Impact changes of climatic extremes on arable farming in the north of the Netherlands

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Abstract Agriculture is vulnerable to climate change in multiple ways. Here, we use the northern region of the Netherlands as a case study to explore how risk assessments for climate change impacts on crop production can address multiple vulnerabilities. We present a methodology, which we call agro climate calendar (ACC) that (i) includes potential yield losses, as well as loss of product quality, and (ii) assesses the risks of a variety of climate factors including weather extremes and the emergence and abundance of pests and diseases. Climate factors are defined for two time slices: 1990 (1976–2005) and 2040 (2026–2055); the frequency of occurrence of the factors is compared for the two periods, and the resulting frequency shifts are presented in a crop calendar on a monthly basis. This yields an indication of the magnitude and direction of changes in climatic conditions that can lead to damage by extreme events and pests and diseases. We present results for the two most important crops in the region, seed potato, and winter wheat. The results provide a good overview of risks from climate factors, and the most important threats and opportunities are identified. This semi-quantitative approach is firmly rooted in farm management, which is

the level where operational and strategic decisions are made. Thus, the approach is well suited to assist local stakeholders such as farmers and policy makers to explore farm-level adaptation. This work is complementary to previous modeling work that focused mainly on the relation between mean climate change factors (i.e., temperature) and crop yield.

Keywords Climate change · Extreme events · Agriculture · Adaptation · Arable · Risk assessment · Vulnerability · The Netherlands

Introduction

Agriculture is an important economic sector for the Netherlands currently using about two-thirds of the total land area. And although the number of farmers is gradually declining, the total land surface used for agricultural purposes is relatively stable, indicating a trend toward larger farms (Meerburg et al. 2009a). Besides this trend toward fewer and larger farms, climatic change will also shape the future of agriculture in the Netherlands. Changes in climatic conditions are expected to affect agriculture in the Netherlands in various ways (Alcamo et al. 2007), despite the fact that compared to regions in Asia (Matthews et al. 1997), Africa (Jones and Thornton 2003; Fischer et al. 2005), Latin America (Jones and Thornton 2003), and Australia (Asseng et al. 2004), agriculture in North-West Europe is not very sensitive (Ewert et al. 2005; Alcamo et al. 2007).

In the northern provinces of the Netherlands, agriculture is a major driver of the local economy (Hermans et al. 2010; Hermans and Verhagen 2008), and climate change is an additional risk for agriculture and hence to the economic development of the region. Therefore, in 2005, policy

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makers and other local stakeholders initiated a study to assess whether agriculture in the region can maintain its strong position given the expected impacts of climate change on the major crops. Policy makers are interested to see which local adaption policies are needed to maintain a strong agricultural sector in the region. Local policy makers, who partly funded this study, were together with farmers and the agricultural sector involved in the research process.

Decisions by farmers are often based on risks related to market forces and policy decisions (Smit and Skinner 2002; Howden et al. 2007). Climate change is not yet included in most decision making processes of farmers in the Netherlands, which may lead to suboptimal decisions by farmers that can result in economic losses or missed opportunities. These opportunities are important, as climate impacts are not always negative. In fact, climate change may also have positive effects and provide opportunities (Adams et al. 1995; Olesen and Bindi 2002; Chloupek et al. 2004; Alcamo et al. 2007) that require action, e.g., the production of new vegetables or fruits such as grapes in areas where this was previously not possible (Jones et al. 2005).

Crop growth models are a commonly used tool to assess the effects of elevated CO₂ levels and climate change on agricultural yields (e.g., Adams et al. 1995; Reilly 2002; Reilly et al. 2003; Parry et al. 2004; Porter and Semenov 2005; Wolfe et al. 2008; Rosenzweig et al. 1996; Downing et al. 2000). The results from these studies show positive and negative impacts on yields. For northern latitudes, most of the modeling studies show a positive combined effect of elevated CO₂ levels and increased temperatures (Adams et al. 1995) and some report a slightly negative effect (Parry et al. 2004). Others point out that higher temperatures could also lead to lower wheat yields because of a shorter grain filling stage and a shorter growing season (Eitzinger et al. 2008; Wolf and van Diepen 1995). When including technological development as a yield-determining factor, the relative change is mostly positive (Ewert et al. 2005; Meerburg et al. 2009b).

These model studies provide valuable insight into the effects of biological processes influenced by temperature and CO₂ increase; unfortunately, they often do not include all factors that determine actual crop yields (Wolfe et al. 2008; Tubiello et al. 2007). This also makes results from modeling studies difficult to translate into actual changes in regional productivity (Ewert et al. 2002; Tubiello et al. 2007). Often, yield-determining factors such as pests and diseases and extreme events are not modeled, while these factors could be more important than changes of CO₂ levels and temperature (Porter and Semenov 2005; Cobon et al. 2009; Rosenzweig et al. 2002; Tubiello et al. 2007).

Some authors (Vereijken and Hermans 2010; Hermans et al. 2010) addressed the combined impact of climatic change and changing market conditions on agriculture in

Europe. For the northern part of the Netherlands, consisting of the provinces Groningen, Friesland, and Drenthe (Fig. 1), the results from these studies indicate that gradual changes are not expected to lead to a disruption of the agricultural sector. The relative strong position of agriculture in this region is the combined result of a favorable biophysical and institutional environment. This is, however, not a guarantee for the future position of the region as an important producer and exporter of agricultural products. Extreme events and pests and diseases can potentially have a strong impact on the yield and quality of high value crops (Olesen and Grevsen 1993; Maracchi et al. 2005; Jones et al. 2005) and can threaten the relative strong position of this predominantly agricultural area (Hermans et al. 2010) as markets may not accept a decline of product quality (e.g., spread of pests and diseases).

As agriculture is of importance to the local economy of the northern Netherlands, and because this sector will be impacted by climate change, a risk assessment of climate factors can help to identify opportunities and threats to crop production. By combining information (climate sensitivity of crops, occurrence of climate factors, farm management) from various sources, we assess the risk of climatic change on agriculture in the northern part of the Netherlands. To complement other crop impact studies, we will not assess mean warming and the rise of CO₂ levels, but we rather focus on extreme events including the emergence and abundance of pests and diseases. Furthermore, this study does not only include potential yield losses, but also loss of product quality. The aim of the risk assessment is to inform stakeholders (e.g., farmers and policy makers) about the direction and order of magnitude of change of climate

Fig. 1 Map of the study region with the three northern Provinces Groningen, Friesland, and Drenthe

factors and to give an overview of the most important threats and opportunities. Farmers can use this overview to develop farm-level management responses, or adaptation measures (e.g., the use of better adapted crop varieties) and policy makers can use the overview as a basis for regional adaptation strategies (e.g., regional water management strategies).

Methodology

This study identifies the most important impacts of extreme climate events and climate-driven changes in pests and diseases on crop production and crop quality. We use multiple climate thresholds for a selection of the most important crops of the selected region. The vulnerability of crops is analyzed for two distinct periods: 1976–2005 (further referred to as 1990) and 2026–2055 (further referred to as 2040). A total number of 15 crops have been analyzed, but only two crops are presented. To illustrate the method, we selected the most important crop for the region in terms of value, which is seed potato, and the most common crop in terms of area, which is winter wheat (Table 1).

In order to identify the specific impacts of extreme weather events on arable farming systems in the northern region of the Netherlands, we look at the frequency of these extreme events, the potential development of pests and diseases and the effects of extreme events on the quality of the agricultural products.

To assess the possible impacts of extreme weather events on crop production, we identified five different steps. In the first step, relevant crops were selected based on their economic importance and spatial claim in the region (Table 1).

In the second step, we collected location-specific weather and climate information.

In the third step, we identified crop- and crop management-specific vulnerable periods and climate factors. These climate factors are critical weather thresholds for crop damage that occur in specific periods in the year. This was done by combining information from peer reviewed and

“gray” literature, results from model studies and expert judgment.

In the fourth step, changes in the frequency of occurrence of the climate extremes based on the historic data records for 1990 (1976–2005) and for the predicted future climate 2040 (2026–2055) for two climate change scenarios (van den Hurk et al. 2006) are determined for a representative meteorological station in the selected region. A 30-year period is commonly used to describe and define the climate.

In the fifth and final step, the climate factors and changes in frequency of extreme events are confronted with each other resulting in a change of impact of climate factors on crop production and quality levels, see Fig. 2. The resulting agro climate calendar (ACC) gives insight into the changes that are critical for crop production and quality. This information will be used in a follow-up study in which crop- and farm-level adaptation options are defined and prioritized.

Step one: crop selection

The fifteen most important crops in the region were selected on basis of four criteria: area occupied, economic importance according to the European Size Unit (ESU) for size of production, type of product (food, fodder, ornamental, or energy source), and sector (arable, livestock, horticulture). The area occupied, extent, and economic importance are taken from the Geographical Information System for Agricultural Businesses (GIAB) dataset (Naeff 2006).

The crop list contains the following traditional crops: potato (three types of potato; seed, consumption, and starch), grass, wheat, sugar beet, carrot, lily, rapeseed, cherry, and onion. The list was extended with crops that might have economic potential in the region under future climate conditions. Selected crops are sunflower, grape, and artichoke. The selection of these crops was based on their importance in regions with current climatic conditions that are expected in the northern part of the Netherlands in the future, such as northern France (Kattenberg 2008). Additionally, also a biofuel crop was selected: common

Table 1 Important arable crops for the northern Netherlands measured by area (ha) and the Economic Size Unit (ESU) per hectare, 1 ESU represents about 1200 €/Ecu, source: (European commission 2010)

Crop	Area (×1000 ha)	ESU/ha	Total ESU (×10 ⁶)
Seed potato	13.4	4310	57.7
Winter wheat	36.5	1180	43.1
Sugar beet	24.3	2460	60.0

Fig. 2 Diagram of the steps used in the ACC

reed. Local stakeholders were consulted in order to give their expert judgment on the list of selected crops.

To illustrate the methodology, we present the results for two of the 15 selected crops; seed potato, the most important crop in terms of value, and winter wheat, the most common crop measured in terms of area (Table 1). When describing the results, we follow the sequence of farming events, starting from field preparations until crop storage.

Step two: local climate data

To assess the changes in extreme events from the reference period 1990 to 2040, we used historical data records from the Royal Netherlands Meteorological Institute (KNMI) from weather station Eelde (Fig. 1) and the KNMI'06 scenarios (van den Hurk et al. 2006).

The KNMI'06 scenarios were obtained by downscaling a range of Global Circulation Model (GCM) simulations and Regional Climate Models (RCMs), and by transforming historic weather into future weather conditions, as described by van den Hurk et al. 2006. It is problematic that not all RCMs indicate a change of prevailing winds (circulation change) that will affect rainfall patterns. Therefore, next to temperature rise, the KNMI'06 scenarios make use of an additional steering parameter—the index of circulation (Fig. 3). The plus sign in Fig. 3 indicates that there is a change of circulation and thus an altered rainfall pattern. In such a scenario, the temporal distribution of rainfall will be different from the current situation (i.e., same amount of rainfall in summer periods but less evenly spread). The scaling procedure produces predicted weather toward 2100 with a daily time scale for weather station Eelde.

For this study, we selected two contrasting climate scenarios from the KNMI'06 scenarios for the 2040 time horizon: the G+ and the W+ scenario. The G+ scenario is comparable to the B1 and B2 scenarios used in IPCC SRES (Parry et al. 2004) while the W+ scenario corresponds to

the SRES A1 and A2 scenarios. The weather and climate data are the basic input for step four.

Step three: climate factors

Each crop has a specific development sequence and requires a series of management activities during its development. Standard management practice in agriculture starts with soil tillage and field preparation and ends with harvest and storage. Weather is an important driver of crop development and determines the timing and effectiveness of management activities. The ACC follows this sequence of events and lists climate factors that have a potential direct or indirect negative effect (in terms of damage) on crop production and quality.

For example, tuber bulking and maturation of potatoes are critical phases that can be negatively affected by extreme wet or dry conditions. Extreme wet conditions can also hamper seeding or harvest activities. Moreover, the occurrence and abundance of pests and diseases are strongly linked to climate factors such as warm and wet conditions or prolonged wet periods. Specific crop factors and potential impacts are based on expert judgment, literature, and crop models as presented in Tables 2, 3.

Step four: occurrence of climatic extremes

The weather and climate information collected in step one is used to calculate the change in frequency of each climate factor on a monthly basis. We assessed the reference climate of 1990 where the current frequencies are listed and the frequency shifts are calculated based on the climate projections for 2040 for the two contrasting scenarios (G+ and W+).

Step five: impact of climatic extremes

In this step, the possible impacts and damage levels related to the changes in occurrence of the climate factors are determined. This information can then be used as a basis for field and farm-level adaptation strategies.

Results

Seed potato and winter wheat were selected as example crops because they are the main components of the rotation in the region (step one). Seed potato is the most important crop as the ESU in the study area is about 4 times higher than that of winter wheat (Table 1). Winter wheat is not considered a high value crop in this region, and it is mainly grown to keep disease pressures down. Nevertheless, winter wheat is the most common crop measured by area.

Fig. 3 The KNMI'06 scenarios of the Royal Netherlands Meteorological Institute (adapted from: van den Hurk et al. 2006)

Table 2 Agro climate calendar; this calendar describes climate factors, their meteorological description, the type of farm management if applicable, its impact on the crop (winter wheat), the vulnerable period, and an estimated range of crop losses (in % market value)

Climate factor	Vulnerable period	Meteorological description	Farm management	Impact on crop	Weight of economic loss (%)	Reference
Wet field	Oct–Dec	Period of 21 days of more than 0.5 mm rainfall on 75% of the days	Plowing and preparation of sowing bed	Delayed planting date	–	(Darwinkel 1997)
Frost-thaw	Nov–Mar	Period of minimal 3 days of repeated frost and thawing (night $T < -1^{\circ}\text{C}$ and day $T > 1^{\circ}\text{C}$) after period of strong frost (Min. $T < -10^{\circ}\text{C}$), incl. a 2 day transition period to thawing	–	Root damage	10–50	(Timmer 2008)
Drought	Jun–Aug	At least 40 days with less than 10 mm rainfall	–	Lower grain yield	10–50	(Timmer 2008)
Sustained wet	Apr–May	At least 21 days with more than 0.5 mm precipitation on 75% of the days	–	Yield decrease by Leaf blotch <i>Septoria tritici</i>	25–75	(Timmer 2008)
Sustained humid	May–Jul	At least 21 days with more than 0.5 mm precipitation on 75% of the days	–	Yield decrease by Seedling blight <i>Fusarium spp.</i> , <i>Septoria nodorum</i> , reduced product quality (mycotoxins)	25–75	(Darwinkel 1997)
Wind and rain surges	May–Aug	Precipitation of 45 mm or more in 1 day	Harvest	Lodging, inability to harvest	Unknown	(Timmer 2008)
Sustained wet	Jul–Sep	Period of 21 days of more than 0.5 mm rainfall on 75% of the days	Harvest	Inability to harvest	10–75	(Timmer 2008)

Agro climate calendar

Winter wheat

Plowing and sowing of winter wheat generally starts as early as possible after the harvest of the previous crop. Sometimes in a wet autumn after a delayed harvest, plowing and sowing of winter wheat can fail and generally spring wheat is sown the next year. During the winter period, from November to March, repeated frost and thawing can cause damage to the roots of winter wheat (Darwinkel 1997). Droughts in the June to August period can cause severe yield decreases if the drought occurs after stem elongation (Foulkes et al. 2007). Prolonged wet periods can trigger leaf blotch (*Septoria tritici*), which can cause severe yield decreases (Shaw and Royle 1993). Moreover, humid conditions can stimulate *Fusarium spp.* which has an effect not only on the yield, but also on product quality as toxic mycotoxins are produced (Rosenzweig et al. 2001; Gervais et al. 2003). Wind and rain surges in the vulnerable period of May to August can cause the wheat to lodge. If the wheat is unable to recover, the harvest can be completely lost because harvesters are, currently, unable to recover the lodged wheat (Timmer 2008).

Seed potato

Land preparation for seed potato starts with plowing during the October–March period. Exact timing of plowing depends among others on field conditions. In a wet winter, plowing may be hampered (Bus et al. 2003). Moreover, humid conditions can delay the preparation of the planting bed and subsequent planting during spring.

High-intensity rainfall events after tuber formation are particularly damaging to potatoes because after approximately 24 h of anaerobic conditions, potato tubers start to rot. In the recent past, the northern region of the Netherlands has encountered extreme rainfall events that caused major quality losses. In 1998, such an event caused such a major quality decrease as result of rotting that farmers in the region even decided not to harvest (Haverkort 2008).

A sudden switch from a warm to a cooler period during tuber formation (e.g., after a heat wave) causes second growth. This means that a tuber forms many smaller tubers instead of a few bigger ones, which reduces the economic value of the crop (Ewing and Struik 1992).

Warm and wet conditions are favorable for *Pectobacterium* (previously *Erwinia*) *carotovorum* that causes soft

Table 3 Agro climate calendar; climate factor, meteorological description of the climate factor, type of operational management if applicable, the impact on the seed potato crop, the potentially vulnerable period, and the estimated range of crop losses expressed as percentage of the market value

Climate factor	Vulnerable period	Meteorological description	Farm management	Impact on crop	Weight of economic loss (%)	Reference
Wet field	Oct–Apr	Period of 21 days of more than 0.5 mm rainfall on 75% of the days	Plowing and preparation of planting bed	Delayed planting date	–	(Bus et al. 2003)
High-intensity rainfall	May–Sep	Daily precipitation of at least 45 mm or at least 60 mm in 3 days	–	Rotting of the tubers	25–75	(Haverkort 2008)
Heat wave	Jul–Sep	Heat wave (at least 3 days with more than 30°C in a period of at least 5 days above 25°C)	–	Second growth	25–75	(Haverkort 2008; Haverkort and Verhagen 2008; Jackson 1999)
Warm and wet	Jul–Sep	At least 14 consecutive days with a maximum temperature above 20°C and for 50% of the days at least 0.5 mm precipitation	–	<i>Pectobacterium</i> (previously <i>Erwinia carotovorum</i>) causes soft rot and black leg	10–50	(Haverkort 2008; Czajkowski et al. 2009; Haverkort and Verhagen 2008)
Sustained wet weather	Jun–Sep	A period of at least 21 days with more than 0.5 mm precipitation on 75% of the days	Spraying	Not possible to spray against <i>Phytophthora infestans</i>	50–100	(Haverkort 2008; Zwankhuizen and Zadoks 2002)
Wet field	Aug–Oct	Period of 21 days of more than 0.5 mm rainfall on 75% of the days	Harvest	Damage to tubers	N.A.	(Bus et al. 2003)
Warm winter	Dec–Mar	Period of at least 14 days with a maximum temperature above 10°C	Storage	More rotting of tubers and early sprouting in March	25–75	(Bus et al. 2003; Haverkort and Verhagen 2008)

rot and black leg (Czajkowski et al. 2009). This occurs mainly from July to September. Sustained wet conditions during the green leaf period can lead to potato late blight (*Phytophthora infestans*). Most farmers spray fungicides against potato late blight, but this can be hampered by prolonged periods of wet weather (Haverkort 2008). Wet fields during harvesting can be problematic for mechanical harvesters and increase the risk of tuber damage, which may result in rotting of the stored harvested potatoes. Warm winters can be problematic during storage. Warm conditions can lead to dormancy break and sprouting, which degrades the economic value of the stored product (Bus et al. 2003). Table 3 presents the agro climate calendar for seed potatoes.

Changes in frequency

Winter wheat

In Table 4, the monthly frequencies for the climate factors for the baseline period 1990 are shown for winter wheat. The changes in frequency for the two scenarios (G+ and

W+) in 2040 that might affect this crop are presented in Table 5.

Seed potato

In Table 6, the monthly frequencies for the climate factors of seed potato for the baseline period 1990 are shown. The

Table 4 Frequencies of climate factors for winter wheat in potentially vulnerable months for the 1990 period for weather station Eelde (Lat/Lon: 53.13/6.58) based on measurements by KNMI during 30 years in the 1976–2005 period

Climate factor	J	F	M	A	M	J	J	A	S	O	N	D
Wet field										5	8	9
Frost-thaw	1	0	1								0	0
Drought						0	1	0				
Sustained wet				0	5							
Sustained humid					4	9	8					
Wind and rain surges					0	0	0	1				
Sustained wet							7	5	2			

Table 5 Changes in frequencies of climate factors for winter wheat in potentially vulnerable months in scenario G+ (light gray) and W+ (gray) for the period around 2040 for weather station Eelde (Lat/Lon:

53.13/6.58) (based on the KNMI '06 scenarios for 30 years in the period 2026–2055)

Climate factor	Scenario	J	F	M	A	M	J	J	A	S	O	N	D
Wet field	G+										0	+1	+2
	W+										−1	0	+3
Frost-thaw	G+	0	+2	0								0	0
	W+	0	+3	+1								0	0
Drought	G+						+1	+1	+1				
	W+						+2	+1	+2				
Sustained wet weather	G+				0	−2							
	W+				0	−2							
Sustained humid	G+					−1	+1	−1					
	W+					0	−2	−4					
Wind & rain surges	G+					0	0	0	+1				
	W+					0	0	0	+1				
Sustained wet weather	G+							−2	−4	0			
	W+							−5	−3	−1			

Table 6 Frequencies of climate factors for seed potato in potentially vulnerable months for the 1990 period for weather station Eelde (Lat/Lon: 53.13/6.58) based on measurements by KNMI during 30 years in the 1976–2005 period

Climate factor	J	F	M	A	M	J	J	A	S	O	N	D
Wet field	13	5	5	0						5	8	9
High-intensity rainfall					0	0	0	2	1			
Heat wave							2	6	0			
Warm and wet							0	1	0			
Sustained wet					5	8	7	5				
Wet field								5	4	5		
Warm winter	0	0	3									0

changes in frequency for the two scenarios (G+ and W+) in 2040 are presented in Table 7.

Impact

Winter wheat

The sowing of winter wheat can sometimes be problematic if the previous crop is late (e.g., after mid October) and when the period between October and early December is wet. Wet periods in October to December do occur regularly, but fortunately farmers can sow spring wheat in the next year instead of winter wheat. At present, frost and thawing does not occur often, but according to Table 5 it will occur more in the future and may cause a potential yield loss of 10–50% for individual fields. Drought

(40 days with less than 10 mm rain) is not a frequent phenomenon and it seems that it will not occur significantly more under a G+ scenario or W+ scenario. Sustained periods of wet and humid weather do not seem to increase, and in August even a modest decrease in the W+ scenario can be identified. Consequently, the conditions for the development of leaf blotch (*Septoria tritici*) and *Fusarium* are not more favorable: *Fusarium* might even decrease in August. Wind and rain surges are not likely to change significantly. Harvesting may prove difficult because of the occurrence of wet periods from July to September.

Seed potato

Currently, wet fields between October and March are problematic for plowing (Tables 3, 6). This may lead to lower yields or increased costs if planting starts too late or under unfavorable conditions. A too dry soil between March and April can lead to planting delays. Moreover, the growth of the potato tubers can be reduced if moisture conditions are suboptimal for the newly planted potatoes. Intense rainfall during the growing season is not very common in the northern part of the Netherlands: it only occurred twice in August and once in September during the reference period 1976–2005. Heat waves occur more regularly. The frequencies of sustained wet weather are high compared to other climate factors. It is expected that in 2040, there will be a notable increase in the frequency of warm winter months. Consequently, farms without adequate cold storage facilities will be negatively affected. As mentioned before, wet field conditions between August and

Table 7 Changes in frequencies of climate factors for seed potato in potentially vulnerable months in scenario G+ (light gray) and W+ (gray) for the period around 2040 for weather station Eelde (Lat/Lon:

53.13/6.58) (based on the KNMI '06 scenarios for 30 years in the period 2026–2055)

Climate factor	Scenario	J	F	M	A	M	J	J	A	S	O	N	D
Wet field	G+	+1	0	0	0						0	+1	+2
	W+	+4	+1	0	0						−1	0	+3
High-intensity rainfall	G+					0	0	0	0	+1			
	W+					0	0	0	−1	+1			
Heat wave	G+							+2	+7	+1			
	W+							+12	+12	+3			
Warm and wet	G+							+4	+5	+1			
	W+							+6	+6	+2			
Sustained wet	G+					−2	−2	−2	−4				
	W+					−2	−4	−5	−3				
Wet field	G+								−3	0	0		
	W+								−3	−1	−1		
Warm winter	G+	0	+1	+3									+1
	W+	+2	+3	+8									+1

October can become problematic when harvesting with heavy machinery.

According to Table 7 the frequencies of high-intensity rainfall will not increase dramatically relative to the baseline frequencies presented in Table 6. However, it is expected that heat waves will occur more frequently: they range from an extra 1–7 events under the G+ scenario from June to August, and from 3 to 12 events under the warmer W+ scenario. Thus, increased occurrence of second growth can be expected. The environmental conditions for the development of *Pectobacterium carotovorum* become more favorable in both the G+ and the W+ scenarios. This may lead to increased yield losses. Interestingly, it may become easier to battle one of the current major hazards in potato production, late blight (*Phytophthora infestans*). The period when fungicides against late blight need to be applied will become drier, which reduces spraying difficulties. Both under the G+ and the W+ scenarios, the occurrence of sustained periods of humid weather will decrease. However, storage problems may occur because of higher winter temperatures, especially under the W+ scenario. High-intensity rainfall (which can lead to rotting of tubers) may increase, but the frequency change is expected to be rather limited.

Discussion and conclusions

The semi-quantitative approach presented in this paper provides an overview of current and possible future climate-related risks of extreme events and pests and diseases on crop production and product quality. The ACC

methodology is illustrated for two crops: seed potato and winter wheat. We successfully applied the methodology to a wide range of other crops: consumption potato, starch potato, grass, wheat, sugar beet, carrot, lily, rapeseed, cherry, onion, sunflower, grape, artichoke, and common reed (Schaap et al. 2009).

At first glance, most of the frequency changes are small (Tables 5, 7). However, even small frequency changes of some of the climate factors can have severe consequences for crop production and quality. For seed potato, both experts and farmers emphasized that crop quality is more important than high yield levels; low quality will inevitably lead to low economic returns. For winter wheat, it is important that the crop does not contain mycotoxins, which renders the crop unmarketable.

This study assumes that the data of one weather station (Eelde) accurately represent the climate of the northern Netherlands. However, it should be noted that spatial and temporal variation can be large. This will have consequences for the validity of the frequency changes if used in specific locations. In addition, we used two contrasting (G+ and W+) of the possible four scenarios. This limits the outcome as generally more climate scenarios are used to deal with uncertainties in the climate models (Easterling et al. 2007). Although the 30-year period that is used has the disadvantage that not all extreme weather events are characterized in the ACC, the 30-year period does allow for good comparison of the current occurrence of climate factors around 1990 and possible future occurrence of climate factors around 2040. We used an arbitrary temporal resolution of a month, a common time lag in the agricultural management and phenology of crops, to capture relevant data.

As this study partly relies on expert judgment, an additional source of uncertainty was introduced. For the definition of crop-specific thresholds, experts had to make assumptions about average field and management conditions.

Another uncertainty that was introduced is related to the translation of crop damage to a meteorological description of the climate factor (Tables 2, 3). For example, the description “warm and wet” used to indicate favorable conditions for *Pectobacterium* (previously *Erwinia*) *carotovorum* is defined as follows: “at least 14 consecutive days with a maximum temperature above 20°C and for 50% of the days at least 0.5 mm precipitation”. A slightly different definition could lead to other outcome frequencies.

For the ACC approach, generalizations had to be made to define the thresholds of climate factors that are related to pests and diseases. Although not all processes and interactions are sufficiently understood, the ACC approach indicates the directions of change of some of the key conditions for the occurrence of pests and diseases. Because of its flexibility and scalability to local conditions, the ACC is a valuable tool for farmers and policy makers to assess the most relevant risks.

The ACC provides a methodology to assess the risk of specific climate factors for crop production and crop quality. Moreover, this method can be used at various spatial and temporal scales depending on the heterogeneity of the region (e.g., of soils) and the need for a specific temporal resolution (e.g., 10 days vs. 1 month). The ACC method is complementary to crop simulation models that assess the impact of global warming and increased CO₂ levels but do not address the occurrence of extreme events and pests and diseases.

This study is a first risk assessment on changes in extreme events and pests and diseases on arable crops in the northern Netherlands. The results of the frequency shifts provide an indication of the order of magnitude and direction of change. The methodology can be used for more detailed studies on crop impacts, but data availability and the detail at which experts are able to evaluate the crop responses may limit the use of this method elsewhere, for example in developing countries.

The ACC approach provides an overview of possible impacts for which farm-level adaptation strategies can be explored. The method includes an assessment of product quality as well as crop yield, a combination not often considered in other assessments (Howden et al. 2007). Another advantage is that this semi-quantitative approach is rooted in practical farm management—the level where operational and strategic decisions are made. Consequently, it is easier to involve farmers and other stakeholders to explore farm-level adaptation. At the regional

scale, local policy makers can benefit from the farm-level results because the range of potential impacts is explored for all crops grown in the region. Future research will focus on the exploration of local farm-level adaptation and regional adaptation strategies by policy makers and the agricultural sector.

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