has not increased in the past 30 years. Thus, this project was carried out with the goal to carrying out further research and validation on the limiting factors of the Dutch potato yield.

This project will analyze the potential yield of the Dutch ware (consumption) potato by using the LINTUL-POTATO-DSS model. This will be helpful to farmers, researchers, non-governmental organizations involved in potato research and production. Moreover, the project would explore the main yield limiting factors of potato in respect to Dutch conditions. The limiting factors for potato yield will have implications for farmers, policy makers and researchers. The project will also focus on climate change and its possible impacts on potato production including disease incidence, particularly early and late blight. This will basically provide ideas for future resilient potato farming. The report will also review the existing laws and regulations on fertilizer use and genetic modification techniques which could provide insights to policy makers involved in the potato sector.

The project mainly answers the research question 'How to increase the Dutch potato yield?' This question links directly to the problem. Yield increase in this project means a higher production of consumer potatoes in kg (or tons) per hectare. To answer this main question, we used the following sub questions; 'What is the yield potential of the consumer potatoes in the Netherlands?' For this we used the LINTUL-POTATO-DSS model to access the potential yield of the Dutch consumer potatoes. Secondly, the drivers behind these potentials were identified. Then these factors were ranked on their potential to increase the yield. These factors can both be influenced or not be influenced (for example climate change). Here we ask; 'Which factors are most limiting and therefore have the most potential to increase the Dutch potato yield? Yield is related to climate conditions, therefore we ask 'how does climate change influence the potato yield?' In the end, solutions to improve these factors or suggestions for future research are given in an advice to BOA. These factors are both short- and long-term solutions. Sub questions for this advice will be: 'What can be done by the sector to tackle limiting factors?', 'What can growers do in the future to cope with climate change related conditions and regulations?' We answered these questions by literature research on yield potentials, limiting factors and the driving factors of yield. Furthermore, we have visited growers and interviewed experts, in order to determine possible gaps between ideal situations described by literature and actual growing practices.

Materials and methods

Field research

The gathering of information to answer the research question started with an exploratory field research. To get a clear and fast direction for the project, several farmers were called and interviewed about their main factors that cause yield reduction. The reason for choosing the exploratory field research instead of other methods is the quick way to clarify the true practical issues which thereafter were acknowledged and confirmed by farmers. Experts within the field of potato production were also interviewed to understand their findings and provide high quality information.

Model

The Potato-DSS model was tested on its sensitivity to the main points/limiting factors to find the maximum theoretical potential yield in the Netherlands. The model is used to rerun several limiting factors with the same consistency in results. The model can give reliable results with changing one parameter, while all other factors remain the same, in contrast to practical trials, where the environmental factors can differ between tested objects. In order to find the limiting factors, a sensitivity analysis was carried out.

Literature study

To confirm the limiting factors, a literature study was carried out per factor and its impact. Information from the model and the literature study were compared and adjusted towards reality based on the teams expertise. However to connect the model with practice, the literature study will add its confirmation to find limiting factors. Then per limiting factor, future and current legislation were described including its effect. Where possible, found values were confirmed by calculation.

Advice

Based on all findings, an advice is written towards the Brancheorganisatie Akkerbouw (BOA). This advice combines the model, literature study and field research. As a model remains a simplification of reality, both literature and the model need to be combined to form one stable answer. This advice does not only summarize the findings but also gives recommendations, new methods/techniques and directions the potato sector which can be used to obtain the maximum yield.

Supporting activities

The main line of actions had several supporting activities. For the group, especially the international students, a potato farmer was visited and interviewed in order to get a better view on the production and sector. To find out whether location had influence on the current yield performance, a short meta-analysis was done to confirm the influence of location. The result of the meta-analysis came out negative as location had no influence on the current yield.

Chapter 1. Actual yield, potential yield and limiting factor assessment according to the LINTUL-model

The first chapter is about the gap between the actual and potential potato yield in the Netherlands. Next to this, it describes the most limiting factors of potato yield according to the used model.

1.1 Actual and potential yield

Within the project, it was necessary to know what the potential yield of (ware) potatoes in the Netherlands is. In this sense yield potential is defined as the theoretical yield that can be attained by a cultivar under optimum environmental conditions (Haverkort and Struik, 2015). Different values for potential yields under Dutch conditions have been suggested in literature. For instance Vasco *et al.* (2017) calculated a ware potato potential yield of 72.6 t ha^{-1} through WOFOST model for the Netherlands while Haverkort and Struik (2015) modelled a potential yield of 90 t ha^{-1} for Flevoland by using the LINTUL model. To know if the production can be improved and by how much actual yield was determined.

Actual yield can be understood as the yield obtained by farmers depending mainly on weather and management practices defined by input availability and economical traits (Haverkort and Struik, 2015). A comparison of data obtained from 'Centraal Bureau voor Statistiek' (CBS, 2018) showed an average ware potato yield of 49.3 t ha^{-1} in the period 1994-2017 (Fig.1).

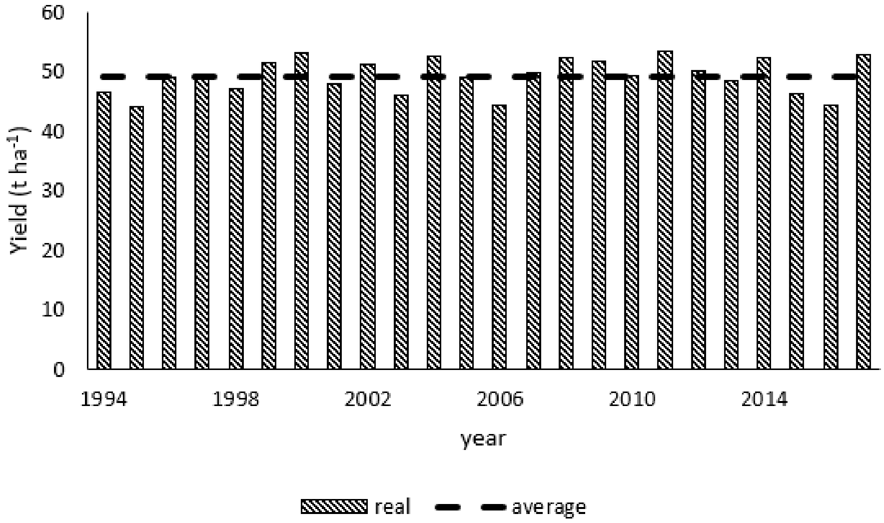


Fig.1 Average and real yield in the Netherlands (1994-2017)

1.2 Determining limiting factors

1.2.1 Interviews

During week two and five of this project, researchers, farmers and different stakeholders in potato production were interviewed on their knowledge and expertise on yield limiting factors. According to the people interviewed these were the main limiting factors:

- **Water stress**: Irrigation implies costs in potato production and optimum time of irrigation is hard to determine. Farmers rather not irrigate until really necessary. However, this optimum time could be improved. Next to this, farmers do not always have the capability to irrigate all crop which is in demand of water.

- **Plant diseases**: If pesticides are not applied at optimum times or the application is not carried out correctly, diseases will act as a limiting factor for yield. Furthermore, rainy years tend to increase this problem as some fungi or bacteria develop in humid conditions.
- **Nitrogen fertilizers**: The current regulations regarding limited amount of nitrogen per hectare that can be applied are perceived as limiting.
- **Breeding and genetics**: Cultivars available for production are not tolerant to diseases and potato genome arrangement represents difficulties for breeding.
- **Seed tuber**: Variability in time but also the conditions during storage can influence crop development and therefore yield. Optimum yield starts with optimum tubers.
- **Tuberization:** The tuberization process determines the potential yield. Abiotic factors and genetics determine how big the potential can be.

1.2.2 Sensitivity analysis

Model explanation and input variables

LINTUL-POTATO-DSS (Haverkort et al, 2015) is a model derived from the LINTUL-POTATO model. The main differences between both models are that LINTUL-POTATO-DSS model requires less input data (Table 1 Appendix) with less equations compared to the LINTUL-POTATO model. This makes it a more useful model for yield gap analysis among other kind of studies (Haverkort et. al, 2015). The model consist of 12 input variables that are related to management practices and 5 which are weather variables and cannot be controlled but only measured.

The model works under reasonable assumptions. Temperature rules the early stage crop processes of potato such as sprout growth, leaf area index (LAI) increase (from 0 to 3) and harvest index increase (from 0 after emergence to 0.75 at crop end). It is assumed that the light interception is increased proportionally from 0 to 100% when LAI is 0 and 3 respectively. Furthermore temperature influences light use efficiency (LUE). In the model the range of temperatures to obtain the highest LUE should be established. A fixed LUE is established through all the simulations. The base temperature for crop development is 0°C and the crop will not be damaged by low temperatures and only the developmental rate would decrease.

Water availability is also included in the model. Precipitation, drainage, evapotranspiration (ET), soil water holding capacity and rooting depth are considered for the water balance. According to the model it is assumed that photosynthesis rate is proportional to the actual ET/Potential ET ratio. Only 80% of the precipitation is assumed to infiltrate and the crop cannot absorb water when the available water in the soil is 50% of the difference between field capacity and permanent wilting point. Furthermore it is assumed that once the soil reaches field capacity extra water would run off or drain.

Dry matter accumulation depends on radiation, LAI and LUE. The dry matter content of potato will at the end determine fresh yield.

1.2.3 Sensitivity analysis results

The sensitivity analysis can be a powerful tool to assess the impact of different independent variables on a dependent variable (Investopedia, 2018). To find out the factors that limit potato yield, a sensitivity analysis was carried out using the LINTUL-POTATO-DSS model. Furthermore, the only input factors included in this analysis are those that can be directly manipulated by the farmer (Table 1). The input variables were increased and decreased 20 percent of the default value while the rest of the input variables were kept the same. Weather data were taken from 'Koninklijk Nederlands Meteorologish Instituut' (KNMI) website (2018). The average weather data considered come from De Bilt weather station and were averaged from 2013 to 2017 (see appendix II).

Table 1. Yield obtained through the LINTUL-POTATO-DSS model. The weather data was averaged across five years (2013-2017) and was taken from De Bilt weather station. The yield obtained with the default input values was 72.4 t ha-1.

Input variable	-20% value	+20% value	-20% yield (ton ha^{-1})	+20% yield (ton ha^{-1})
Planting depth (cm)	14	21	75.2 (+3.9%[1])	69.9 (-3.5%)
Planting date	Apr 9th	May 7th	79.4 (+9.6%)	64.9 (-10.4%)
Harvest-haulm killing date	August 24th	September 21th	63.2 (-13.8%)	79.6 (+9.9%)
Rooting depth (cm)	24	36	72.4 (-)	72.4 (-)
Clay-Silt content (%)	15	25	72.4 (-)	72.4 (-)
[1] Values in parenthesis represent the percentage increase or decrease of yield compared to default model input situation				

From the sensitivity analysis planting depth and season length (planting and harvest date) showed to be limiting yield (Table 1)

Even though no effect was found by increasing or decreasing rooting depth when the 5 years average data was used this parameter related to water uptake and storage can be more relevant in dry years (Table 2). In 2013, the precipitation to ET ratio during the growing season was 0.56 (Appendix III)

Table 2. Ware potato yield obtained through the LINTUL-POTATO-DSS model. The 2013 weather data used and was taken from De Bilt weather station. The yield obtained with the default input values was 65.4 (with irrigation) and 44.9 t ha-1 (without irrigation)

Input variable	-20% value	+20% value	-20% yield (ton ha^{-1})	+20% yield (ton ha^{-1})
Rooting depth (cm)	24	36	42.7 (4.9%)	46.3 (3.1%)
Clay-Silt content (%)	15	25	44.9 (-)	44.9 (-)
[1] Values in parenthesis represent the percentage increase or decrease of yield compared to default model input situation				

Clay-Silt content can be more relevant when precipitation is distributed in less events of higher intensity. Further explanation will be given on the limiting factors found through interviewing and modelling.

Chapter 2. Yield limiting factors

2.1 Water management

2.1.1 Field water

The physical properties of soil have a major impact on water management. Good quality soil is easier to manage, resilient to extreme weather events and has the potential to produce a good yielding crop. Water entering the soil is affected by two forces. The gravitational force and the force of water molecules that tends to be attracted to soil particles (adhesion). Ideally, after a heavy rainfall the soil needs to reach its field capacity as soon as possible. Long periods of waterlogging will result in yield losses, due to anaerobic conditions. A high infiltration rate is determined by the soil texture, structure, organic matter content, water table and soil compaction and is mainly determined by farmers practices (Kirkham, 2014). Recording to the Kostiakov equation (Equation 1) the infiltration rate (I) only depends on soil constants (k, A and f0) and time (T). Farmers need to increase the infiltration rate, without extending the time. Therefore, soil characteristics need to be adjusted in order to increase the infiltration rate (Jurrïens *et al.*, 2001).

$$I = k.A.T^{A-1} + f_0$$

Equation 1: Kostiakov equation (Jurrïens et al., 2001)

The three soil properties biological, chemical and physical determine the quality of the soil and all have influence on its water dynamics. The biological properties, which consist of all the living organisms in the soil, ensure the breakdown of organic matter and the aeration of the soil (Magdoff and van Es, 2000). Magnesium, calcium and sodium have the most effect on the chemical property of the soil. The balance between these elements determine the physical behavior of the soil. Magnesium and calcium stabilize clay particles which results in a good soil structure. Sodium tend to make the binding of the clay particles weaker (van Dam, 2009). The physical conditions of the soil is determined by the proportion of solid soil particles, water and air including the texture of the particles. In the past decade farmers in the Netherlands (clay soils) did not carefully look after these three soil properties. They used their soils intensively, which resulted in soil degradation including soil organic matter depletion, pollution, compaction, erosion and loss of biodiversity (Römkens and Oenema, 2004). All these factors do not contribute to a good water management on the field. Appropriate cultivation practices could improve the three soil properties in such a way that it becomes fertile and resilient against different environmental conditions.

Especially organic matter content is important. Not only for the infiltration rate, but also for all the three soil properties. Organic matter positively influences all soil properties. Physically, the structure, aeration and water retention will be better if the organic matter increases. The influence of organic matter on the biological property of the soil is the improvement of the mineralization, disease suppression and biodiversity. Furthermore, organic matter consist of different nutrients in different quantities, the potential available nutrients are higher when there is more organic matter in the soil. Therefore, the chemically part of the soil will be better (Magdoff and van Es, 2009). A meta-analysis carried out by Hijbeek *et al.*(2017) showed that there is a positive correlation between yield and the increase of soil organic matter. But they concluded that a higher input of organic matter not necessary leads to more yield. Additional side effects of organic matter ensure the yield improvement. Soil organic carbon (SOC) is keystone to indicate the soil quality and it is well known that in an intensive cropping system the SOC declines, without extensive soil management and input of SOC (Reeves, 1997). Input of manure, crop residuals and compost is therefore essential to retain the SOC. Long-term studies showed that intensive tillage and high SOC input hardly sustains the organic matter content (Reeves, 1997). Preserving and improving soil quality in order to manage the soil water dynamics in continuous cropping system is highly important in the future as well as maintaining agronomic productivity and economic sustainability.

2.1.2 Constrains of water deficit

Crop water

The total water requirement for a potato crop is around 500 – 700 mm per growing season (FAO, 2008). According to the model this is 400 mm per growing season. In the Netherlands, the precipitation is about 600 – 800 mm (CBS, 2018) which means that we can meet the crop requirement if the distribution of the precipitation follows the crop demand. In the current situation and in future, there will be more extreme weather events and the distribution will be uneven. This has a major impact on the yield. Water stress is one of the most critical abiotic stress factors that limit plant growth, crop yield and quality concerning food production. The moisture availability has a major influence on the yield and crop performance. Tuber physiological disorders such as brown center, hollow heart, growth cracks, second growth are all associated with water stress (Shock *et al.*, 2007). The reason why water is important, is because of a strong relationship between yield and transpiration (Figure 2)(Carli *et al.*, 2014; Kirkham, 2014). Transpiration is mainly driven by the availability of soil moisture and at water deficit the dry matter production will decrease. The transpiration is correlated to the carbon fixation process, which influences the crop growth and yield potential. The transpiration is in a significant part of the growing season a limiting factor.

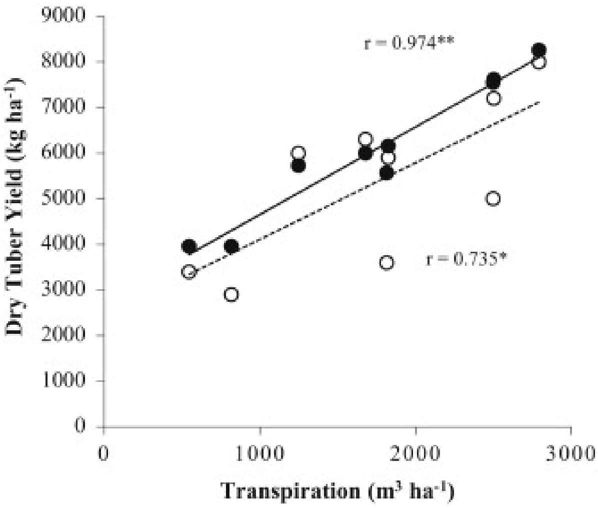


Figure 2: Relationship between transpiration (m^3 ha^{-1}) and dry tuber yield (t ha^{-1}) (Carli et al., 2014)

Tuberization

A potato crop is very sensitive to drought stress in the tuberization period. Therefore, it is important to understand the tuberization process and the special distribution of tuber development in order to get higher yields. The yield potential is determined during the tuberization process. Therefore farmers have the most influence on the yield during the tuberization period (Bus *et al.*, 2004). Stolons develop from underground axillary buds at the base of the main stem. The stolons then grow longitudinal and diagravitropically (horizontal at a certain angle) until tuber induction (Morris *et al.*,2014). The tuberization is promoted by short-day periods, cold nights and low nitrogen fertilization rates but there is a genetically variation between varieties (Morris *et al.*, 2014). The quantity and quality of stolons depends on many factors. Besides genetics, water is considered as the most important factor that determines the amount of tubers. Multiple research papers concluded that a deficit in soil moisture in the tuberization process reduced the total amount of tubers per stem (MacKerron and Jefferies, 1986; van Loon, 1981; Haverkort,1990; Struik, unpublished). In Figure 3 the relationship between water and tuber number is visualized. Furthermore, during drought conditions there will be less tubers, but yielding bigger tubers. During moist conditions there will develop more tubers but yielding relative smaller tubers (Struik, unpublished; Haverkort,1990).

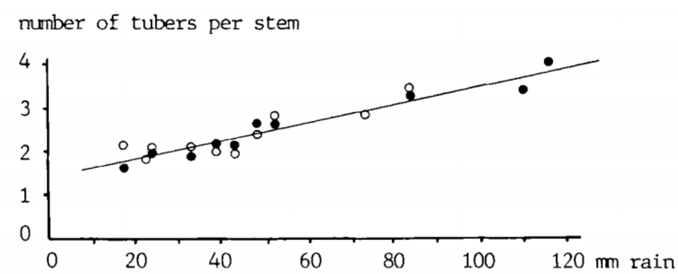


Figure 3: Relation between total precipitation during the first 40 days after planting and numbers of tubers and stems (Haverkort, 1990)

Temperature

Furthermore, the temperature is also important for the initiation and development of tubers and canopy. The optimal temperature for canopy development is 20-25°C. However, the optimal temperature for tuberization is 15-20°C, above this temperature, it can cause reduction of, or inhibit, the tuberization process (Rykaczewska, 2013; Rykaczewska, 2015; Reynolds and Ewing, 1989). Various research papers showed that there is a yield reduction when the soil temperature is higher than the optimal tuberization temperature during tuber development. Rykaczewska (2015), concluded that the yield can be reduced by 35% if the crop suffers heat stress during flowering. This has to do with enzymatic activity reduction in the stolon during heat stress (Lafta and Lorenzen 1995; Obata-sasamoto and Suzuki, 1979) and with the photo-assimilate partitioning to tubers, which is greatly reduced by high temperatures (Rykaczewska, 2017). Furthermore, heat stress reduces the size of individual tubers (Rykaczewska, 2017).

Planting depth

The crop emergence will be delayed with an increase in planting depth. The soil is colder deeper in the soil and it takes longer for the emerging stem to reach to the surface. The planting depth has influence on the stolon length. There is a relationship between stolon length and planting depth. The stolon length decreases with increasing planting depth (Swenson, 1962). This positions the tubers closer to the main stem, which means that the chance of potato greening also decreases. Furthermore, the stolon number per stem increased as planting depth increased. Also the tuber numbers per stem increased as planting depth increased (Pavek and Thornton, 2009). This will result in less yield, which is visual in Figure 4.

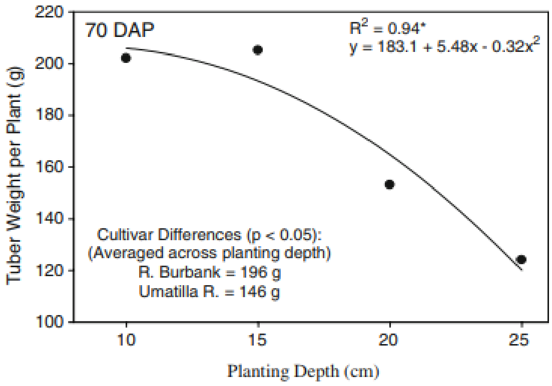


Figure 4: effect of planting depth (cm) on tuber weight per plant (g) (Pavek and Thornton, 2009)

Genotype

The number of stolons that ends as a harvestable tuber, is mainly genetically controlled. Gene expression, gibberellin syntheses and sink source relationship, controls the tuber development (Stunik *et al.* 1999; Katoh *et al.*, 2015). Katoh *et al.*(2015) also mentioned that an overexpression of RAN1-gene, results in more tubers per plant (Figure 5). There are numerous reports that have isolated genes which are expressed during tuberization and occur in a natural variation (Strunik, 1999). But the genetic control of tuber set is really complex and not easy to describe. Summarized, tuber formation is a plastic and complex morphological, physiological and biochemical event (Strunik, 1999). Genotype and environment will finally determine the total amount of tubers.

Figure 5: potato plants expressing CLRAN1 formed more tubers (right), than non-transformed potato plants (left)

2.1.3 Drainage system

Currently, several drainage methods are used by farmers. Not only the supply of water towards the plants can be a challenge, heavy rainfall periods can cause a large problem as well. These techniques are mostly aimed at driving water out of the field and control the water level. Farmers use drainage systems for several reasons as they can harvest earlier due to drier field conditions and less damage by water, as wet spots can be drained. This latter case is trending for several years now, as heavier rainfall in shorter periods causes fields to flood and crops to drown and rot. Exact info on the damage done by heavy rainfall on the potato crop differ from year to year in each region. According to growing organization Nedato in 2016, approximately 15% of the total planted area of growers were completely destroyed by heavy rainfall and hail before the summer was over (Nedato, 2016). This shows the impact the weather can have on crop damage. To prevent the damage as much as possible, several actions can be taken.

Preventive drainage

Preventable drainage or digging preventive ditches on the field can help the water run of the field greatly. However most farmers start digging these ditches when the water has already fallen and the fields are flooded. Another method to get rid of the water is to pump it out off the field. Exact numbers on how many farmers apply these techniques and the effectiveness of these methods are not known. Another cause of the problem can be the water flow towards rivers/seas which cannot manage the outflow of water and start flowing water back to the fields.

Water authority agency

The water authority agency ('het Waterschap') is responsible for all the waterways in the Netherlands. It manages and maintain them as well. According to farmers (Boerenbusiness, 2015), the lack of good quality maintenance on the waterways causes a much lower outflow required to get rid of the water during the periods of heavy rainfall. As well as the reaction of the water authority agency on the damage, almost no extra effort was put in to get rid of the water.

(Level-controlled) drainage

Another method in controlling the water level within a field is to make use of drainage tubes in the soil. The depth in which they are placed varies, but is most of the time around 60-80 cm deep for horizontal drainage. Vertical drainage tubes are mainly used for providing water for drainage. In Figure 6, you can see the difference between horizontal and vertical drainage.

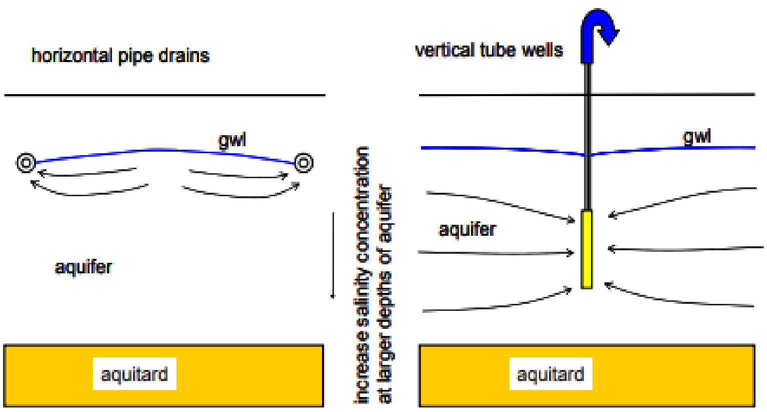


Figure 6 Overview of structure horizontal (right) and vertical drainage systems (left). The influence of drainage on the ground water level (gwl) can be observed. Source: (Dam, 2009)

By putting drainage in the field, the farmer is able to control soil water levels much better. There are two types of drainage, the conventional one and level controlled. Conventional drainage basically works just on gravity and difference in water levels. Level controlled drainage can be connected to a pump and actively remove water from the field. Also, the field is divided in sections thus the water level of wetter parts can be lowered first. An initial lower water percentage in the field can take up more water in periods of heavy rainfall, preventing drowning of potatoes (anaerobic field conditions).

Levelling fields
To ensure a good water flow on a field, some farmers level their field in such a way that the water will always run off towards a water way. This is mostly done in combination with drainage so that water will always run toward the lowest point (ditch). Another way is to cultivate potatoes in line with the height of the field, making artificial waterways between the potato hills which ends in the waterways, instead of having a headland of which the potato hills lay perpendicular on the rest of the field, preventing an outflow of water of the field. This will increase the outflow of water of the field, so it is prepared against heavy rainfall periods.

2.1.4 Irrigation
The potato is a quite water sensitive crop, relatively intolerant to water stress. In the interview with potato grower van Geel, van Geel mentioned that irrigation is not carried out in its full potential. In the model, the actual water availability has a great influence on the yield potential, as it should meet the daily ET (ET). Also, watering the potatoes has quite an impact on the cost price of the potatoes which may be a reason for farmers to tend to skip it and accept the yield loss. Research on the effect of watering on the yield has been done several times. Reducing the watering with 35% of the ET of potatoes results in a yield loss of 50% (in summer, Peru). While reducing the watering with 20% of the ET, the yield decreased with 16% (in winter, Peru, Trebejo, 1989). Worth mentioning, is that watering was done with drip irrigation, compared to overhead irrigation in the Netherlands. Another research done in Turkey, showed that reducing watering with 50% of the ET of the potatoes, yield decreases with 85% (Serhat Ayas, 2009). A rule of thumb in irrigating potatoes in the Netherlands is, that for every mm (1 L / m^2) shortage will result in a loss of 250 kg fresh weight/ha (Dekkers, 2000). Actual data on the average shortage of water in the Netherlands are not present. However, to make an assumption: the total assumed crop ET in 2017 was 404,4 mm, the precipitation in 2017 was 297 mm, leaving a gap of 107,4 mm (Koninklijk Nederlands Meteorologisch Insituut, 2018).

2.2 Fertilizer
The chapter of fertilizers only aims at nitrogen, as for nitrogen many researches have been conducted as well as it is one of the main points of discussions in politics. These discussions aim at reducing leaching of nitrogen and phosphate from fields to surface waters. Phosphate is for potatoes a nutrient which is needed, but within the current laws perfectly available for the crop. Nitrogen however, is a problem for current cultivation practices as crop requirements are not met.

2.2.1 Nitrogen model
The LINTUL-model estimates the maximal potential yield based upon a sufficient supply of nutrients with no direct input variables of nitrogen or nutrients at all. However, 3.3 g Nitrogen per kg fresh weight yield is present in the potato crop. (Dijk, L., & Reuler, 2005). With this information, the amount required for the models prediction can be calculated. This means for 90 tons, 90,000*3.3/1000= 297kg N/ha is required. The amount given by this calculation gives the N-uptake of

the fresh weight of the yield. This doesn't define from which source (deposition, mineralization, fertilizer or manure) it came from.

Another method to calculate this, is using data from research about the N-applied versus N-uptake. According to this research, 61 tons/ha with an N-applied of 265 kg/ha gave an N-uptake of 222 kg/ha on sandy soils (Dijk *et al.*, 2007). Assuming that the N-uptake remains in the 61 tons, an amount of 3.6 g N/ kg yield is taken up while 4.3 g N /kg yield is applied. To recalculate this back to the model in which 90 tons is produced, an amount of 90.000*4.3/1000 = 387 kg N/ha should be applied on sandy soils. However, there is no linear relation between N-applied, N-uptake and the yield which is assumed in these calculation as deposition and mineralization are not explicitly defined here.

To confirm this statement above, data from a recent study have been analyzed (Maltas, Dupuis, & Sinaj, 2017). It shows that a certain increase of fertilizer doesn't lead to a similar increase in yield or N-uptake. Figure 7 shows that, ideally, the nitrogen uptake and nitrogen applied should remain constant. If the uptake of nitrogen per kg potatoes increases with an increase of nitrogen applied, it means that the yield didn't increase accordingly.

2.2.2 Current advice and Legislation

The following advices are given by former research of the "Productschap Akkerbouw" which is now dismantled. The role of the productschap is now fulfilled by Brancheorganisatie Akkerbouw. Current nitrogen advice is aimed at obtaining a sufficient yield without harming the environment (table 3) . The highest yield can be obtained with a higher application however can be harmful to the environment (table 4 below).

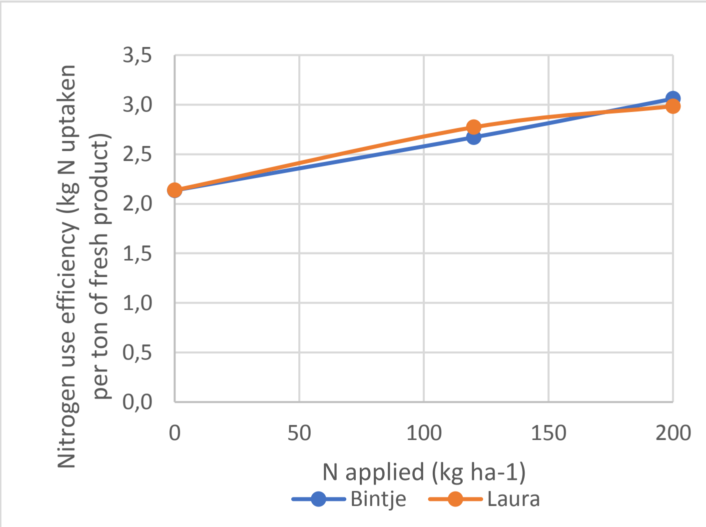


Figure 7 Amount of nitrogen taken up by the potatoes according a certain fertilizer scheme

Table 3 Guideline of nitrogen advice neglecting tuber quality and environment (Kennisakker, 2018).

Soiltype	***Guideline (KG N/HA)***
Consumptionpotatoes, Clay	285 - 1,1 * (N-mineral 0-60 cm)
Consumptionpotatoes, Sand	300 - 1,8 * (N-mineral 0-60 cm)

Table 4 Guidelines of nitrogen advice without neglecting tuber quality and environment (Kennisakker, 2018).

Soiltype	***Guideline (KG N/HA)***
Consumptionpotatoes, Clay	240 - 1,1 * (N-mineral 0-60 cm)
Consumptionpotatoes, Sand	260 - 1,8 * (N-mineral 0-60 cm)

However, the current advice doesn't agree with the legislation. As the legislation is mostly aimed at reducing the outflow of nutrients into the environment, strict application laws have been made. These laws aim both at Nitrogen and Phosphate, taking nitrogen into account for this part. In

Table 5 the amount of nitrogen in kg/ha that can be added depending on the region, soil type and cultivar is shown.

Table 5 Legal standards for nitrogen application per soil type, cultivar and region

Gewas	Klei 2018	en centraal[12] zand 2018	Zuidelijk[13] zand 2018	Löss[4] 2018	Veen 2018
Consumptieaardappelrassen hoge norm (zie tabel 1a)	275	260	208	204	270
Consumptieaardappelrassen overig	250	235	188	184	245
Consumptieaardappelrassen lage norm (zie tabel 1a)	225	210	168	164	220
Consumptieaardappel, vroeg (loofvernietiging voor 15 juli)	120	120	96	96	120

Comparing the current legislation with the current advice, for sandy soils and loessic soils there is a nutritional gap. The restrictions on sandy/loessic soils are much harder due to their incapability to hold the applied nitrogen and their high percentage of leaching to surface waters (Fraters, Boumans, Leeuwen, & Reijs, 2007).

In short, nitrogen is depending on the cultivar grown. In general, the more nitrogen applied results in a higher yield but this depends heavily on cultivar. In order to get a higher yield, nitrogen use efficiency of the potato crop needs to be improved or the legal standards need to be increased to obtain this high yield as more nitrogen is required within the crop at the yield potential of 90 tons than is allowed to apply in the crop.

2.2.3 Future legislation

Nitrogen fertilizer is one of the most legislated nutrients in Dutch agricultural production. It being a societal and political point of debate, future regulations might be important driving factors for future yield potential. The Netherlands is strict within its rules of applying nitrogen as it should remain within the farming land and not leach towards the environment. The Dutch government set up an action plan in the so called '' Zesde Nederlandse actieprogramma betreffende de Nitraatrichtlijn'' which aims at the following (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2017):

- Reducing water pollution caused by nitrates from agricultural sources
- Prevent further pollution caused by this nature

These rules are based on the European Nitrate guidelines Art. 1. Current legislation is based on these rules, lowering the nitrogen application towards a crop required standard. The advice is also to split towards soil type related applications. All these measures are taken to obtain a good yield while minimizing negative impacts on the environment.

Currently, sandy and loessal soils are regulated more strictly in applying nitrogen fertilizer due to their inability to hold applied nitrogen and their high leaching fraction. If the water pollution isn't reduced by the current legislation, the action plan will be reviewed and adjusted to obtain a reduction. In future, this can cause a reduction of nitrogen that can be applied. Also a single application may be forbidden on certain soils, farmers will have to give split dosages during the growth season on crop demand. To prevent leaching, famers may have to sow cover crops by law on certain soil types to prevent leaching. Increasing the soil organic matter can also become obligatory towards farmers in fragile areas.

Farmers are from January 1th, 2021 obligated to sow a cover crop or catch crop before the 31th of October after growing consumption potatoes on south sandy soils or loessal soils. Which according to the report itself, can lead to a shorter harvesting season thus an increase of capacity of the harvest machinery.

Starting in January 1th, 2021, farmers on clay and loessal soils are obliged to take measures against run off of water. These measures include making barriers between the hills of the potatoes. This is to prevent run off of water to waterways under normal weather conditions. This also forbids digging preventive trenches (Ministerie van Landbouw, Natuur en Voedselkwaliteit. (2017). *Zesde Nederlandse actieprogramma betreffende de Nitraatrichtlijn)*.

2.3 Growing management

2.3.1 Physiological age of tuber

The seed tuber quality will be determined during the cultivation and storage in combination with the genetics of the cultivar. There is a big interaction with genotype x environment during all stages of the potato life cycle (Struik, *unpublished*). The physiological age of the seed tuber can be classified in dormancy stage and physiological age stage. Dormancy is the temporary interruption of any plant structure containing a meristem (Muthoni *et al.*, 2014). This means that the tuber is not able to start sprouting for a certain period of time. The length of this endodormancy is mainly determined by the genotype of the cultivar, but is strongly influenced by the growing conditions, temperature, storage conditions, skin condition and wound healing (Struik, *unpublished*). During this first phase of dormancy, the tuber stays metabolically active and prepares itself to bud activation. After endodormancy, external factors can inhibit sprouting. Physiological age is the stage of development of a seed tuber, determined by genotype, chronological age and environment conditions from tuberization until emergence (Struik, *unpublished*). The physiological age has a strong impact on the performance of the crop and is considered a yield limiting factor (Figure 8). It influences for example, the emergence, stem number, tuber per stem and growth rate (Struik, *unpublished*; Muthoni *et al.*,2014). The amount of stems per tuber will increase with an increase in physiological age. Besides, the number of stems is higher when the tuber is stored under long cold conditions and low when stored under warm conditions. This has to do with the loss of apical dominance of the seed tuber. Furthermore, the tuber size has an effect on the number of stems per tuber because older tubers developed more meristems. Also the vigour is stronger when the seed tuber is bigger (Struik and Wiersema, 1999). In Table 6 the characteristics of the seed tuber with different physiological ages is shown and the difference between old and young seed tubers is described. Old and young can also been seen as big and small seed tubers. Chronical older seed tubers are generally larger in size.

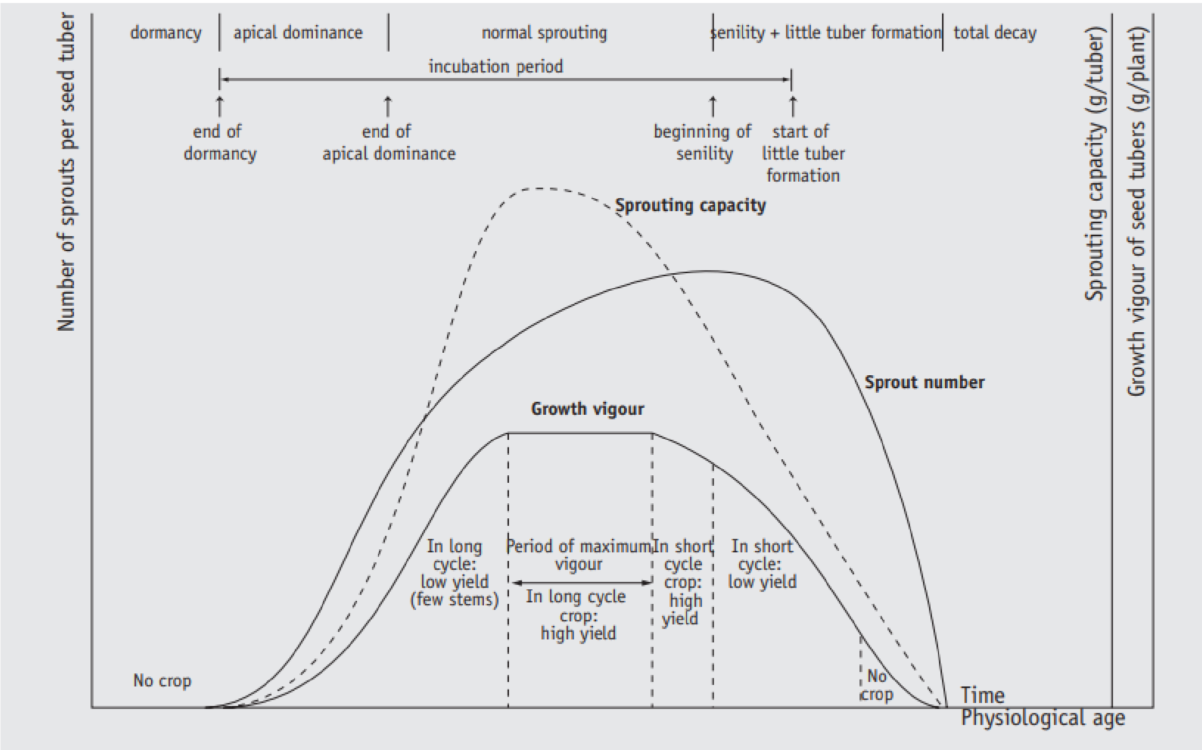


Figure 8: . Hypothetical scheme for the number of sprouts per seed tuber, the sprouting capacity of the seed tuber, and its growth vigour, as functions of chronological or physiological age (Struik and Wiersema, 1999)

Table 6: Quality characteristics of young and old seed tubers (source: Struik, unpublished).

	Young	**Old**
Time of emergence	Late	Early
Rate of emergence	Slower	Faster
Number of stems per seed tuber	Lower	Higher
Time of tuber initiation	Later	Earlier
Number of tuber per stem	Higher	Lower
Change of secondary growth	Lower	Higher
Canopy development	Exuberant	Poor
Tuber yield in short season	Lower	Higher
Tuber yield in long season	Higher	Lower
Maturity	Later	Earlier

2.3.2 Reduced tillage

The cultivation of potato is known as the cultivation with the highest risk to soil erosion. The combination of intensive soil preparation, hilling and soil disturbance during harvest makes it prone for soil degradation. Additionally, the soil coverage is short and the harvest index is high, which makes it even worse (Auerswald, 2006). Furthermore, intensive tillage decrease the organic matter in the soil. Even with a high input of organic matter the organic matter content is difficult to retain.

The global atmospheric carbon can be stored roughly two times in the total soil area (Conijn and Lesschen, 2015). Therefore, the carbon sequestration into agricultural soil is an important topic currently and will be the future (FAO, 2018; European commission, 2018). In Dutch agricultural soils, the organic matter decomposition is annually 2%, which is used as a rule of thumb. This is roughly between 2200 and 4000 kg/ha^{-1}. In the first year after organic matter input 5-80% of the carbon will be lost as CO_2. The organic matter part that remains after one year is the effective organic matter (EOM)(Conijn and Lesschen, 2015). There is a possibility that reduced tillage will be obligated in a certain degree in the future. Reducing the tillage can increase the soil organic matter rapidly. Research showed that in 2 – 5 years of reduced tillage the organic matter content can increase with 0.3 – 1.0% (van Balen and Haagsma, 2017; Wang, 2014). Furthermore, research showed that the soil nitrogen can increase with 50 kg/N/ha^{-1} from the start of reduced tillage management, annually. In this research from 2009 until 2016 the total stored nitrogen in the top layer (0-25 cm) was 400 kg/N/ha^{-1} (van Balen and Haagsma, 2017). Other benefits of reduced tillage are increase in microbes, soil structure and soil resilience.

The practical definition of reduced tillage is 100% ground coverage (cover crops), minimal tillage (shallow as possible) and crop rotation. Implementing reduced tillage seems to have two important benefits, but in the cultivation of potato there are major constrains. Especially, the ground coverage will leave a lot of crop residues, which are not incorporated into the soil. This has influence on the plant bed preparation for the next year. Crop residues can cause problems during planting and harvest and disturb the emergence. Also the weed and disease management will be more challenging (Collins *et al.*,2010) Furthermore, minimal tillage will have negative effect on the soil structure and soil conditions during the first couple of years. Ploughing and tillage is used in order to be able to plant earlier. The soil temperature will increase earlier, therefore, the soil will dry faster. Research in the Netherlands showed that the potato yield will decrease with 10% when reduced tillage is implemented (Drakopoulos 2014). Another research concluded that the yield reduction is 9% and reduced tillage results on average in smaller tubers (Padmos, 2011). A research in Washington (USA) concluded that the yield will not decrease in a reduced tillage rotation with potato-maize-maize. (Collins et al,. 2010).

2.4 Pests

Potato is the second most important arable crop after wheat in Europe and severely infested by many pathogens. Potatoes are threatened by several types of pests: bacteria, fungi, oomycetes, viruses and nematodes(Nicot *et al.*, 2005). Among these pathogens, two are extremely harmful in the current commercial potato production in the Netherlands: *Phytophthora infestans* (*P.infestans*) (late blight) and *Alternaria solani* (*A. solani*) (early blight). Early and late are terms related to the moment the pathogens affects the crops. However, it can happen that both diseases occur simultaneously causing serious damage (Secor & Gudmestad, 1999). As so, we consider these two pathogens to be most important in regards to yield limitations.

2.4.1 Phytophthora infestans

P. infestans is an Oomycete and if symptoms are visible on the potato crop, the production is compromised. *P. infestans* affects leaf tips and plant stems and can quickly spread (Larsen *et al.*, 2016). In ideal conditions *P. infestans* can complete the life cycle in 5 days. Once completed it produces spores that can be dispersed by water or wind and which can successively infect tubers. Tubers infected present different dark/grey patches that are brown beneath the peel (Govers, *et al.*, 1997). The rapid decay of tubers is often due to the concomitant conjunction of another pathogen *Pectobacterium carotovora* (Reiter, B. *et al.*, 2002). Moreover, tubers affected in early stages can apparently seem healthy and can easily affect the entire storage if adequate precautions are not taken. In the website of EuroBlight (http://euroblight.net/) it is possible to see the extension of *P. infestans* infection in the North of Europe in three different years (Figure 9). This figure shows that *P. infestans* is a globalized pathogen. The presence of infection is relatively homogeneous across this area (except for Germany), and the rate of infection differs from year to year.

Figure 9: Monitoring P. infestans in 2017 (left), 2016 (middle) and 2015 (right) in the area which include Belgium, The Netherland the South-east England. Each orange dot represent a potato field P. infestans was detected (http://euroblight.net/).

As mentioned, it is interesting to note that *P. infestans* it is barely detected in Germany.

2.4.2 Alternaria solani

A. solani can also cause significant damage to the potato production. *A.solani* is mainly soil borne plant pathogen fungus with a necrotrophic lifestyle (Shtienberg, 1996). Symptoms of early blight are visible on the leaves and on stems of potatoes. *A. solani* symptoms are small brown or black lesions which enlarge in humid environmental condition. Lesions which expand up to 10 mm in diameter have dark pigmented concentric rings characteristic of early blight. At this stage the entire leaf is dehisce and this directly affect the production of potatoes. In 2014 a survey was conducted to monitor the presence of *A. solani* in the Netherlands (Figure 10). Based on this survey the regions where the early bright was detected are mainly: Friesland, Drenthe, Zeeland, North Brabant and Limburg. These are the main regions for Dutch potato production (*Chapter 1*).

Figure 10: Results of the Monitoring in the Netherlands realised in 2014-2015. A. solani, (black dots) and in 2015 (orange dots) (http://euroblight.net/).

2.4.3 Regulation

Pesticides regulation European Union

In 2009 the European parliament established a framework of Community action to achieve the sustainable use of pesticides. This action was taken because of the severe consequences pesticides have in EU and around the world (Krupke, C. H., 2012). To concretely deal with this problem the Member States of EU agreed to adopt National Action Plans (NAPs) to implement the Directive for the first time by November 2012. These plans should contain quantitative objectives, targets, measurements and timetables to reduce the risks and impacts of pesticide use. These plans should be reviewed at least every five years. The Netherland identifies specific measures that Member States are required to include in their plans for proper implementation. The main actions relate to training of users, advisors and distributors, inspection of pesticide application equipment the prohibition of aerial spraying, limitation of pesticide use in sensitive areas, information and awareness raising about pesticide risks, systems for gathering information on pesticide acute poisoning incidents, as well as chronic poisoning developments, where available.

National crop protection plan

In the past decades, the Dutch arable and horticultural sector made much progress on sustainable way of production. Risks of the use of pesticides have decreased while water quality increased. This, without being at the expense of the sector itself. However, the quality of surface water is not yet as good as policy makers want it to be. Next to this, more attention is needed for the grower's safety that make use of crop protection chemicals, residents living around farms that apply pesticides and the population of wildlife insects such as bees (NOTA 2014). Therefore the Dutch government set up a new memorandum, called 'Gezonde Groei, Duurzame Oogst', towards 2023 which aims at a sustainable crop protection in the future. By then, all national and international targets concerning environment, water quality, food safety, human health and labour circumstances, will need to be accomplished by this action plan.

One of the main focus point this action plan is the use of integrated pest management. This integrated crop protection according to EU-standards for sustainability is defined as follows: ''the careful consideration of all available crop protection methods, followed by integration of appropriate measurements that prevents the development of harmful organisms, the use of crop protection mechanisms and other forms of intervention limited towards an economic and ecological responsible level''.

2.4.4 Pesticides in potato production

In 2016 an external scientific report called "Collection of pesticide application data in view of performing Environmental Risk Assessments for pesticides" was carried out (Garthwaite, 2016). This project was addressing the following questions: Are there effects of cumulative exposure to plant protection products? Which are the potential combined non-target effects of multiple applications of pesticides? To address these question surveys were carried out in 8 European countries. Among these members it is interesting to see the number of pesticides used in the Netherland and in Belgium for potatoes production and the number of spraying frequency in average (Table 6).

Table 6: average use of pesticides sample taken in 8 EU countries

EU Member State/crop	Average No of pesticides used	Average spraying frequency	Main pesticide type sprayed
NL oignons	42	21	Herbicide/fungicide
IT apples	41	26	Fungicide
IT wine grapes	38a	14	Fungicide
UK apples	37	17	Fungicide
NL potatoes	36	19	Fungicide
NL lettuces	30	9	Fungicide/insecticide
BE potatoes	29b	13	Fungicide

a Total No of pesticides used in wine grapes: 56; b Total No of pesticides used in BE potatoes: 42

It is remarkable to note that the number of pesticides used in Belgium for potato crops in average is lower than in the Netherland, as the number of spraying frequency. These data are even more interesting when compared with the number of active compounds in the products sold to the farmers. While the number of active compounds to protect potato crops are the same in Belgium and the Netherland, the number of products is different (Table 7). It might be suggested that in Belgium the higher number of pesticides product, containing different combination, has a higher impact on the pests in the fields, resulting in a reduction of number of times the crop is sprayed. However, further investigation should be conducted to explore if there is a causal effect relationship among these factors.

Table 7: Summary of the number of active substances, formulations and products uses on each crops surveyed for each county in 2013. AI= Active copound, PR= product.

fera

Collection of application data in view of performing ERA for pesticides

Crop type	BE		ES		GR		IT		LT		NL		PL		UK	
	AI	PR	AI	PR	AI	PR	AI	PR	AI	PR	AI	PR	AI	PR	AI	PR
Peppers					4	6										
Plums													16	16	7	9
Potatoes	44	86			5	5	8	6	36	38	42	45	32	38	45	95

<u>Future perspective</u>

With the introduction of Integrated Pest Management, crop protection entered a new chapter. The cultivation of plants were viewed differently. As we know, plants are complex and so are the interactions with pathogens. However, until now, current plant protection methods were viewed as a simple solution for a complex problem. Now we know, that these require complex solutions too. As pathogens continue to develop, the introduction of new chemical families stagnate. Furthermore, current chemical solutions reach their political, economic, technical and social boundaries. This development calls for a new and sustainable approach to crop protection.

<u>Spraying Interference Gene Silencing (SIGS)</u>

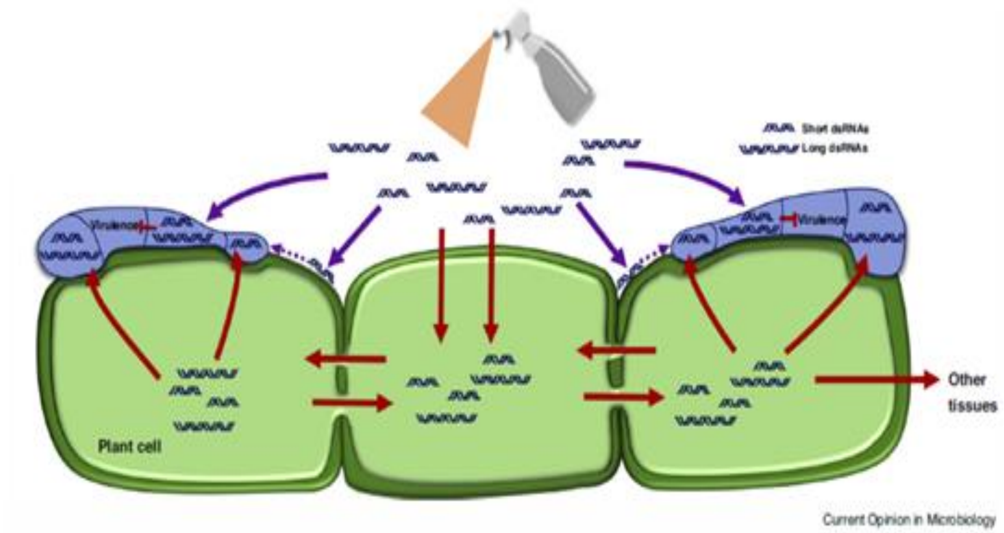
As previously mentioned the Member States of EU have as objective to introduce limitations on the use and application of the employed pesticides. Therefore, many efforts have been recently made to investigate a new type of pesticides based on Ribonucleic acid (RNA). External RNAs may be translocated into pathogens/pests by either direct or indirect mechanisms (Wang, Thomas, & Jin, 2017). This new generation of sustainable and environmentally friendly RNA-based fungicides can help reduce the yield loss caused by post-harvest damage as well as prevent the accumulation of toxic chemicals produced by pathogens. Spraying Interference Gene Silencing (SIGS) is a new power plant protection that can specifically target plant pathogens without collateral effects on other species. These small double stranded sequences of RNA have been designed to target the transcripts of pathogens in a highly specific way. In brief, the mechanism behind the SIGS technology is the following:

First small RNA double stranded RNA are sprayed on the plants. sRNA and dsRNA application can defend plants from pathogens up to 10 days after spraying (Fire *et al.*, 1998). This is due to the instability of RNA. However, recently it has been shown that when dsRNAs are incorporated into layered double hydroxide (LDH) clay nanosheets, the duration of protection against viral infection can extend to more than 20 days (Mitter, 2017). These nanosheets are called BioClay and prevent dsRNAs from being degraded by RNases or sunlight. Moreover, since the nanoparticles and the small RNA are non-toxic, they can be easily degraded.

Once the pathogen gets in contact with the plant the pathogen takes up these small RNA nanoparticles and by means of RNA interference (RNAi) mechanism it hampers its own growth (Figure 11). Several experiments have shown that this mechanism can protect plants from a wide range of pathogens. Transgenic crops expressing dsRNAs targeting essential and/or pathogenicity genes are more resistant to viruses, viroids, bacteria, fungi, oomycetes, nematodes, and insects.

This technique is an environmentally conscious method that improves the efficacy of plant disease management in the field using SIGS. However many research have to be lead to understand the molecular mechanism of mobile sRNA selection under different developmental and environmental conditions. Another limiting factor are the cost to produce this small RNA. However, in the future this problems might be solved by future approaches synthetic biology.

Figure 11: representation of SIGS. Small RNA are uptaken by the pathogen directly (purple arrows) or indirectly (red arrows).



2.5 Genetics

2.5.1 Hybrid potato production: a way forward in crop improvement
The potato exists in a varied level of ploidy, from diploid to hexaploid. Most of the diploid and pentaploids species are wild relatives and found in the periphery of the *Andes Mountains* region where the potato was originated. Recently, diploids species are generally used for potato breeding programs. Cultivated and wild relatives of potato species have a complex genetic structure which hinders the crop improvement program. Moreover, self-incompatibility during selfing in diploids and tetraploids limits the breeding activities. Nevertheless, most of the recent researches are concentrated in diploid breeding. Currently, there are over 200 wild species reported to be diploids and successfully employed in crossing with tetraploids (Watanabe, 2015).

Globally, the common cultivated potato species are tetraploids (2n=4x=48). The basic chromosome number of tetraploids is 12. The genetic complexity of a tetraploid species is more complicated than diploid species. Tetraploids have four sets of chromosomes whereas diploids potato plants have two sets of chromosomes per cell. As a result the probability of finding target parental gene in progeny populations is lower in tetraploids than diploids during crossing. In tetraploids, genomes exists in various auto tetraploid species like nulliplex (aaaa), simplex (Aaaa), (AAaa), triplex (AAAa), and quadruplex (AAAA) (Tiemens-Hulscher *et al.*, 2013). The genetic variations and heterozygosity in the subsequent offspring are the barriers in potato breeding. Hererozygosity of the offspring makes difficulties in the selection of target genes in potato improvement programs (Watanabe, 2015).

Use of a vegetative tuber is the common method of propagation in potatoes. Moreover, propagation is also possible through use of true seeds and tissue culture technique. Potato plants have over 45 fruits per plants (Arndt *et al.*, 1990) and each fruits bear approximately 200 true seeds (Huamari, 1992). During the selfing process the pollination causes segregation of desirable traits. If these desirable traits segregates the result is a heterozygous true seed. Heterozygous true seeds contain dissimilar pairs of alleles or genes. As a result growing potato using true seeds may not be uniform, distinct and stable which could affect the market value of the potato. Moreover, in these breeding activities it is very difficult to obtain homozygous lines if the parental is a tetraploid specie.

To increase the potato yield in the future, the development of diploid hybrid potato varieties will become a bigger priority. Research has reported that diploid hybrids achieve higher yields than cultivated species of tetraploids. Cubillos and Plaisted (1976) reported 15 to 17% more yield of F1 diploid hybrids over cultivated tetraploid (4X) species. However, the yield of F1 hybrid was reliant on the day length of the potato growing area. In contrary, Veilleux and Lauer (1981) reported comparable yield of parents and hybrids, however, hybrids showed more tuber numbers and a bigger size. De Jong and Tai (1977) reported a higher yield (17.8%) and showed superiority of all the tested traits in hybrids than cultivated potato varieties. However, obtaining hybrid potato varieties by crossing wild and tetraploids varieties is a lengthy process, and can take up to 15 years.

It is easier to achieve homozygous lines in of diploid varieties than in tetraploid ones (Comai, 2005). Therefore diploid varieties are used more and more in recent practices of potato breeding (Hajja, 2007). The tetraploids varieties, faces the problem of self-incompatibility in potato breeding. Recently, research showed that the problem of self-incompatibility in diploids can be solved by backcrossing with a homozygous progenitor having the *Sli* gene (Figure 12). This method helped to produce self-compatible offspring from the parents (Lindhout *et al.et al.*, 2011). At the same time grading tuber shape and size of obtained inbreed lines were necessary, because this helped in the fixation of the homozygous fixation of donor genes. Recently, the concept of an exotic library is the emerging concept for a crop improvement program. The valuable and desirable traits can be conserved in library and introgressed in cultivated species (Zamir, 2001). Similarly, in potato breeding the exotic library can make the breeding process easier, regarding resistance breeding and overall breeding in diploid potatoes. The exotic library is the gene bank of wild landraces of potato having the desirable traits for potato. The exotic library might help to maintain genetic variations in cultivated potato varieties which otherwise might be lost during domestication. Through introgression breeding techniques the desirable traits of the wild potato relatives can be identified whilst the undesirable traits can be removed.

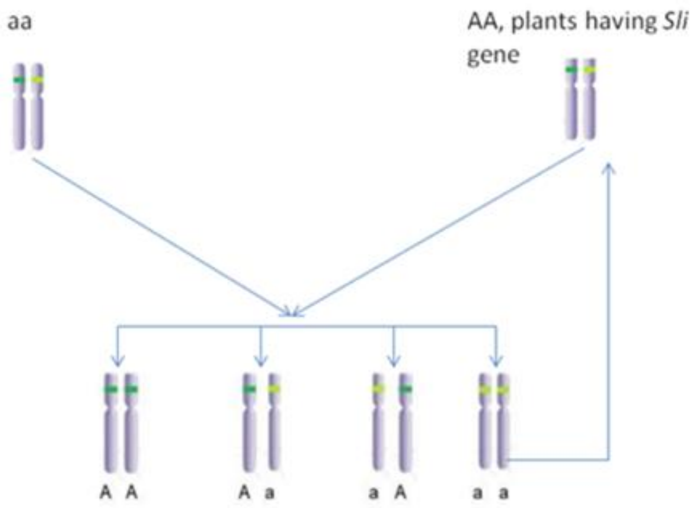


Figure 12 shows the methods of getting self-compatible offspring in diploid breeding programs. The produced offspring is backcrossed with the parent having the Sli gene.

2.5.2 Resistance breeding in potato

The potato is invaded by different biotic and abiotic agents. Biotic factors mainly include early and late blight diseases. Both of these disease are caused by fungus; *Alternaria solani* and *Phytophthora infestans,* respectively. The pathogen Phytophthora is a heterophilic fungus having mating type A1 and A2, and in Europe both mating types are prevalent (Drenth *et al.,* 1993, Hwang *et al.,* 2014). In the last 20 years, the pathogenicity of *Phytophthora infestans* has been increasing at an alarming rate (Turkensteen and Mulder, 1999). Currently, disease management in The Netherlands is done by applications of systemic fungicides. Chemical control can also be ineffective under favorable environmental conditions, since pathogens can multiply fast. Moreover, preventive and frequent applications of chemicals may lead to selection pressure for the pathogen (Cohen *et al.*, 2007). As a result, the pathogen develops resistance against chemicals. The resistance breeding in the potato crop is in an infant stage in The Netherlands. To tackle this problem, scientists have been introducing resistance genes in cultivated potatoes from wild potatoes, which *Solanum demissum* is one of them at the very beginning. They relied on the use of a single resistance gene. As the late blight pathogen is very virulent, they cause a quick breakdown of the introduced gene. This leads to susceptible potato plants again. Recently, more research focuses on introducing multiple genes in the same plant, this is called gene staking.

The source of the resistance gene in a wide array of wild potatoes is recently discovered (table 8). This durable resistance gene is now introduced in the current potatoes that farmers prefer to grow. Most of the donor wild potato plants are compatible for conventional or introgression breeding. Introducing genes through this approach is widely accepted. Moreover, for many genes listed in table 1, molecular markers have been already developed. This overview of genes makes it easier to breed new varieties with resistance characteristics.

2.5.3 Making potato farming resilient in future

In terms of consumption, the potato is the third most important food crop in the world and serves as the primary food in regions of the world with food insecurity (Visser *et al.*, 2009). In the Netherlands, potato is the major source of starch. However, the global temperature is increasing at an alarming rate and this might have an impact on this important crop. An increase in the likelihood of drought in the summer and increased intensity of daily precipitation has been predicted in the Netherlands (Hunk *et al.*, 2011). Therefore, the potato crop has to adapt to this change in climate conditions like drought, rise in temperature and precipitation, created by an increased carbon dioxide concentration (George *et al.*, 2018). Increasing carbon dioxide concentration in the atmosphere will enhance the potato yield.

The possible impact of climate change on the potato crop may be either biotic or abiotic stress. The abiotic stresses are likely to have negative impacts on the potato production. Therefore, future research should focus on genes and traits that can cope with the abiotic stresses created by climate change.

Table 8: resistance genes from different wild varieties

SN	Potato crop wild relatives	Reliant resistant gene	References
1	*Solanum bulbocastanum*	*Rpi-blb1, Rpi-blb2 and Rpi-blb3*	(van der Vossen *et al.,* 2003; van der Vossen *et al.,* 2005)
2	*Solanum berthaultii*	*Rpi-ber*	(Rauscher *et al.,* 2006)
3	*Solanum capsicibaccatum*	*Rpi-cap1*	(Jacobs *et al.*, 2010)
4	*Solanum microdontum*	*Rpi-mcd1*	(Tan *et al.,* 2008)

Chapter 3. Climate Change

In the future the climate will continue to change in The Netherlands. It is therefore important to anticipate on the coming changes in weather conditions. These change might result in potential dangers to grow crops, but can also provide interesting opportunities.

3.1 KNMI Climate Scenarios

In 2014 KNMI presented four different scenarios regarding the future climate change (Figure 13) that might be the case for The Netherlands. Even though they presented four different scenarios, they all have the following characteristics in common: increasing temperatures, an increasing amount and severity of precipitation in the winter. Furthermore, hail storms will get fiercer and there will be a small increase of sun radiation. The four different scenarios can be distinguished by the amount of increase in temperature (modest or warm) and the change in airflow pattern (low and high values). Figure 13 visualizes all the different scenarios. The scenarios that assume a modest increase in temperature expect an increase of 1 ˚C in 2050 compared to 2010. The other scenarios that assume a warmer climate expect an increase of at least 2 ˚C in 2050 compared to 2010. The scenarios that assume high value for the airflow show a bigger impact of the wind direction on weather conditions. High value scenarios predict more airflow coming from the west side of the country during the winter, causing a wetter climate. For the summers, more airflow will come from the east side resulting in warmer and dryer climate conditions. Low values scenarios, wherein the change in wind direction won´t be that big, predict colder and drier climate during the winter compared to the high value scenarios, summers will be cooler and more precipitation is predicted than the high value scenarios since the airflow comes mainly out of the west of the country.

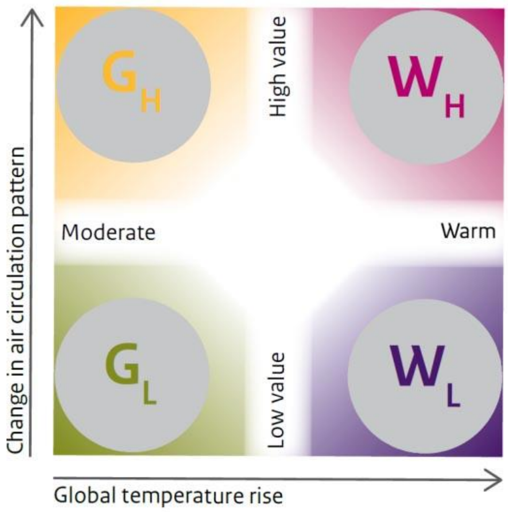


Figure 13. Four climates scenario predicted by KNMI for the Netherlands in 2050. L represents "..." W represents ".."

3.2 Potential limiting factors due to climate change

Trends

In the past 120 years the average global temperature raised with 0,8 C° due to the increase of greenhouse gases in the atmosphere. It is expected that this rising development will maintain in the coming decades. The greenhouse gases which have the highest potential to global warming are carbon dioxide, methane and nitrous oxide. Even though the average change in temperature seems small, the effect is has on weather conditions has a large significance. An higher atmospheric temperature means it can hold more water vapor. More water vapor means more clouds and thus higher chance of precipitation. Effects of climate change on crop production varies globally. For the Netherlands, the annual precipitation will be less gradually and more abrupt. Also, longer periods of drought will occur with a higher rate of radiation and winters will be warmer and wetter (IPCC, 2013). The bottom line is that weather conditions will be more extreme which will affect crop production in the Netherlands. A study which estimates the effects of future climate conditions on the yield of potato, showed that for the Netherlands, the yield potential will decrease with 20% when no adaptation measurements are taken. However, if growers do adapt, yield potential reduction will only be 10% (Hijmans, 2003).

3.2.1 Change of limiting factors due to climate change

Due to higher concentrations of CO_2 in the atmosphere, most crops will profit from this increase. However this yield increase mainly applies to sugar beets, whereas this effect is lower for potatoes (remains under debate) (Schaap et al, 2014). In Figure 14, the factors which define yield are visualized. Potential is defined by climatic abiotic factors plus crop characteristics. Thereafter, yield is defined by water and nutrients. Lastly, reducing factors such as weeds, pests and deceases determine final 'actual' yield (van Ittersum *et al.* 2003).

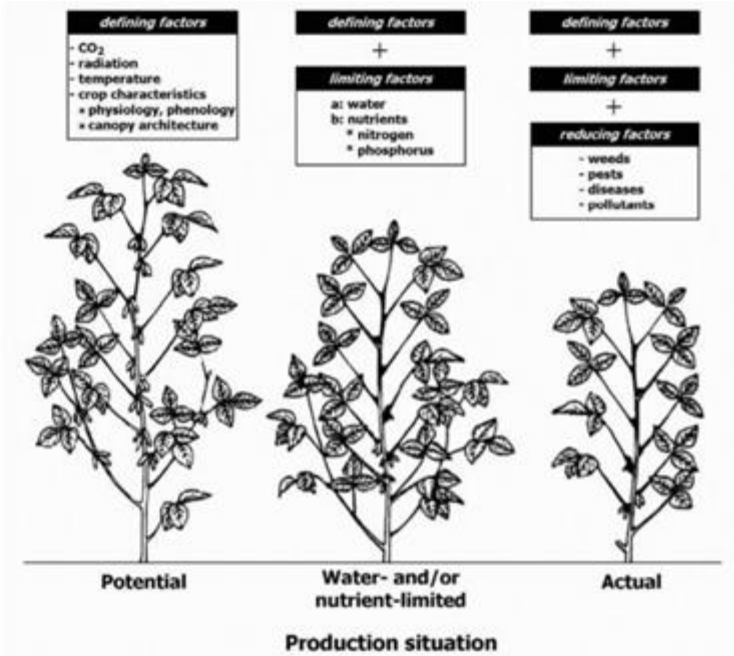


Figure 64 Factors that define yield (source: van Ittersum et al, 2003)

CO_2

One of the most important factor that determines the potential yield is CO_2 (van Ittersum *et al.* 2003). An increasing concentration of CO_2 in the atmosphere will lead to higher yields, especially for C3 crops.(Tubiello & Ewert, 2002). However, over the years, estimates of higher yields have decreased. Results on plant level, where smaller increases occurred, differed from result on field level. A different effect of the increasing CO_2 level is the higher water use efficiency of the crop. The closing stomata cause lower transpiration of the crop (Schaap *et al.* 2014, Balazs Varga *et al.* 2015). Even though estimates about the increase of yield have dropped, crop models show how dry matter yield of tubers increases with 22% for late cultivars and 29% for early cultivars when CO_2 in the atmosphere rises from 350 to 700 ppm in Dutch weather conditions (Schapendonk *et al.* 1995). This increase in yield is due to the increased concentration of intracellular CO_2. This enhances dry matter accumulation through more photosynthesis and, as mentioned before, reduces transpiration through smaller aperture of the stomata (Schapendonk *et al.* 2000). De Temmerman *et al.* (2002) described how the average yield of potatoes would increase with 20% (North Europe) assuming that the average temperature rises with 2 C° and atmospheric CO2 levels increase with 50%.

Precipitation and droughts

Globally, water vapor in the atmosphere increased from 1970 until now, as a consequence of a warmer temperature. Between 1910 and 2013, yearly Dutch precipitation increased with 26%. All seasons except for summer, became more wet. All climate scenarios shows that precipitation will increase with exception for the summers whereas here precipitation will be less even but more intense. Regionally, precipitation will likely not differ much in the Netherlands. Only a small amount of model calculations show a difference of 5-10% higher precipitation along the coast compared to inland provinces. However, most models do not show this and depend much on wind direction, temperature contrast between land and sea and temperature increase (KNMI, 2014). In the growing season of the potato, most precipitation will be more extreme. This has repercussions on the growth factors. Heavy rainfall in combination with higher temperatures creates appropriate conditions for fungi and other harmful plant pathogens, described in 'Pest and deceases', to develop. As for precipitation, droughts also seem to occur more frequently. With droughts, longer periods of precipitation shortage is meant. The importance of water is high in the cultivation. A lack of water during tuberization leads to significant yield losses as also described in Chapter 2.1 'Crop water'.

Temperature
Next to CO_2, temperature has a large influence on yield. Crops differ in their optimum growing temperature. However, for most crops this temperature is around 20 °C (Gobin, 2012). For potatoes, this temperature depends on cultivar and region (Koopman, 1995) but on average range from 18 to 21 C°. In the past 118 years, the average temperature in the Netherlands has increased from 8.9 °C to 11 °C. In longer periods of heat, soil temperature rises which cause an effect on the new formed tubers. This could cause 'second growth', a physiological phenomenon that causes the dormancy of the new tubers to be broken through which occurs in consequence of longer periods of high soil temperatures. This second growth could appear when the maximum temperature of the soil is higher than 25 °C for a few days in a row. New 'secondary' tubers will develop after temperature of the soil decreased in combination with rainfall (Kennisakker, *(doorwas in aardappelen*), 2018).

Pests and diseases
If the average temperature increases, it is likely that the growing season will extend. This will cause an effect on the lifecycles of many pests and diseases. The higher temperature causes a higher multiplication rate and the longer season provides a longer timeframe for multiplication. Therefore, more generations per season could arrive. Hannukkala *et al.* (2000) showed that late blight pressure between 1933 and 2002 increased along with the warming climate. The milder winters cause residual tubers to survive as hosts for pathogens, including *Phytophthora infestans*, which become harmful when the residual tubers emerges (Haverkort & Verhagen, 2008). A study carried out in Finland, showed that every increase of degree will lead to 4-7 day earlier late blight incidence and a 10-20 day longer time for the crop to be susceptible (Kaukaranta, 1996). It is estimated that the use of pesticides will be higher if pressure from diseases increases, which consequently offsets the gains of higher yields.
Next to fungi, pressure of nematodes and the Colorado beetle both contain high potential to increase with the current warming climate in the North of Europe. It is estimated that with an temperature rise of 2 C°, insects may have up to five more generations during one season (Yamamaura & Iritani, 1998). As temperature increases, so does biodiversity. This is due to the introduction of new insects because of appropriate climates. For insects, the population buildup is hard to predict. Awmack *et al.* (1997) discovered that this is due to the increase of vulnerability of aphids to natural enemies; ''as they become less responsive to alarm pheromones at high temperatures''.
Higher temperatures combined with an higher intensity of rainfall causes a higher chance of bacterial infections like soft rot or black leg, also known as '*Erwinia'*. These bacteria only multiply when environmental factors allow to. Which are wet conditions (during long contact with soil water) and high temperatures. Same is true for brown rot, which hardly overwinters in cool climates but can when winters are more mild. The heavy rainfall can help spread this disease from plant to plant.

Sea level rise
As temperature increases, temperature of seawater increases along. This makes water to expand and the sea level to rise. The average annual rise between 1901-2010 was 1,7 mm (KNMI, 2014). This resulted in a total rise of 19cm. For the Netherlands this has an effect on the salinization of soils along coast areas. As sea level rises, pressure on soil water increases and groundwater will rise and become more salty. Potatoes are relatively sensitive for salinity (Maas & Hoffman, 1997). Yields can decline when the crop is irrigated with surface water higher than 2 dS/m or drip irrigation of 3-4 dS/m (van Hoorn *et al.*, 1993, Sing *et al.*, 1978). Salty soils makes it harder for plants to absorb water therefore has strong potential for yield decrease.

3.3 Growing season

Current opportunities growing season

Haverkort and Verhagen (2008) mention in their publication 'Climate Change and Its Repercussions for the Potato Supply Chain' that the last decennia the effects of global warming are being perceived. The interview that was done with prof.dr.ir. P.C. Struik confirms this. He said that the growing season already has been extending for the last couple of decades. This phenomenon will continue since climate change will cause a decreasing number of freezing days and a lengthening of the growing season (Haverkort *et al.*, 2008). However, potato growers have not been able to benefit from this so far. Even though the conditions to start planting are considered to be good for the potato, farmers cannot enter their fields with their machinery. The past decades the machinery size has been increasing (Kutzbach, 2002), resulting in the requirement that soils need to be dry enough to enter the field. Entering fields under these humid soil conditions will inevitable damage their fields, even though the conditions are good enough for the potato to be planted. So potato growers still plant and harvest on the same dates as they used to do in the past.

According to the publication 'The effects of Climate Change in the Netherlands: 2012' the current growing season starts already 2 to 3 weeks earlier than in 1950, observed from 1997-2012. The assumption is that a longer growing season will increase the current yield. Dr. Ir. D.E. van der Zaag (1992) even states that yield of 70 to 80 tons per hectare is practically possible, provided that the potato is grown on high quality soil. Nowadays, some growers in The Netherlands obtain these high yields, however this is not common. Therefore, simulations are done with LINTUL POTATO DSS to predict more realistic yields for the Dutch average that can be obtained with a longer growing season. Assuming that farmers still plant and harvest on the exact same dates, 21 days of potential growth is not used so far. Based on data from 'Interprovinciaal proefcentrum voor de aardappelteelt' and Blauwer *et al.* (2014), we assume an average growth season of 137 days. Based on this, we assume an average planting date on 23rd of April (last week of April) and an average harvest date on 7th of September (first week of September). The number of days in between count up to 137 days. We assume that the day of haulm killing is also the day of harvesting. Depending on the practice the Dutch farmer uses, he can choose to spray the potato plants and kill the haulms or choose to mechanically remove the haulms. Either way the potato stops growing and yield does not increase anymore, so therefore the day of haulm killing is equal to the day of harvest. Each year the exact date for growers to start planting fluctuates, just like the harvest date. However, taking into account that the growing season now exists of 151 to 158 days and only 137 days are used so far. Literature shows us that the growing season actually starts 2 to 3 weeks earlier. So, considering the best scenario the planting date should be the 2nd of April. Especially the start is important, because benefit for the rest of the growing season (mainly summer months).

Yield estimation with longer growing season

The weather data which are used to carry out the simulation are obtained from the website of the KNMI. The average weather conditions of the years 2013 to 2017 are used in the simulation. For the simulation we only changed the value for the planting date, this is changed to 2nd of April. We kept the exact same values for all the other parameters as we used to estimate the potential yield in chapter 1. The simulation all estimate an increase in the yield potential. A planting date on the 7th of April shows an yield potential of 79.4 tons per hectare and a planting date on the 2nd of April shows an yield potential of 82.6 tons per hectare. The simulation done with the average planting date, 23rd of April, finds a yield potential of 72.4 tons per hectare, which is in line with the yield potential described in the first chapter. So an earlier planting date results in an yield increase of 9.7% and 14%, respectively.

Increased rainfall and insurance

This year, 2018, there have already been a few days with heavy rainfall in The Netherlands, especially in the south west of the country. This rainfall happened in early April. This might make farmers hesitant to actually start planting earlier, since short periods with heavy rainfall are getting more common. Heavy rainfall might damage the potatoes in such a way that the benefit of the extra yield is gone. However, KNMI estimated that such a heavy rainfall, 50-62 mm of rain in one day, only occurs once every ten years in The Netherlands. Furthermore, this heavy rainfall can also occur in other periods of the year, even in the summer when potatoes are fully grown. So this should not be a reason to start planting later than possible. Farmers can avoid this economical risk by insuring their crops.

In 2018, there are four insurance companies that provide the so called 'Brede Weersvezekering' for growers to insure their crops. These companies are: AgriVer B.A., Avéro Achmea, Interpolis, OFH / BFAO U.A. (only for fruit growers) and Vereinigte Hagel. Each insurance company has their own conditions that make clear when the insurance starts on the crops. From an interview with Agriver B.A. they told us that consumption potatoes are insured after 1st of March for South-West of The Netherlands and from the 1st of April for the rest of The Netherlands. Vereinigte Hagel has totally different insurance requirements. The insurance can be applied from the moment that the plant emerges. So when the potato plant is not yet growing, the potato planted field is not insured. For Avéro Achmea and Interpolis the crops are insured when the insurance accept the crop plan of the grower. This can be changed when an important weather forecast comes up, done by KNMI or Meteoconsult, then the insurance starts 24 hours later (Nieuwe oogst 2018, RVO 2018).

Future opportunities growing season

In the beginning of the chapter all the future scenarios regarding the climate change have been described. Since climate change will continue in the future and will affect the growing season and also other values for parameters that are important for growing crops, simulations are run to see how farmers might benefit from these changes in the future. The aim of the simulation is again to predict the yield in the future. The simulation was done for the year 2050.

In the subchapter trends it was mentioned that when growers do not adapt to the climate change that there is a potential of 20% decrease in yield. However, there will also be opportunities to benefit from climate change, apart from the temperature and CO2 increase. According to Ligtvoet *et al.* (2013) the growing season regarding the ecosystem and biodiversity will extend by 1 to 1.5 months in 2050 compared with 2000. Even though this only accounts for the ecosystem and biodiversity chapter, we assume that such an extension is a reasonable assumption to also happen in agriculture. For the simulation an extension of the growing season with 5 weeks is assumed, so in total 35 more growing days. Adding the current amount of growing days to this extension makes the growing season in 2050 counting of 172 days. The lowest prediction in an increase of 1 degrees Celsius, the other assumes an increase of 2 degrees. And since these are only estimations the average was take to run the simulation. with an average additional temperature of 1.5 degrees.

Four simulations were run, since it is unclear in what way the growing season will extend. It might start earlier or only end later. Again, the reference dates of 23rd of April as planting date and harvest date of 7th of September is assumed. Therefore, one simulation was done with an earlier start of the growing season of two weeks and a harvest date 3 weeks later. The second simulation was done with a planting date 3 weeks earlier, so 2nd of April and a harvest date of two weeks later, so 21 September. Both possibilities were tested with the KNMI scenarios, the scenario that assumes a modest increase in temperature with low values for the airflow pattern and the scenario that assumes a warmer temperature increase with high values for the airflow pattern.

Changed parameters

The following parameters that are included in the model will be different in 2050 than the current values:

-*CO_2* will be increased from 400 ppm to 550 ppm (Haverkort, Franke, Engelbrecht and Steyn, 2013). However, since CO_2 is not a variable that can be adjusted, we assume that the light use efficiency of the potato in 2050 increases from 1.25 to 1.55. This is based on research that discovered that an increase in the CO_2 concentration will result in an increased radiation use efficiency with 0.002 gMJ^{-1} ppm CO_2^{-1} (Haverkort *et al.*, 2013).

-For the simulation it is assumed that the *temperature* increases for the whole year average with 0.9 degrees Celsius (modest, low values scenario) and 2.6 degrees Celsius (warm, high values scenario).

-Regarding the precipitation, the whole year averages are increased with +3% for the modest, low values scenario. For the warm, high values scenario the averages were decreases with -2%

The average weather values of the years 2013-2017 are used to complete the estimated weather values in 2050.

Results

In table 9 the results of the four simulations are shown. In both scenarios the yield potential will increase with at least 30 tons if growers are able to benefit from this extension of the growing season compared with the yield potential growers can achieve nowadays if they make use of the whole growing season. For simulation two and four, the model showed that the potato plant would have water stress if no irrigation is available. This would then result in a reduction of 0.1 ton per hectare and 0.7 ton per hectare, respectively. What the table also shows us is that the especially the length of the growing season is important. The actual date when the growing season starts or ends does not influence the yield potential in a significant way.

Table 9. Results of the four climate scenario simulations

	Planting date	Harvest date	Temperature (˚C)	Precipitation	Yield potential (tons/hectare)
Simulation 1 (modest, low values)	2 weeks earlier (9th april)	3 weeks later (28 september)	+0.9	+3%	113.8
Simulation 2 (warm, high values)	2 weeks earlier (9th april)	3 weeks later (28 september)	+2.6	-2%	114.0
Simulation 3 (modest, low values)	3 weeks earlier (2th april)	2 weeks later (21 september)	+0.9	+3%	114.3
Simulation 4 (warm, high values)	3 weeks earlier (2th april)	2 weeks later (21 september)	+2.6	-2%	115

Insurance

Since heavier rainfalls will be common around 2050 this might be a bigger problem in future, since there is an increase in risk that this precipitation will occur in early spring. Increase in this risk will therefore result in higher insurance cost. It will be more challenging to benefit from an earlier starting date of the growing season, since farmers might outweigh the extra yield against the increased financial risk.

Chapter 4. Discussion

This report focused on the assessment of limiting factors within the consumption potato cultivation, including recommendations and a future outlook of the Dutch potato sector. The main findings in literature research are described in chapters 1 and 2 of this report. In the discussion the limitations of this consultancy project are mentioned. Also the constraints of the found literature related to the yield improvement are discussed in this chapter. The overall limitation of the project was the short time frame. In some topics, no clear researches were found so assumptions had to be made.

The LINTUL-POTATO-DSS model was employed to estimate the impact of different factors on the yield. The conditions which were set resemble the conditions of the last 5 years in the Netherlands, including weather data. The model is used as a base for the report regarding limiting factors however the model is a simplification of reality since just a limited number of factors are considered. This might exclude important factors and if not adjusted correctly to real life experiments, it gives unreliable results. The limited number of factors also makes it hard to translate into the input variables of farmers. A sensitivity analysis was conducted to estimate the impact of each factor on the final yield. The sensitivity analyses in the report have been done at country level, which currently neglects the regional differences between regions. If farmers want specific advice based on their region, an additional review of the found results should be made region specific. The main limitation of the model itself was the inability to modify parameters related to water. The ET and precipitation meet each other in several years and could not be changed within our capabilities. While experts and farmers interviewed explicitly noted that water is one of the lacking factors of why the potential is not reached. The reason behind this might be that the calculated ET of the potato crop does not correspond to the actual ET of the crop. Furthermore, there were a limited amount of parameters that could be changed. Therefore, not all of the desired limiting factors are analyzed in the model.

In the chapter 2.1, researches were reviewed to investigate the impact of water management on the yield. More specifically, a direct correlation between the yield (loss) and the ET was found. However, these researches have been conducted in other than Dutch conditions, which might give a distorted comparison. Thus a calculation was made to estimate the water usage of the potato crop in the Netherlands. The model was used, which includes an ET equation and the climate data of the Netherlands. The model used however, is still considered an oversimplification of reality. Thus the results should be considered on their validation. Therefore, to confirm this results, field experiments should be followed. This experiment should be designed to measure the ET of a potato crop throughout the season under Dutch climate conditions taken both irrigation and no irrigation into account. Also no expert on water delivery was contacted during the research, who might have given more in depth insights in processes related the water in the potato crop due to the limited amount of time.

In chapter 2.2 it was investigated in which amount fertilizers can have an impact on yield. Only the nitrogen requirements and legislation are taken into account, excluding other nutrients due to of lack time and proper literature. Many experiments on nitrogen fertilization gave a wide variation between the optimal kilogram of nitrogen per hectare to obtain the highest yield. No consistency was found within these results which makes it hard to make a clear advice.

Chapter 2.3 includes reduced tillage. The used research predicts a yield loss of about 10%. However, this loss cannot directly be related to the tillage part as many other factors may have influenced this outcome. To give a reliable answer on the effect of reduced tillage on the potato yield, a monitoring experiment with a minimum length of 10 years should be constructed to observe the effects of reduced tillage on the potato yield.

Chapter 2.4 includes the number of active compounds of pesticides, the type of pesticides products and the number of applications of pesticides were compared between the Netherlands and Belgium. By observing the data it was inferred that the pesticide management in the Netherland could be improved by imitating the pesticide management of Belgium. Based on the opinion of Professor S. van Heusden and of H. Bouma, an expert of pesticides in BASF, the number of pesticides application in the Netherland has already been reduced up to the minimal optimum. Therefore, the difference in application pesticides frequency might be explained by other causes, as a higher incidence of occurrence of pests. In the report there were also differences observed in the occurrence of P. infestans in Germany compared to the Netherlands. It might be suggested that the different type of pest management in Germany is the reason of these differences. However, it was not possible to investigate this, since it is not clear whether the absence of this pathogen is due to a lack of surveys or due to a different type of pest control management. Further investigation should be done in order to answer these questions to optimize the pest management in The Netherlands.

Chapter 2.5 compares the diploid and tetraploid potatoes. The comparison between yield may give an distorted view between the two types of breeding. As the yield increase of diploid species might not be related to the ploidy level, but to the decrease of several limiting factors which diploids can be bred against. Examples are drought resilience and pest resilience. Thus the genetics do not play a direct role on the increase of potato yield. However, genetics indirectly have a big impact on the yield by increasing the risk of surviving different pests and diseases.

In the chapter 3 'climate change', the predicted weather data of the year 2050 was taken into consideration. The influence of the increase of the CO2 concentration was discussed and modelled. No such input variable as CO2 is present in the model, thus the assumption was made that the CO2 concentration has an influence on the radiation use efficiency, which actually can be adjusted in the model. This assumption may not be as accurate as the relation between the increase of CO2 and radiation use efficiency, because it might not be as efficient as actually putting CO2 in the model as a input variable. Furthermore, water has not been shown as a limiting factor in the model while literature review did show it as a limiting factor. Predictions about the effect of water in the future (2050 scenario) on the potato yield cannot be simulated by the model, it probably will be worse in the future than the model actually predicts. Also, when the temperature was increased in the simulation, the ET was not increased due to too complicated recalculations that then should have been made, time limitations did not allow us to do this. The outcome of an increased yield that already can be achieved next year is about 8.6 tons per ha. This increase is due to an increased growing season length. However, the increased length of the growing season might bring other limiting factors with itself which now cannot be foreseen. Other threads might occur that might decrease the yield on itself.

Chapter 5. Conclusion

In this chapter we conclude our findings. This is done by splitting the main research question in to sub questions.

Main research question:

How to increase the Dutch potato yield?

In the past 30 years, there have been multiple reasons for the consumer potato yield to stagnate. This had to do with many factors which changed and reshaped over time. Such factors were, different breeding programs, regulations, climate factors, trade programs, technology improvements, consumer wishes, different farm practices etc. These factors made it so that yield increased in one region while it did not in others, creating one steady yield average over the last 25 years. Increasing this average cannot be done with only one improvement but asks for a combination of practices where all stakeholders in the production chain are involved with. This means an appropriate breeding program including new technologies, a better physiological understanding of the crop, farming practices that cope with climate change, trading houses and processers that are willing to switch to resilient sustainable cultivars, regulation which allow new technologies, until the changing mindset of the consumer. All parties within the chain can have an influence on the future yield of the potato. However in this report we attempted to answer this main research questions with the described sub questions and concluded the following:

What is the yield potential of the consumer potatoes in the Netherlands?

The literature research shows different consumer potato yield potential values. Vasco *et al.* (2017) calculated 72.6 t of potato ha^{-1} while Haverkort and Struik (2015) modelled a potential yield of 90 t ha^{-1}. Through the use of the model LINTUL-POTATO-DSS a potential yield of 72.4 t ha^{-1} was achieved. However the average actual yield in The Netherlands is significantly lower than the potential yield.

Which factors are most limiting and therefore have the most potential to increase the Dutch potato yield?

Interviews with different stakeholders, modelling and the literature research showed that the main yield limiting factors in potato production grown under Dutch conditions are:

- Water stress
- Plant diseases
- Nitrogen fertilizers
- Breeding and genetics
- Seed tuber
- Tuberization
- Planting depth
- Season length

How does climate change influence the potato yield?

In the future, it is expected that the temperature and CO_2 concentration will increase, while a more erratic and intense precipitations. If potato cultivation in The Netherlands adapts to this scenario a higher yield can be achieved, since potato growers can benefit from the changing climate conditions. Nevertheless, pest pressure and sea level rise may become a threat for the potato production.

What could be possible constraints of future regulations on agrochemical inputs?
For fertilization, in future it might be possible that the legislations get tightened. If the maximum allowed amount of nitrogen application gets decreased, the yield potential might only be reached with cultivars which are highly nitrogen efficient.

What can be done by the sector to tackle limiting factors?
Transpiration is essential to achieve high potato yields. Improving and maintaining soil properties influence positively water storage in the field and water uptake by the crop.
Water availability and soil temperatures around 18°C are needed to achieve a proper tuberization process. Watering and soil cover by the crop are good strategies to maintain suitable soil temperatures for tuberization.
The physiological age of the seed tuber is related to several factors of crop development. Tuber physiological age assessments and ranks should be carried out by seed potato growers. Moreover, these should be transmitted to consumer potato growers before buying the seed potatoes.

There is a lack of knowledge in potato nutrients demand other than potassium or nitrogen. Nitrogen is a nutrient that can be lost very easily form the soil affecting the environment (eutrophication and greenhouse gases). Drip irrigation could bring a higher application uniformity and could help to increase nitrogen uptake.
Breeding is an essential tool to improve the potato crop overall. First of all, using diploid breeding can help to enhance the potato yield. Secondly, breeding can help to get durable resistance against yield threatening pathogen such as phytophthora. And finally through breeding, resilience can be built in the potato to adapt to the climate conditions in the future.

What can growers do in the future to cope with climate change related conditions and regulations?
Potato yield could be increased through a longer growing season. However, machinery and management practices should be adapted in accordance. Furthermore, insurance companies and growers should negotiate with the help of the Brancheorganisatie Akkerbouw about the conditions for the insurance policies in order to take advantage of a longer season.

How can growers be prepared for possible future regulations on agrochemical inputs?
If growers apply drip irrigation in combination with the application of nitrogen. The damage to environment and contamination of surface water will be minimize. As leaching of nitrogen to the environment will be nihil with drip irrigation, the legislation of the maximum amount of nitrogen can even be increased.

Chapter 6. Advice

Literature and interviews confirm that there is a yield gap in the current potato production and the potential potato yield production in the Netherlands. There can be made short and long term improvements in order to increase the potato yield. Tackling limiting factors like, water, growing season length, pest management and seed tuber quality can increase the potato yield in short period of time. In the future the potato yield can be increased by improving soil quality, taking advantage of the climate change and the use of new cultivars including diploids.

4.1 Water management

Big improvements can be made if the potato crop can transpire optimally (water demand). The yield is positively related to transpiration and therefore growers should optimize their irrigation to maximize the ET of their crop. To be able to follow the crop demand plant measurements can easily be done. There are multiple options to measure early plant stress (reduced transpiration), for example ET, soil water tension, leaf temperature and stomata conductance. Suppliers of these techniques should make this more accessible for the growers and growers should invest more in these remote sensing techniques.

Our advice to growers and remote sensing suppliers is to develop a measuring system that calculated the ET of the crop on a daily bases. Together with weather forecast a software program calculate when, where and how much the growers should irrigate. To follow the exact water demand of the crop, the best method to apply water is to use drip irrigation. Drip irrigation has the ability to supply the right amount of water and fertilizer on the right moment. Therefore, the water use efficiency and nitrogen use efficiency (NUE) will increase as less nitrogen will leach away. Out of the total amount of fertilizer applied, the plant will take up a higher percentage. This will lead to an increase of the NUE compared to manure or synthetic fertilizer. Drip irrigation also lowers the soil temperature, which is beneficial for tuberization. Furthermore, it might reduce the pest pressure, as the leaves will not become wet when irrigating via drip irrigation. Our advice is to standardize drip irrigation in the potato cultivation, if it is economically feasible.

Additionally, growers need to manage large amount of rain fall more frequently in the future. Our advice to the growers is to install subsurface drainage and growers should level their soils to prepare for the heavy rainfall periods predicted in the future. Also the planting strategy should be that the potato furrows are in the same direction as the field descends. The head lands should not be planted, which result in a better run off of water. This in combination with the erosion/manure regulation.

4.2 Fertilizing

If drip irrigation is applied in the Dutch potato sector together with fertigation, the government should recheck the application laws of nitrogen and phosphorus. As the main bulk of application will be spread throughout the season, less leaching will occur benefiting the environment. To precisely apply nitrogen and other nutrients on the crops demand, fertilizing companies together with Wageningen University should research the crops demand of certain nutrients throughout the seasons and its different growing stages.

4.3 Growing management

The extension of the growing season is a realistic opportunity to increase the yield. To be able to make use of the current whole growing season, growers should start planting as early as possible. Weather data shows that it is possible to plant earlier, however growers are not able to enter their fields earlier due to the combination of heavy machinery and wet field conditions. The advice for this is to use smaller equipment and develop autonomous vehicles. Since farm equipment is too heavy to enter wet fields, growers should prevent this as much as possible. Our conceptual idea to deal with wet fields is as following: Two reels on each side of the field, pulling a cable which holds sowing/planting/ploughing etc equipment. This way field application can always be done, no matter what the field conditions are. This idea is especially suitable for Flevoland, where large fields all have the shape of a rectangle. Furthermore, in Flevoland the main soil is clay, which can be wet in the early spring, making it even more difficult for these growers to start planting compared to growers that grow crops on sandy soils. The actual possibilities to get this idea working in practice needs further development (Figure 15).

Also the soil quality and structure need to be improved in order to get rid of excess water in the spring and fall as fast as possible. Growers should increase the soil organic matter in all possible ways. Organic matter does not specifically increase the yield, but the additional side effects are really powerful, which makes the soil more productive and resilient. Moreover, reduced tillage can become a regulation in the future, but it is still uncertain. In order to be prepared for a certain reduced tillage regulation organic matter content should also be increase in this situation. If the organic matter content is higher it will minimize the cons of reduced tillage in the first years.

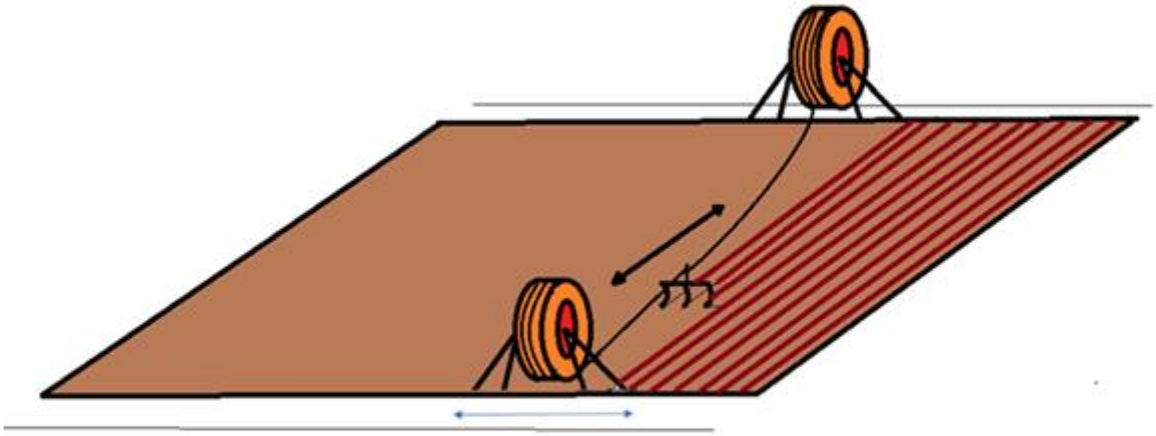


Figure 15. visual explanation of conceptual idea

When seed growers accurately and reliably manipulate the seed tuber physiological age, the farmers will have powerful knowledge to influence the earliness of their crop, independent of the maturity class of the cultivar grown. They can also influence the time of completion of the crop cycle, the average tuber size and tuber size distribution. This is not yet monitored, but if seed growers start doing this, there needs to be a way to exchange this information with the potato growers. Therefore, we advise that seed potato growers should grow seed tubers for a specific cultivation strategy for the potato farmers. We also advise that seed potato growers should work together with NAK to develop a seed tuber quality index. There is a gap in the information exchange of seed tuber quality between farmers and seed potato growers. The information which the growers get from the seed potato producers is in generally only the cultivar, tuber size category and where the seed tuber is grown. By exchanging the quality of the seed tuber more precisely, the grower is able to adapt their cultivation strategy based on the tubers qualities. They should come up with a quality index per cultivar grown in a specific cultivation condition. If the growers can adapt their strategy to their seed potatoes, the yield can be increased. As the seed potatoes can grow more into their potential. Therefore, we advise the ware potato growers to buy their seed potatoes with a specific quality that fits within their cultivation strategy. Additionally, ware potato growers should minimize the time between receiving the seed tubers and planting.

4.4 Pest

Growers have to focus on new and up-to-date methods of crop protection. With the rapid development of precision agriculture systems, decision support systems also continue to show its usability. For the application of pesticides to fightPphytophthora, these systems advise the grower on the optimum timing for application based on near future weather predictions. These systems give insight on multiple aspects of pest management like, actual weather data, what the weather will be, whether the crop is protected or not, when to apply pesticides and what pesticide to use. These systems help farmers to plan their pest management in order to prevent unnecessary applications or to prevent outbreak or further development of the decease. Therefore, these advisory systems work preventive, curative and palliative for the grower and environment. Currently available and adopted systems for the Dutch potato growers are: Akkerweb Phytophthora, Dacom disease management, and GewisOpticrop. Since these systems require an annual payment in order to use it, they might seem less attractive for farmers. Branch organisation Arable Farming could motivate farmers to use these products or arrange government funding. Additional advice for growers is to extent the crop rotation. Furthermore, retailers and supermarkets should allow the growers to grow blight resistance cultivars, regardless of the marketing strength of old well known cultivars, which are not resistant.

4.5 Genetics

Diploid hybrid breeding seems to be promising. The Dutch potato breeding companies are very busy with this new method of potato breeding and propagation. We advise the breeding companies to continue develop and innovate the diploid hybrid breeding. They have to focus on disease resistance (especially Phytopthora), drought resistance and resistance against waterlogging (biotic factors).Another advice is to establish an exotic library with a gene bank of wild species. This could help in hybrid potato production having durable resistance traits. However, to get potato varieties with complete resistance against the pathogen may takes up to 50 years. Furthermore, they have to keep in mind the climate change and breed cultivars that are suitable for longer growing seasons, including cultivars with higher light use efficiency and nitrogen use efficiency. This makes the new cultivars resilient against the future climate.

Acknowledgements

This report would not have been established without the help of several people. Therefore, we would like to thank Willemien Lommen, Paul Struik, Sjaak van Heusden and Pietrick Reitsma for sharing their knowledge with us during interviews. Furthermore, we would also like to thank Annette Pronk from Wageningen Plant research for providing the LINTUL-POTATO-DSS model. With the help of Martine Nieboer we increased the group work efficiency, which helped a lot to come to a better end result. Finally, we would like to thank all the other people who were involved in this project.

References

- *** Rassenproef CONSUMPTIEAARDAPPELEN
- *** Verzekeringspolis - Brede Weersverzekering - Avéro Achmea
- *** Verzekeringspolis - Brede Weersverzekering – Interpolis

A

- Arndt, G. C., & Peloquin, S. J. (1990). The identification and evaluation of hybrid plants among open pollinated tkue seed families. American Potato Journal, 67(7), 393-404.
- Arndt, G. C., Rueda, J. L., Kidane-Mariam, H. M., & Peloquin, S. J. (1990). Pollen fertility in relation to open pollinated true seed production in potatoes. American Potato Journal, 67(8), 499-505.
- Auerswald, K., Gerl, G., & Kainz, M. (2006). Influence of cropping system on harvest erosion under potato. Soil and Tillage Research, 89(1), 22-34.
- AWMACK, C., WOODCOCK, C., & Harrington, R. (1997). Climate change may increase vulnerability of aphids to natural enemies. Ecological Entomology, 22(3), 366-368.

B

- Blauwer, De V., Cauffman, D., Demeyere, A., Eeckhout, I., Martens, D., Vermeulen, P. (2014). Opbrengst en kwaliteit van (half)vroege en late rassen. Landbouwcentrum Aardappelen.
- Boerenbusiness. (2015, Septembre 1). Waterscahp frustreert verzopen aardappeltelers. Opgehaald van www.boerenbusiness.nl: http://www.boerenbusiness.nl/aardappelen/artikel/10865511/waterschap-frustreert-verzopen-aardappeltelers
- Bus, C. B., Struik, P., & Veerman, A. (2004). Sturen van de sortering van aardappelen. Kennisakker. nl, 2004(15 dec.).

C

- Carli, C., Yuldashev, F., Khalikov, D., Condori, B., Mares, V., & Monneveux, P. (2014). Effect of different irrigation regimes on yield, water use efficiency and quality of potato (Solanum tuberosum L.) in the lowlands of Tashkent, Uzbekistan: a field and modeling perspective. Field Crops Research, 163, 90-99.
- CBS2018:statline.cbs.nl/Statweb/selection/?VW=T&DM=SLEN&PA=7100ENG&D1=a&D2=18&D3=12-16&D4=a&LA=EN&HDR=G3,G2,T&STB=G1
- CBS, PBL, RIVM, WUR (2018). Jaarlijkse hoeveelheid neerslag in Nederland, 1910-2017(indicator 0508, versie 07 , 25 april 2018). www.clo.nl. Centraal Bureau voor de Statistiek (CBS), Den Haag; PBL Planbureau voor de Leefomgeving, Den Haag; RIVM Rijksinstituut voor Volksgezondheid en Milieu, Bilthoven; en Wageningen University and Research, Wageningen.

• Cohen, Y., Rubin, E., Hadad, T., Gotlieb, D., Sierotzki, H., & Gisi, U. (2007). Sensitivity of Phytophthora infestans to mandipropamid and the effect of enforced selection pressure in the field. Plant Pathology, 56(5), 836-842.

• Collins, H. P., Alva, A. K., & Boydston, R. (2010). Reduced tillage in an irrigated potato rotation. CSANR research report, 1, 1-18.

• Comai, L. (2005). The advantages and disadvantages of being polyploid. Nature reviews genetics, 6(11), 836.

• Conijn, J.G., Lesschen, J.P. (2015). Soil organic matter in the Netherlands. Plant research Wageningen and Alterra

• Cubillos, A. G., & Plaisted, R. L. (1976). Heterosis for yield in hybrids betweenS. tuberosum ssp. tuberosum and tuberosum ssp. andigena. American Potato Journal, 53(4), 143-150.

D

• Dam, J. v. (2009). Salinity Control. Wageningen: IWE-30806: Water Delivery.

• De Jong, H., & Tai, G. C. C. (1977). Analysis of tetraploid-diploid hybrids in cultivated potatoes. Potato Research, 20(2), 111-121.

• De Temmerman, L., Hacour, A., & Guns, M. (2002). Changing climate and potential impacts on potato yield and quality 'CHIP': introduction, aims and methodology. European journal of agronomy, 17(4), 233-242.

• Dekkers, W. (2000). Beregenen van akkerbouw- en vollegrondsgroente- gewassen. Lelystad: PPO sector AGV.

• Dijk, W. v., Berge, H. t., Dam, A. v., Schoot, J. v., Geel, W. v., & Burgers, S. (2007). Effecten van een verlaagde stikstofbemesting op marktbare opbrengst en stikstofopname van akker- en tuinbouwgewassen. AGV: Praktijkonderzoek Plant & Omgeving B.V.

• Dijk, W. v., L., K., & Reuler, H. v. (2005). Verkenning gebiedsgerichte gebruiksnormen akker- en tuinbouwgewassen op zandgrond. Wageningen: Praktijkonderzoek Plant & Omgeving B.V.

• Drakopoulos, D. (2014). Influence of reduced tillage and organic amendments on an organic potato production system. Wageningen University, the Netherlands.

• Drenth, A., Turkensteen, L. J., & Govers, F. (1993). The occurrence of the A2 mating type of Phytophthora infestans in the Netherlands; significance and consequences. Netherlands Journal of Plant Pathology, 99(3), 57-67.

E

• Eck, H. J. (2011). Towards F1 hybrid seed potato breeding. Potato Res, 54, 301312Livak.

• Eeckhout, I. & Goeminne, M. (2012). Rassenproef consumptieaardappelen. Interprovinciaal Proefcentrum voor de Aardappelteelt.

• Evenhuis, A., Spits, H. G., & Schepers, H. T. A. M. (2008, April). Strategies to control late blight in potatoes in Europe. In III International Late Blight Conference 834 (pp. 79-82).

F

• FAO, (2008). Potato and water resource. International year of the potato 2008.

• FAO, (2018). What is soil carbon sequestration. European Commission, (2018). Carbon capture and storage.

• Fire, A., Xu, S., Montgomery, M. K., Kostas, S. A., Driver, S. E., & Mello, C. C. (1998). Potent and specific genetic interference by double-stranded RNA in Caenorhabditis elegans. nature, 391(6669), 806.

• Flier, W. G., & Turkensteen, L. J. (1999). Foliar aggressiveness of Phytophthora infestans in three potato growing regions in the Netherlands. European Journal of Plant Pathology, 105(4), 381-388.

• Fraters, B., Boumans, L., Leeuwen, T. v., & Reijs, J. (2007). De uitspoeling van het stikstofoverschot naar grond- en oppervlaktewater op landbouwbedrijven. Bilthoven: RIVM.

G

• Garthwaite, D., Sinclair, C., Glass, R., Pote, A., Trevisan, M., Sacchettini, G., ... & Charistou, A. (2015). Collection of pesticide application data in view of performing Environmental Risk Assessments for pesticides. EFSA Supporting Publications, 12(7).

• Geel, J. v. (2018, June 6). Bedrijfsbezoek akkerbouwbedrijf van Geel. (H. Jonkergouw, Interviewer)

• George, T. S., Taylor, M. A., Dodd, I. C., & White, P. J. (2018). Climate Change and Consequences for Potato Production: a Review of Tolerance to Emerging Abiotic Stress. Potato Research, 1-30.

• Gobin, A. (2012). Impact of heat and drought stress on arable crop production in Belgium. Natural Hazards and Earth System Sciences, 12(6), 1911-1922.

• Govers, F., Drenth, A., & Pieterse, C. M. J. (1997). The potato late blight pathogen Phytophthora infestans and other pathogenic oomycota. In Plant Relationships Part B (pp. 17-36). Springer, Berlin, Heidelberg.

H

• Haas, B. J., Kamoun, S., Zody, M. C., Jiang, R. H., Handsaker, R. E., Cano, L. M., ... & Bozkurt, T. O. (2009). Genome sequence and analysis of the Irish potato famine pathogen Phytophthora infestans. Nature, 461(7262), 393.

• Hajjar, R., & Hodgkin, T. (2007). The use of wild relatives in crop improvement: a survey of developments over the last 20 years. Euphytica, 156(1-2), 1-13.

• Hannukkala, A. O., Kaukoranta, T., Lehtinen, A., & Rahkonen, A. (2007). Late-blight epidemics on potato in Finland, 1933–2002; increased and earlier occurrence of epidemics associated with climate change and lack of rotation. Plant Pathology, 56(1), 167-176.

• Haverkort, A. J., & Struik, P. C. (2015). Yield levels of potato crops: recent achievements and future prospects. Field Crops Research, 182, 76-85.

• Haverkort, A. J., & Verhagen, A. (2008). Climate change and its repercussions for the potato supply chain. Potato Research, 51(3-4), 223.

• Haverkort, A. J., Franke, A. C., Engelbrecht, F. A., & Steyn, J. M. (2013). Climate change and potato production in contrasting South African agro-ecosystems 1. Effects on land and water use efficiencies. Potato Research, 56(1), 31-50.

• Haverkort, A. J., Franke, A. C., Steyn, J. M., Pronk, A. A., Caldiz, D. O., & Kooman, P. L. (2015). A Robust Potato Model: LINTUL-POTATO-DSS. Potato research, 58(4), 313-327.

• Haverkort, A. J., Van de Waart, M., & Bodlaender, K. D. (1990). The effect of early drought stress on numbers of tubers and stolons of potato in controlled and field conditions. Potato Research, 33(1), 89-96.

• Hijbeek, R., van Ittersum, M. K., ten Berge, H. F., Gort, G., Spiegel, H., & Whitmore, A. P. (2017). Do organic inputs matter–a meta-analysis of additional yield effects for arable crops in Europe. Plant and Soil, 411(1-2), 293-303.

• Hijmans, R. J. (2003). The effect of climate change on global potato production. American journal of potato research, 80(4), 271-279.

• Huamari, Z. (1992). Systematic botany and morphology of the sweetpotato plant.

• Hwang, Y. T., Wijekoon, C., Kalischuk, M., Johnson, D., Howard, R., Prüfer, D., & Kawchuk, L. (2014). Evolution and management of the Irish potato famine pathogen Phytophthora infestans in Canada and the United States. American journal of potato research, 91(6), 579-593.

I

• I.Trebejo, D. M. (1989). Effect of water stress on potato growth, yield and water use in a hot an d a cool tropcial climate. Cambrigde: Journal of Agriculutral Science.

• Investopedia 2018:investopedia.com/terms/s/sensitivityanalysis.asp

• IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

J

• Jacobs, M. M., Vosman, B., Vleeshouwers, V. G., Visser, R. G., Henken, B., & van den Berg, R. G. (2010). A novel approach to locate Phytophthora infestans resistance genes on the potato genetic map. Theoretical and applied genetics, 120(4), 785-796.

• Jurriëns, M., Zerihun, D., Boonstra, J., & Feyen, J. (2001). SURDEV: surface irrigation software; design, operation, and evaluation of basin, border, and furrow irrigation (No. 59). International Institute for Land Reclamation and Improvement/ILRI.

K

• Katoh, A., Ashida, H., Kasajima, I., Shigeoka, S., & Yokota, A. (2015). Potato yield enhancement through intensification of sink and source performances. Breeding science, 65(1), 77-84.

- Kaukoranta, T. (1996). Impact of global warming on potato late blight: risk, yield loss and control.

- Kennisakker,2018:kennisakker.nl/kenniscentrum/handleidingen/teelthandleiding-consumptieaardappelen-bemesting

- Kennisakker2006:http://www.kennisakker.nl/kenniscentrum/document/doorwas-consumptieaardappelen-2006#2

- Kirkham, M. B. (2014). Principles of soil and plant water relations. Academic Press.

- Klimaatatlas2018:http://www.klimaatatlas.nl/klimaatatlas.php?wel=zon&ws=kaart&wom=Gemiddelde%20globale%20straling

- KNMI 2018:projects.knmi.nl/klimatologie/daggegevens/selectie.cgi

- Kooman, P. L. (1995). Yielding ability of potato crops as influenced by temperature and daylength. Kooman.

- Krupke, C. H., Hunt, G. J., Eitzer, B. D., Andino, G., & Given, K. (2012). Multiple routes of pesticide exposure for honey bees living near agricultural fields. PLoS one, 7(1), e29268.

- Kutzbach, H. D. (2000). Trends in power and machinery. Journal of Agricultural Engineering Research, 76(3), 237-247.

L

- Lafta, A. M., & Lorenzen, J. H. (1995). Effect of high temperature on plant growth and carbohydrate metabolism in potato. Plant Physiology, 109(2), 637-643.

- Larsen, M. K. G., Jørgensen, M. M., Bennike, T. B., & Stensballe, A. (2016). Time-course investigation of Phytophthora infestans infection of potato leaf from three cultivars by quantitative proteomics. Data in brief, 6, 238-248.

- Ligtvoet, W. *et al.* (2013), The effects of Climate Change in the Netherlands: 2012, The Hague: PBL Netherlands Environmental Assessment Agency.

- Lindhout, P., Meijer, D., Schotte, T., Hutten, R. C., Visser, R. G., & van Eck, H. J. (2011). Towards F 1 hybrid seed potato breeding. Potato Research, 54(4), 301-312.

- Lorenz, O. A. (1945). Effect of planting depth on yield and tuber set of potatoes. American Potato Journal, 22(11), 343-349.

M

- Maas, E. V., & Hoffman, G. J. (1977). Crop salt tolerance–current assessment. Journal of the irrigation and drainage division, 103(2), 115-134.

- MacKerron, D. K. L., & Jefferies, R. A. (1986). The influence of early soil moisture stress on tuber numbers in potato. Potato Research, 29(3), 299-312.

- Magdoff, F., & Van Es, H. (2000). Building soils for better crops(pp. 80-82). Beltsville: Sustainable Agriculture Network.

- Maltas, A., Dupuis, B., & Sinaj, S. (2017). Yield and quality respons of two potato cultivars to nitrogen fertilization. Crossmark: European association for potato research.

• Ministerie van Landbouw, Natuur en Voedselkwaliteit. (2017). Zesde Nederlandse actieprogramma betreffende de Nitraatrichlijn.

• Mitter, N., Worrall, E. A., Robinson, K. E., Li, P., Jain, R. G., Taochy, C., ... & Xu, Z. P. (2017). Clay nanosheets for topical delivery of RNAi for sustained protection against plant viruses. Nature plants, 3(2), 16207.

• Morris, W. L., Hancock, R. D., Ducreux, L. J. M., Morris, J. A., Usman, M., Verrall, S. R., ... & Taylor, M. A. (2014). Day length dependent restructuring of the leaf transcriptome and metabolome in potato genotypes with contrasting tuberization phenotypes. Plant, cell & environment, 37(6), 1351-1363.

• Muthoni, J., Kabira, J., Shimelis, H., & Melis, R. (2014). Regulation of potato tuber dormancy: A review. Australian Journal of Crop Science, 8(5), 754.

N

• Nedato. (2016, june 29). Het laatste nieuw van Nedato. Opgehaald van www.nedato.com: http://www.nedato.com/nl/nieuws/wateroverlast-en-schade-aan-aardappelen/

• Nicot, N., Hausman, J. F., Hoffmann, L., & Evers, D. (2005). Housekeeping gene selection for real-time RT-PCR normalization in potato during biotic and abiotic stress. Journal of experimental botany, 56(421), 2907-2914.

• Nieuweoogst2018:https://www.nieuweoogst.nu/nieuws/2018/03/15/agriver-biedt-luxe-variant-brede-weersverzekering

O

• Obata-sasamoto, H. A. M. A. K. O., & Suzki, H. (1979). Activities of enzymes relating to starch synthesis and endogenous levels of growth regulators in potato stolon tips during tuberization. Physiologia plantarum, 45(3), 320-324.

P

• Padmos, T. (2011). Aardappelen bij Niet Kerende Grondbewerking. DLV plant and HAS hogenschool.

• Park, T. H., Gros, J., Sikkema, A., Vleeshouwers, V. G., Muskens, M., Allefs, S., ... & van der Vossen, E. A. (2005). The late blight resistance locus Rpi-blb3 from Solanum bulbocastanum belongs to a major late blight R gene cluster on chromosome 4 of potato. Molecular Plant-Microbe Interactions, 18(7), 722-729.

• Pavek, M. J., & Thornton, R. E. (2009). Planting depth influences potato plant morphology and economic value. American journal of potato research, 86(1), 56.

• Peloquin, S. J., Yerk, G. L., Werner, J. E., & Darmo, E. (1989). Potato breeding with haploids and 2 n gametes. Genome, 31(2), 1000-1004.

R

• Rauscher, G. M., Smart, C. D., Simko, I., Bonierbale, M., Mayton, H., Greenland, A., & Fry, W. E. (2006). Characterization and mapping of R Pi-ber, a novel potato late blight resistance gene from Solanum berthaultii. Theoretical and applied genetics, 112(4), 674-687.

• Reeves, D. W. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil and Tillage Research, 43(1-2), 131-167.

• Reiter, B., Pfeifer, U., Schwab, H., & Sessitsch, A. (2002). Response of endophytic bacterial communities in potato plants to infection with Erwinia carotovora subsp. Atroseptica Applied and Environmental Microbiology, 68(5), 2261-2268.

• Reynolds, M. P., & Ewing, E. E. (1989). Effects of high air and soil temperature stress on growth and tuberization in Solanum tuberosum. Annals of Botany, 64(3), 241-247.

• Römkens, P. F. A. M., & Oenema, O. (2004). Quick scan soils in the Netherlands; overview of the soil status with reference to the forthcoming EU soil strategy (No. 948). Alterra.

• RVO2018:https://www.rvo.nl/subsidies-regelingen/tegemoetkoming-premie-brede-weersverzekering

• Rykaczewska, K. (2013). The impact of high temperature during growing season on potato cultivars with different response to environmental stresses. American journal of plant sciences, 4(12), 2386.

• Rykaczewska, K. (2015). The effect of high temperature occurring in subsequent stages of plant development on potato yield and tuber physiological defects. American Journal of Potato Research, 92(3), 339-349.

• Rykaczewska, K. (2017). Impact of heat and drought stresses on size and quality of the potato yield. Plant, Soil and Environment, 63(1), 40-46.

S

• Schaap, B. F., Reidsma, P., & Verhagen, A. (2014). Klimaatrisico’s en–kansen voor de landbouw (No. 601). Wageningen UR, PRI, Business Unit Agrosysteemkunde.

• Schapendonk, A. H. C. M., Pot, C. S., & Goudriaan, J. (1995). Simulated effects of elevated carbon dioxide concentration and temperature on the productivity of potato. In Potato Ecology And modelling of crops under conditions limiting growth (pp. 101-113). Springer, Dordrecht.

• Schapendonk, A. H., van Oijen, M., Dijkstra, P., Pot, C. S., Jordi, W. J., & Stoopen, G. M. (2000). Effects of elevated CO2 concentration on photosynthetic acclimation and productivity of two potato cultivars grown in open-top chambers. Functional Plant Biology, 27(12), 1119-1130.

• Secor, G. A., & Gudmestad, N. C. (1999). Managing fungal diseases of potato. Canadian Journal of Plant Pathology, 21(3), 213-221.

• Serhat Ayas, A. K. (2009). Water-Yield Relationships in Deficit Irrigated Potato. Bursa: Journal of Agricultural Faculty of Uludag University.

• Shock, C. C., Pereira, A. B., & Eldredge, E. P. (2007). Irrigation best management practices for potato. American Journal of Potato Research, 84(1), 29-37.

• Shtienberg, D., Blachinsky, D., Ben-Hador, G., & Dinoor, A. (1996). Effects of growing season and fungicide type on the development of Alternaria solani and on potato yield. Plant disease (USA).

• Silva, J. V., Reidsma, P., & van Ittersum, M. K. (2017). Yield gaps in Dutch arable farming systems: Analysis at crop and crop rotation level. Agricultural Systems, 158, 78-92.

• Singh, S. D., Gupta, J. P., & Singh, P. (1978). Water Economy and Saline Water Use by Drip Irrigation 1. Agronomy journal, 70(6), 948-951.

• Struik, P. (2018, 6 14). Meeting ACT group 2116: Discussing the progress. (A. g. 2116, Interviewer)

• Struik, P. (unpublisched). Understanding ageing processes in seed potatoes, Wageningen University, the Netherlands.

• Struik, P. C., & Wiersema, S. G. (1999). Seed potato technology. Wageningen Academic Pub.

• Strunik, P. C., Vreugdenhil, D., van Eck, H. J., Bachem, C. W., & Visser, R. G. (1999). Physiological and genetic control of tuber formation. Potato Research, 42(2), 313-331.

• Svensson, B. (1962). Some factors affecting stolon and tuber formation in the potato plant. European Potato Journal, 5(1), 28-39.

T

• Tan, M. A., Hutten, R. C., Celis, C., Park, T. H., Niks, R. E., Visser, R. G., & van Eck, H. J. (2008). The RPi-mcd1 locus from Solanum microdontum involved in resistance to Phytophthora infestans, causing a delay in infection, maps on potato chromosome 4 in a cluster of NBS-LRR genes. Molecular Plant-Microbe Interactions, 21(7), 909-918.

• Tiemens-Hulscher, M., Delleman, J., Eisinger, E., & Van Bueren, E. L. (2013). Potato breeding: a practical manual for the potato chain.

• Tubiello, F. N., & Ewert, F. (2002). Simulating the effects of elevated CO2 on crops: approaches and applications for climate change. European journal of agronomy, 18(1-2), 57-74.

• Turkensteen, L.J., Mulder, A. (1999). De aardappelziekte Phytophthora infestans. Gewasbescherming 30(4):106–112

V

• van Balen, D., Haagsma, L. (2017). De effecten van gereduceerde grondbewerking. Ecoland.

• van Dam, J.C. (2009). Soil physics, Ecohydrology and Groundwater management. WUR course IWE-30806: Water Delivery

• Van den Hurk, B. J. J. M., Tank, A. K., Lenderink, G., Van Ulden, A., Van Oldenborgh, G. J., Katsman, C., ... & Komen, G. (2007). New climate change scenarios for the Netherlands. Water science and technology, 56(4), 27-33.

• Van der Zaag, D.E. (1992). Potatoes and their cultivation in The Netherlands, The Hague: NIVAA (Netherlands Potato Consultative Institute).

• Van Hoorn, J. W., Katerji, N., Hamdy, A., & Mastrorilli, M. (1993). Effect of saline water on soil salinity and on water stress, growth, and yield of wheat and potatoes. Agricultural Water Management, 23(3), 247-265.

• van Ittersum, M. K., Leffelaar, P. A., Van Keulen, H., Kropff, M. J., Bastiaans, L., & Goudriaan, J. (2003). On approaches and applications of the Wageningen crop models. European journal of agronomy, 18(3-4), 201-234.

• Van Loon, C. D. (1981). The effect of water stress on potato growth, development, and yield. American Potato Journal, 58(1), 51-69.

• Van Loon, C. D. (1981). The effect of water stress on potato growth, development, and yield. American Potato Journal, 58(1), 51-69.

• Varga, B., Bencze, S., Balla, K., & Veisz, O. (2015). Effects of the elevated atmospheric CO2 concentration on the water use efficiency of winter wheat. Procedia Environmental Sciences, 29, 180-181.

• Veilleux, R. E., & Lauer, F. I. (1981). Breeding behavior of yield components and hollow heart in tetraploid-diploid vs. conventionally derived potato hybrids. Euphytica, 30(3), 547-561.

• Visser, R. G., Bachem, C. W., de Boer, J. M., Bryan, G. J., Chakrabati, S. K., Feingold, S., ... & Kuznetsov, B. (2009). Sequencing the potato genome: outline and first results to come from the elucidation of the sequence of the world's third most important food crop. American Journal of Potato Research, 86(6), 417.

W

• Wang, M., Thomas, N., & Jin, H. (2017). Cross-kingdom RNA trafficking and environmental RNAi for powerful innovative pre-and post-harvest plant protection. Current opinion in plant biology, 38, 133-141.

• Wang, S. (2014). Short- and medium-term effects of tillage systems on soil properties and organic spring wheat performance. Wageningen University, the Netherlands.

• Watanabe, K. (2015). Potato genetics, genomics, and applications. Breeding science, 65(1), 53-68.

Y

• Yamamura, K., & Kiritani, K. (1998). A simple method to estimate the potential increase in the number of generations under global warming in temperate zones. Applied Entomology and Zoology, 33(2), 289-298.

Z

• Zamir, D. (2001). Improving plant breeding with exotic genetic libraries. Nature reviews genetics, 2(12), 983.

• Zhu, S., Li, Y., Vossen, J. H., Visser, R. G., & Jacobsen, E. (2012). Functional stacking of three resistance genes against Phytophthora infestans in potato. Transgenic research, 21(1), 89-99.

Appendix

I. Input variables LINTUL-POTATO-DSS

TABLE 1. INPUT VARIABLES REQUIRED FOR LINTUL-POTATO-DSS MODIFIED FROM (HAVERKORT *ET AL.*, 2015)

INPUT DATA	**Default value**	**Explanation and range**
DAILY MAXIMUM AND MINIMUM TEMPERATURE	-	°C
DAILY SOLAR RADIATION	-	MJ m^{-2}
DAILY PRECIPITATION	-	mm
DAILY ET	-	mm
MONTH OF PLANTING	4	1-12
DAY OF MONTH OF PLANTING	23	1-31
PLANTING DEPTH	17,5	Cm from tuber to hill top, used to calculate emergence date
SPROUT GROWTH RATE MM/CD	0.7	Cd = degree day
MONTH OF HAULM KILLING - HARVEST	9	When foliage is destroyed and the crop is harvested (1-12)
DAY OF HAULM KILLING - HARVEST	7	1-31
DAY OF TUBER INITIATION AFTER EMERGENCE	14	5-20 days after emergence, maturity type dependent
ROOTING DEPTH (CM)	30	Depth of soil layer with roots
TEXTURE (% CLAY AND SILT)	20	For water-holding capacity estimation
DM CONCENTRATION OF TUBERS (%)	20	Expected or measured
AREA UNDER IRRIGATION (%)	0	0 or 100 for a field, intermediate for a region
HARVEST INDEX (%)	75	At crop end for all crops
DEGREE-DAYS EMERGENCE – 100% CROP COVER	650	Initial crop development
LUE (GLOBAL SOLAR RADIATION) G/MJ RADIATION INTERCEPTED	1.25	Light use efficiency

II. Monthly weather data 2013-2017. De bilt weather station

Month	Averaged Air Maximum temperature (°C)	Averaged Air Minimum temperature (°C)	Daily averaged Solar Radiation (MJ m^{-2})	Accumulated averaged precipitation (mm)	Accumulated averaged ETo (mm)
Jan	6.0	0.9	2.4	82.7	8.7
Feb	7.3	1.3	4.6	67.0	15.4
Mar	10.5	1.7	9.4	48.0	38.4
Apr	14.2	4.0	14.7	42.1	63.1
May	17.9	7.9	17.0	63.6	84.4
Jun	21.1	11.0	18.5	64.4	94.9
Jul	23.5	13.5	18.2	96.4	101.1
Aug	22.4	12.2	15.6	83.3	84.6
Sep	19.8	10.1	11.0	72.5	54.8
Oct	15.4	8.1	6.1	80.5	28.9
Nov	10.5	4.4	2.9	91.8	11.8
Dec	8.4	3.4	1.8	77.6	7.3

III. Monthly weather data 2013. De bilt weather station

Month	Averaged Air Maximum temperature (°C)	Averaged Air Minimum temperature (°C)	Daily averaged Solar Radiation (MJ m^{-2})	Accumulated averaged precipitation (mm)	Accumulated averaged ETo (mm)
Jan	4.2	-0.6	2.4	59.7	8.4
Feb	4.3	-0.8	4.5	47.8	14.1
Mar	6.0	-1.1	8.5	37.0	30.1
Apr	13.1	2.6	14.2	23.3	59.2
May	15.7	6.8	14.6	87.2	69.6
Jun	19.9	10.1	17.5	50.1	87.1
Jul	24.3	13.3	19.6	40.4	109.6
Aug	23.4	11.9	16.4	27.7	90.1
Sep	18.9	10.0	10.1	113.9	49.1
Oct	15.8	8.2	6.1	161.2	29.1
Nov	9.5	3.7	2.5	115.0	9.9
Dec	8.6	3.2	2.1	66.6	8.4