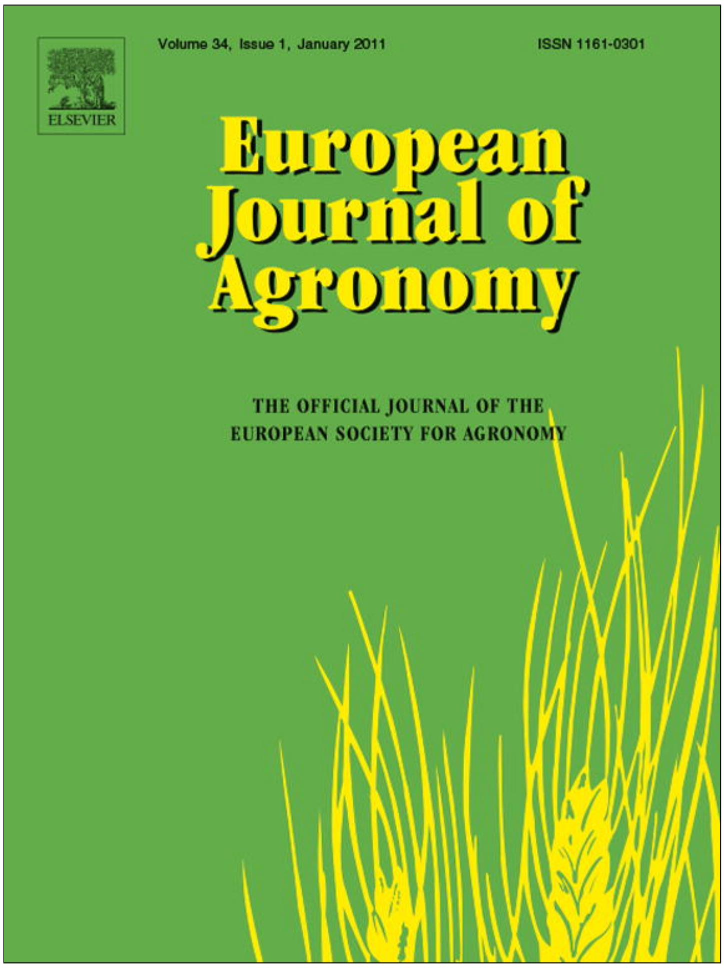
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Key weather extremes affecting potato production in The Netherlands

P.A.J. Van Oort*, B.G.H. Timmermans, H. Meinke, M.K. Van Ittersum

Wageningen University, Department of Plant Sciences, The Netherlands

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ABSTRACT

The possible impact of climate change on frequency and severity of weather extremes is hotly debated among climate scientists. Weather extremes can have a significant impact on agricultural production, but their effect is often unclear; this due to interaction with other factors that affect yield and due to lack of precise definitions of relevant weather extremes. We show that an empirical analysis of historical yields can help to identifying such rare, high impact climate events. A reconstructed time series of ware potato production in Flevoland (The Netherlands) over the last 60 years (1951–2010) enabled us to identify the two main yield affecting weather extremes. In around 10% of the years yield anomalies were larger than −20%. We found that these anomalies could be explained from two weather extremes (and no other), namely a wet start of the growing season and wet end of the growing season. We derived quantitative, meteorological definitions of these extremes. Climate change scenarios for 2050 show either no change or increased frequency of the two extremes. We demonstrate there is large uncertainty about past and future frequencies of the extremes, caused by a lack of sufficiently long historical weather records and uncertainties in climate change projections on precipitation. The approach to identify weather extremes presented here is generally applicable and shows the importance of long term crop and weather observations for investigating key climatic risks to production.

1. Introduction

There is a growing concern that along with increasing CO_2 and temperature, the frequency of weather extremes will increase as the climate continues to change (Beniston et al., 2007; Solomon et al., 2007; van den Hurk et al., 2006). In the broadest possible definition (followed in this paper) a weather extreme can be both a rare weather event or a rare sequence of weather events. Alternatively, one could define a weather extreme as a rare (single) weather event (such as a hail storm) and define a seasonal extreme as a rare sequence of weather events (e.g. a rare high frequency of rainfall events). Various authors have proclaimed that extremes are more important than the gradual changes that are projected (Katz and Brown, 1992; Jentsch et al., 2007; Taleb, 2010). The debate on whether frequencies of extremes will actually change is still ongoing and contingent on our understanding (definitions) of extremes.

We take potato as a case study for identifying high impact weather extremes. Potato (*Solanum tuberosum*) is a major food crop throughout the world (Haverkort, 1990; Scott et al., 2000). Variability in potato yields is caused by rainfall (e.g. Dalla Costa et al., 1997), temperature (e.g. Kooman et al., 1996a), radiation (e.g. Kooman et al., 1996b) and CO_2 (e.g. Miglietta et al., 1998; Taub et al., 2008). Many of these factors have been incorporated in crop models and used for climate change (CC) impact assessments (Haverkort, 1990; Peiris et al., 1996; Rosenzweig et al., 1996; Davies et al., 1997; Wolf, 2002; Hijmans, 2003; Holden et al., 2003; Gobin, 2010).

There is a lack of empirical evidence and knowledge on which weather extremes have strong impacts. In agriculture, extremes are unlikely to be identified with crop models, because these models are not designed/developed to accurately simulate yields under rare weather conditions. An interesting approach to model validation in this respect is found in Gobin (2010) who simulated historical (1960–2008) and future yields of winter wheat, winter barley, potato and sugar beet in Belgium. Gobin's tests showed that her model accurately predicted the normal and highest yields (90 percentile and above), but poorly predicted the lowest 10% of observed yields. In the lower 10th percentile, observed yields were consistently lower than simulated yields and for good reasons: the yields were the consequence of rare, yield-reducing processes and events that are usually not included in crop models (e.g. Van Ittersum et al., 2003). Occasionally sheer bad luck or poor management might be to blame for such low yields, but mostly the causes are somehow related to weather conditions. To identify these rare, damaging processes and events we need to turn to more detailed observations from and analysis of those years with very low yields.

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* Corresponding author at: Centre for Crop Systems Analysis, Department of Plant Sciences, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands. Tel.: +31 317 481357; fax: +31 317 485572.
E-mail address: pepijn.vanoort@wur.nl (P.A.J. Van Oort).

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The problems with investigating extreme events (or extreme sequences of events) are two-fold: (1) by definition, such events are rare, making empirical research difficult and (2) final crop yield depends on many other factors. The latter makes clear attribution of cause and effect difficult, and therefore also identification of causes per se. A viable approach may be to start from the impact side, identifying those years with the largest negative yield anomalies. Large time series are needed for this because (as noted) the events are rare. Using historical weather data, agronomic knowledge, and farmers' descriptions of weather, management and crop (metadata) we searched for differences between weather in the yield-anomalous years and weather in the average years. The use of metadata helps focus the quest for finding relevant weather extremes and to avoid coincidental associations between weather anomalies and yield anomalies. We follow the above approach in a case study on weather extremes with large impact on potato yields in The Netherlands.

The objectives of this paper are to (1) identify key weather extremes that impact on Dutch ware potato production; (2) precisely define these weather extremes and (3) investigate how the frequency of such weather extremes might change based on climate change projections.

2. Materials and methods

We have reconstructed a time series of 60 years of ware potato yield data. For all years, except the very first, descriptions of weather, crop and management could be recovered from archives. From these we derived first qualitative and next quantitative definitions of key weather extremes. We used national climate change scenarios to assess possible changes in the frequency of the extremes. Data and methods are described in more detail below.

2.1. General approach

Crop yields are determined by a range of factors that include weather, soil and management, whereby weather is generally the most variable of these factors. Therefore annual variation in crop yield can be regarded as a bio-indicator of the climatic conditions that the crop experienced during its growth. By using yield anomalies as such bio-indicators for the occurrence of weather extremes, we essentially use a reverse-engineering approach – we start with the consequence (yield anomaly) to determine its cause (e.g. a weather extreme). This is similar to the approach used by Potgieter et al. (2005) who used simulated wheat yields to quantify ENSO related rainfall anomalies throughout Australia. This method is well-suited to quickly hone in on the weather extremes that matter. Our method entails 6 steps:

1. Compile time series of crop yield data.
2. Identify years with large negative yield anomalies on more than one site in a region. We defined 'anomalous yields' as being 20% or more below the long term de-trended average; just over 10% of all years from 1951 to 2010 fell into this category.
3. Search for causal links between large negative yield anomalies and weather or management events in historical documentation such as research and extension reports (this resulted in qualitative definitions of weather extremes).
4. Link time series of crop yield data to a weather station (Fig. 1).
5. Calibrate and evaluate quantitative meteorological definitions of weather extremes.
6. Calculate past and future frequencies of the extremes (this resulted in quantitative evaluations of weather extreme impacts).

Our method is contingent on data availability. In searching for data we relied heavily on senior staff members' recall of names of experimental farms. Most of these farms closed in the late 1980s and as time goes by their legacy is easily forgotten. Appendix A lists all yield time series of 8 or more years that we managed to reconstruct. All references listed in Appendix A are publicly available through the library of Wageningen University. For this paper we used only those data sources with sufficient metadata (descriptions of management and weather of each year):

- "Bedrijven in eigen beheer", 1951–1978 (Lalkens, 1985);
- RIVRO Dronten, 1967-1989 (RIVRO, 1967–1989);
- Minderhoudhoeve, 1970–1983 (Landbouwhogeschool Wageningen, 1970–1983);
- De Schreef, 1965–1990 (Hoekstra et al., 1993);
- CBS, 1994 (www.cbs.nl).

The "Bedrijven in eigen beheer" series and the CBS series are regional statistics, the other three are point data from experimental farms. The "Bedrijven in eigen beheer" time series contains yield data averaged over 10 commercial farms in the Wieringermeer region and over 14 farms in the Noordoostpolder region. We used the data of the Noordoostpolder region which is located in the North East of the province of Flevoland, close to the three experimental farms. The "Rijksinstituut voor Rassen Onderzoek" (RIVRO) conducted variety trials on clay soils (Dronten) with recorded yields during the years 1969–1989. The Minderhoudhoeve was for a long time an experimental farm as part of Wageningen University with regular agronomic and soil science experiments. Annual reports with crop yields are available for the period 1970–1983. The time series for the experimental farm "De Schreef" covers the period 1965–1990. A synthesis is available (Hoekstra et al., 1993), including appendices on crop yields and other variables for each year. The three experimental farms are all located close to each other in the province of Flevoland, shown as the black square in Fig. 1. The regional statistics from the national bureau of statistics (CBS, www.cbs.nl), at the provincial level, are aggregated from data provided by individual farmers (compulsory to obtain subsidies and related to environmental policies).

For the calculation of the yield anomalies in step (2) we calculated expected yield using the linear trend over time, that is $Y_y = b_0 + b_1 * y$, where Y_y is the expected yield in year y and b_0 and b_1 are regression coefficients. From these we calculated yield anomalies as $(Y_y - Y_{act})/Y_y$ where Y_{act} is the observed yield in year y. To avoid the disproportionally high impact of outliers on the trend line parameters b_0 and b_1 we removed the anomalously low yields (with $(Y_y - Y_{act})/Y_y < -20\%$) and then re-estimated b_0 and b_1 with these outliers removed. With the re-estimated b_0 and b_1 we calculated the final de-trended yield anomalies for all years in the time series. Regional yield can be calculated in two ways: $Y1$ = production/harvested area and $Y2$ = production/planted area. The distinction is relevant when in a given year and region a large portion of the planted area is not harvested. In such a year a $Y2$ time series will show a clear yield anomaly, while a $Y1$ time series might show no yield anomaly at all. The yield anomalies shown in this paper for the CBS data are based on yields calculated as $Y2$.

In step 3 we qualitatively established the likely cause for different yield anomalies, using all available metadata from the crop yield time series. Often the effects on yield are indirect, i.e. it is not a weather extreme per se that causes a yield decline, but a whole chain of events triggered by a weather extreme (e.g. inaccessibility of waterlogged fields leading to planting and/or harvest delays). The output from step 3 was a qualitative definition of a weather extreme and the likely chain of events triggered by this weather extreme. In steps 4 and 5 we derived quantitative meteorological rules and parameters for these two extremes, using historical

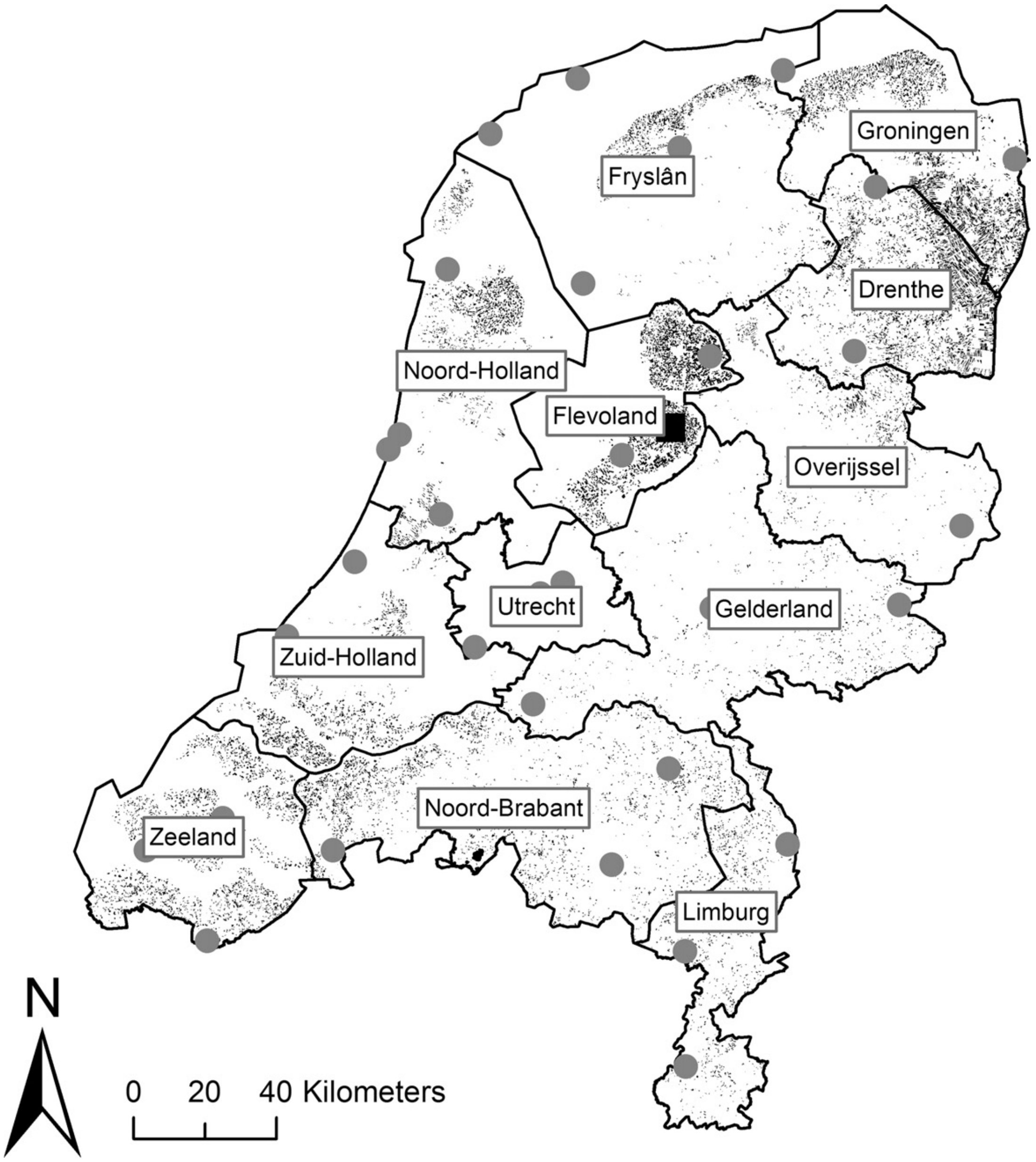


Fig. 1. Map of The Netherlands. Small fine dots: fields where potato is grown. Large grey dots: location of weather stations. Black square: location of the experimental farms of which data were used to define the "wet start" extreme (sections 2.2/3.2). Black lines: provinces used in the regional analysis of the "wet end" extreme (sections 2.3/3.3).

weather data from the Royal Netherlands Meteorological Institute (KNMI, www.knmi.nl).

As a final step (step 6) we calculated the past and possible future frequencies of the extremes identified in step 5. We used climate change projections by KNMI, available from www.knmi.nl/klimaatscenarios/index.php. KNMI has downscaled GCM/RCM climate change model output to the station level. Data and techniques used are discussed in detail in van den Hurk et al. (2006). To represent weather variability around the year 1990 historical weather records from 1976 to 2005 are used. The weather variables for each day of each year in this series of 1976–2005 were transformed by KNMI on the basis of expected changes (2050 versus 1990) in each of the weather variables. This yielded 30 transformed years representing weather variability around 2050 (van den Hurk et al., 2006). Two anticipated circulation regime changes are included in the KNMI scenarios: a strong change of circulation, which induces warmer and moister winter seasons and increasing the likelihood of dry and warm summertime situations, and a weak change of circulation. Both regimes are presented for the +1 °C and +2 °C global temperature increases, producing a total of four scenarios:

LW = +1 °C temp. rise 1990–2050, weak change in circulation patterns
LS = +1 °C temp. rise 1990–2050, strong change in circulation patterns
HW = +2 °C temp. rise 1990–2050, weak change in circulation patterns
HS = +2 °C temp. rise 1990–2050, strong change in circulation patterns

Calculations on frequency change require a choice of the historical reference period with which the future weather is compared.

We used the default reference period 1976–2005 and, for sensitivity analysis, also other reference periods.

As we will show in the results, the two most important extremes identified were “wet start of season” and “wet end of season”. None of the yield anomalies identified here were related to drought or heat, or other causes such as pests and diseases (for the latter see Zwankhuizen and Zadoks, 2002). Probably this is due to the mild climate in The Netherlands, ample access to irrigation water and ample technology and chemicals to controls weeds, pests and diseases. Possibly in other environments other extremes are more important and we encourage similar research as reported here in other environments. This paper however is about key weather extremes affecting potato production in The Netherlands. In the two following sections we describe specific data and methods used to derive quantitative (meteorological) definitions of the two weather extremes “wet start” and “wet end”.

2.2. Wet start of the growing season

The first extreme identified in step 3 was late planting due to a wet start of the growing season. The main causal links between this weather extreme and its effect on ware potato yield are:

- if the top soil layer is too wet the potato crop cannot be planted;
- late planting results in a shorter growing season;
- when seed potatoes are taken out of storage and kept under suboptimal temperatures while waiting for a planting opportunity their physiological age increases (Van Ittersum et al., 1990), eventually resulting in reduced vigour.

To define the “wet start of the growing season”, we needed data on planting dates. Only two time series (RIVRO Dronten and Minderhoudhoeve) contained reported planting dates. The “De Schreef” time series had no planting dates but did list the three years with late planting (1975 and 1977 “early May”, 1983 “second week of June”). Under benign weather conditions farmers select their planting dates depending on weather, logistics and convenience. As a wet season evolves and prevents planting, the urgency to plant increases. Late plantings are probably solely determined by meteorological variables; farmers would not chose planting late thereby foregoing yields and ultimately profits. In a first step towards quantification of “the wet start of the season”, we calculated planting rules using combinations of minimum temperature, maximum temperature, rainfall and radiation. We used the root mean square error (RMSE) between observed and calculated planting dates as the selection criterion. We found that rainfall strongly affected late planting, whereas including temperature or radiation did not make the planting rules more accurate. Secondly, we calibrated two most accurate planting rules to simulate planting date:

- The ‘dry days rule’, which states that within a pre-defined planting window (in this case any day after 21 March) farmers will plant during a dry spell, when for x days the accumulated rainfall is less than y mm.
- The ‘rainsum rule’, which estimates planting date using rainfall over a longer period back in time. The equation used is: planting date = $b_0 + b_1 * \text{rainsum}_{\text{start-end}}$ where rainsum is the total rainfall from a given start to end date. This equation has 4 parameters (b_0, b_1, start and end date). Start and end date are iteratively varied. Every iteration produces a different $\text{rainsum}_{\text{start-end}}$ for which regression coefficients b_0 and b_1 are estimated.

The dry days rule is based on the assumption that it takes the surface layer of the soil a certain number of dry days before it becomes sufficiently trafficable. However, when high surface water levels and capillary rise limit the infiltration rate, simply calculating the number of dry days might be insufficient. Under those circumstances it might be more important to calculate the amount of rain received over a longer period, which is what the rainsum rule does.

For the parameterisation of both planting rules we defined a threshold for late planting (the vertical line in Fig. 3, and horizontal line in Figs. 5 and 6), above which yields decline due to late planting. The calibration procedure was then to find a set of parameters that would accurately estimate above threshold planting dates in years with observed late planting (1970, 1975, 1979 and 1983 in Fig. 5). For these years RMSE between observed and simulated planting date was minimised. Correctly estimating planting date in the regular years was not an objective; the only criterion was that estimated planting date should be below the threshold. Rainfall data used were from the Dronten rainfall station which is representative for Flevoland and has records starting in 1960.

2.3. Wet end of the growing season

The second extreme identified in step 3 was a wet end of the growing season. The main causal links between this weather extreme and its effect on ware potato yield are:

- if the soil is too wet, trafficability is reduced resulting in harvest delays and possible other side effects such as soil compaction;
- prolonged water-logging that can cause rotting of the tubers;
- harvesting might be completely terminated if water logging continues for too long.

We used data from 12 provinces within The Netherlands over the period 1994–2010 from the central bureau of statistics (CBS). CBS reports 4 variables: planted area, harvested area, yield and production (=harvested area * yield). From the first two we calculated the percentage of the planted area that had not been harvested. CBS makes a distinction between ware, starch and seed potatoes and between potatoes grown on clay versus potatoes grown on sand/reclaimed peat soils. Using a soil map we could determine where within each province potatoes were grown on these two respective soil types. Thus, we linked each CBS time series to a representative official KNMI station. For large provinces like Gelderland and Overijssel, where potatoes were grown throughout the province, finding one station representative for the whole province was problematic. These provinces were therefore not included in the analysis. Fig. 1 shows the provincial boundaries, where potato is grown within each province and location of weather stations.

We calculated the percentage of area not harvested from CBS data. Metadata clearly attributed the not harvested area to rainfall. Therefore, we sought to estimate this percentage from accumulated rainfall over a given period ($\text{rainsum}_{\text{start-end}}$). We calibrated the following bilinear model using the minimal RMSE as selection criterion:

$$\left(1-\frac{\text{Area}_{\text{planted}}}{\text{Area}_{\text{harvested}}}\right)*100\% = \begin{cases} 0 & \text{if rainsum} \le \text{threshold} \\ b_0+b_1*\text{rainsum}_{\text{start-end}} & \text{if rainsum} > \text{threshold} \end{cases}$$

For the calibration procedure we varied start and end date of the rainsum period with a weekly time step and picked the appropriate threshold for each rainsum. In the CBS data set we had both an extreme year (1998, all provinces) and years close to the threshold (1994, 2001, 2010, some provinces), therefore we could also with reasonable accuracy position the threshold of the bilinear model.

3. Results

Our compilation of time series (Appendix A) shows that yields have increased from around 30 t ha^{-1} (fresh weight; dry matter fraction ca. 21%) in 1950 to 50 t ha^{-1} in 1990, after which yields

Table 1
Largest yield anomalies and their cause.

Year	Cause of yield anomaly[a]	Bedrijven in eigen beheer	RIVRO Dronten	De Schreef	Minderhoud-hoeve	CBS
1954	No data	−24%	–	–	–	–
1956	No data	−31%	–	–	–	–
1965	Late start +	−29%	–	−41%	–	–
1975	Late start	−21%	+1%	−25%	−36%	–
1979	Late start[b]	–	−27%	−12%	−25%	–
1983	Late start	–	−23%	−23%	−34%	–
1998	Harvesting problems	–	–	–	–	−52%

[a] From annual reports; –: period not covered by time series; +: inferred using weather data and rainsum planting rule.

[b] At De Schreef, 1979 is not mentioned as a year with late planting.

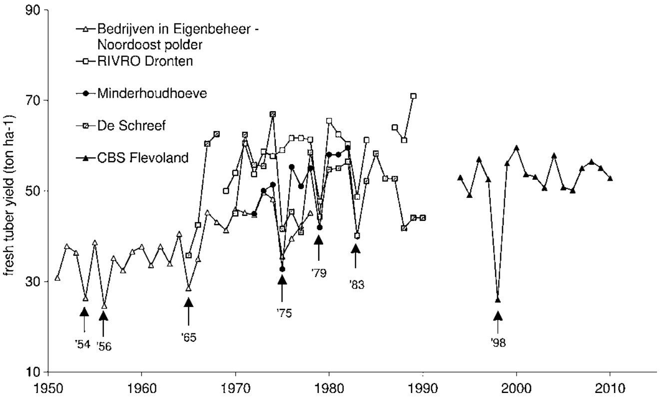


Fig. 2. Time series of potato yields (fresh weight in t ha^{-1}) in the eastern part of Flevoland, The Netherlands. Arrows indicate years with the largest negative yield anomalies. The first and last time series (Bedrijven in Eigen Beheer and CBS) are provincial data, the middle three series (RIVRO, Minderhoudhoeve and De Schreef) are point data.

stabilised. Before 1960, there were only few records. From 1960 to 1990 we found many well documented time series, thereafter records became increasingly sparse.

3.1. Impacts

The largest negative yield anomalies and their causes are shown in Table 1 and Fig. 2. The causes listed in Table 1 are based on metadata in annual reports. For the years 1954, 1956 and 1965 the "Bedrijven in eigen beheer" time series did not describe the possible cause of the low yields. Rainfall data indicate that anomalies in 1954 and 1956 could not be explained by a wet start or end of season, thus the cause remains unclear. For 1965, simulations with the rainsum planting rule suggests that this was a year with a wet start causing very late planting (Fig. 5b).

As noted in the introduction, the relation between yield and weather extreme also depends on other factors. Yield loss due to late planting depends not only on planting date but also on the rest of the growing season, management and cultivar. Nevertheless, it is clear from Fig. 3 that when planting date exceeds a certain threshold (day of year DOY 120, 30 April), chances of a large yield anomaly are far larger than below this threshold. Likewise, it can be seen from Fig. 4 that when end of season rain exceeds a certain threshold there is a large risk of having harvesting problems.

These results indicate that in Flevoland the largest negative yield anomalies over the past 50 years were caused by late planting and harvesting problems; the cause of the 1954 and 1956 yield anomalies remains unknown. Planting and harvesting problems were caused by a wet start of the growing season and a wet end of the growing season. The question addressed in the following two sub sections is: can we accurately define the two weather extremes?

3.2. Wet start of season

The threshold for late planting was set at day 120 (30 April). Farmers planting later than this date have an increased risk of yield loss. The threshold is based on our compilation of crop yields and planting dates (Fig. 3) and on work by Wind (1960), Feddes and van Wijk (1975) and van de Neut et al. (1995). Three of the four late plantings (1975, 1979 and 1983, Fig. 5a and b) caused yield anomalies of more than 20% in at least two out of three farms (Table 1). The fourth late planting (1970: RIVRO day 121, Minderhoudhoeve day

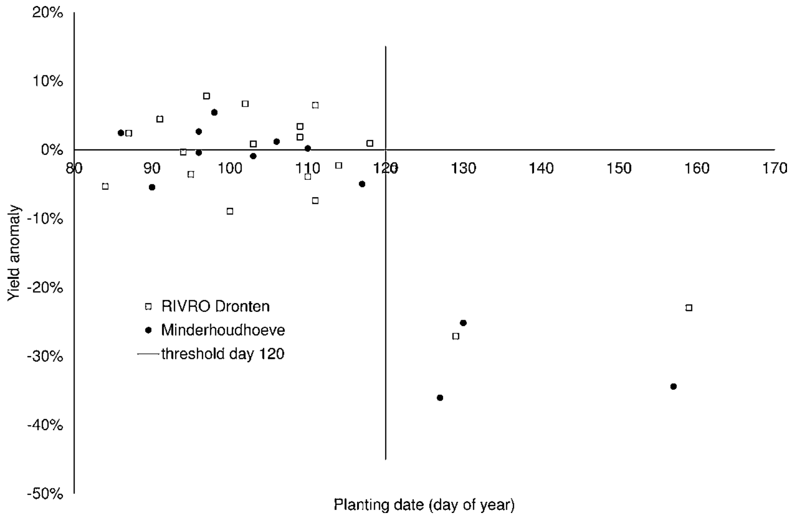


Fig. 3. Planting dates and yield anomalies at two experimental farms in Flevoland, The Netherlands.

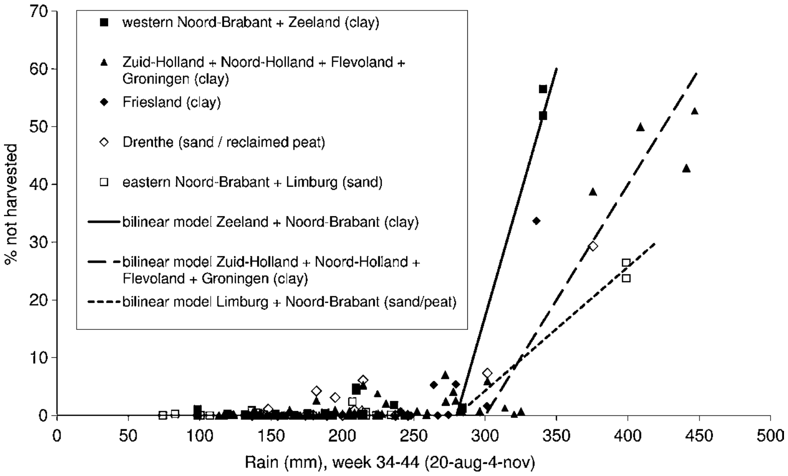


Fig. 4. Percentage of planted area of ware potatoes not harvested (time series from www.cbs.nl, 1994–2010. Each point in the figure represents an observation in one of the provinces in one particular year. Provinces with a similar response to end of season rain have been given the same symbol. The points in the top right are all observations from the year 1998, in other years (1994–2010) always 90% or more of the planted area was harvested.

126, de Schreef "early May") caused a large anomaly at De Schreef (−22%) but not at RIVRO (−3%) and not in the "bedrijven in eigen beheer" time series (+8%). Unfortunately no yield data were found for the Minderhoudhoeve for the year 1970.

Both planting rules ('dry days rule' and 'rainsum rule') accurately simulated the late planting dates and simulated no late plantings in years where these did not occur. The rainsum rule (Fig. 5b) simulates the 1970, 1975, 1979 and 1983 late plantings well (planting

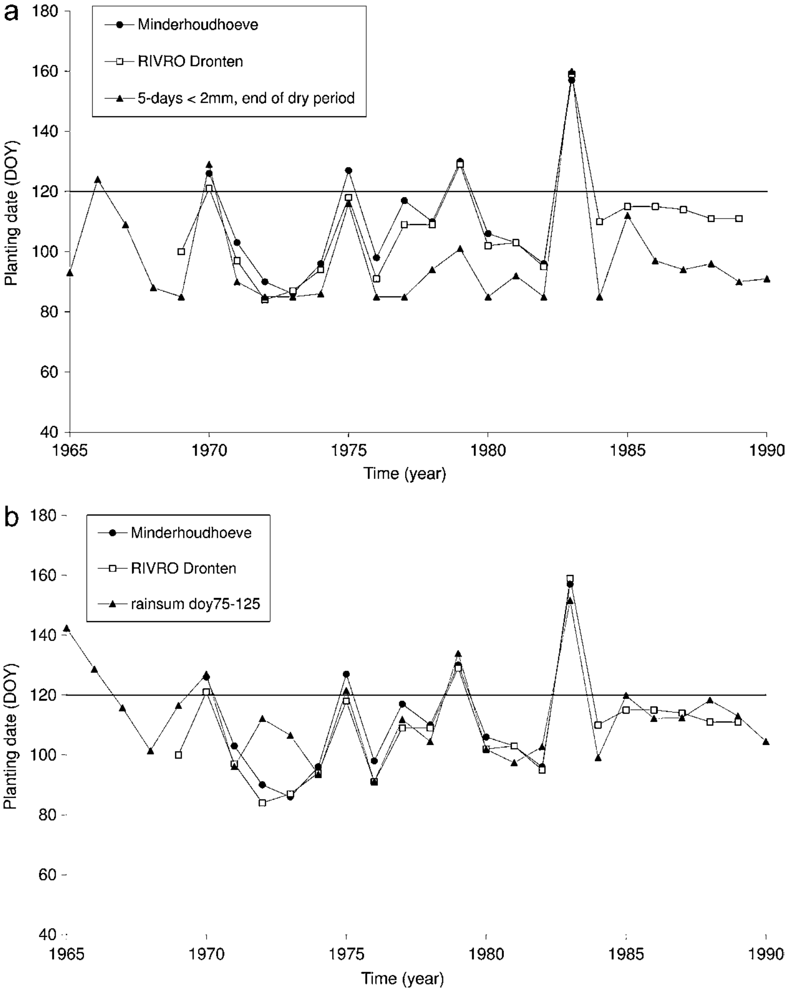


Fig. 5. Actual and simulated earliest planting dates (using the dry days model (a) and the rainsum planting rule (b)) for two experimental farms in Flevoland, with rainfall data from the station in Dronten. The rainsum rule used was: planting day = 76.7 + 0.388 * rainsum_{75_125}. Both planting rules were calibrated to correctly predict the very late planting dates and to predict no extreme planting dates in regular years. Correctly predicting planting date in regular years was not an objective.

Table 2
Bilinear models for predicting % of area of ware potato not harvested.

Region	Area not harvested (%)
Zeeland, Noord-Brabant (clay)	0.86*(rainsum$_{34-44}$ − 280)
Flevoland, Zuid-Holland, Noord-Holland, Groningen (clay)	0.40*(rainsum$_{34-44}$ − 300)
Limburg, Noord-Brabant (sand)	0.21*(rainsum$_{34-44}$ − 280)

Rainsum$_{34-44}$ is the total rainfall from week 34 to 44 (20 August to 4 November). Below the thresholds of 280 or 300 mm the estimated % of planted area not harvested is 0%.

day of year $DOY_{plant} = 76.7 + 0.388 * rainsum_{75-125}$, RMSE = 4.1/5.6 days for the extremes at the two farms). The dry days rule (Fig. 5a, 5 days with in total less than 2 mm rain, RMSE = 14.6/15.7 days) simulates the late plantings of 1970, 1975 and 1983 well, but not the 1979 late planting. In 1979 planting would according to this rule occur during the dry spell occurring between day 96 and day 102. The dry days planting rule does correctly simulate the 1979 late planting date when we force it to skip the first dry spell of DOY 96–102 (RMSE becomes 4.8/6.8, only slightly less accurate than the rainsum rule). Did farmers miss their chance during the first dry spell and were then confronted with 25 days of rain or was there another (weather) effect that we failed to notice? Unfortunately annual reports provide no information on this. The comparison with the rainsum planting rule suggests that possibly the preceding period was so wet that the first dry spell was too short for the soil to dry up sufficiently. Outside the calibration range (1969–1989), where we do not have planting dates, 1965 was simulated as a year with very late planting (Fig. 5b, DOY 145). Yield anomalies in this year were −29% and −41% (Table 1).

Based on our planting rules, the DOY 120 threshold is exceeded under the following conditions:

- No dry period of 5 days < 2 mm rain during the period DOY 80–120 (21 March to 30 April).
- More than 110 mm of rain during the period DOY 75–125 (16 March to 5 May).

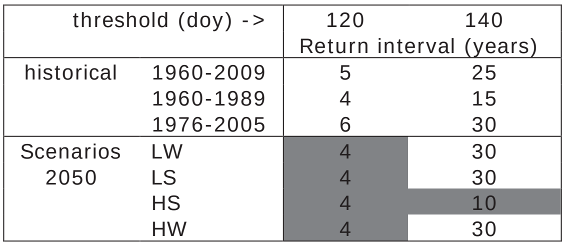
3.3. *Wet end of season*

The CBS provincial data (1994–2010) contained one year (1998) with excessive harvesting problems throughout the country. In this particular year, ware potato harvesting problems were much larger on clay soils than on sandy soils (Fig. 4); the reclaimed peat soils in Groningen/Drenthe are somewhere in between.

When August is extremely wet then soils may still become accessible later in September. When September is extremely wet then a share of the farmers will have harvested their crop already in August and some may be able to postpone till October. Only a prolonged period of continuous rain can cause unresolvable problems. We found that harvesting problems were best explained using total rainfall over the period from 20 August to 4 November and a threshold set at 280 or 300 mm (Fig. 4 and Table 2). For some stations the years 1994, 2001 and 2010 were close to this threshold, sometimes slightly above, sometimes slightly below. These years are known as difficult, but in the end almost all farmers managed to harvest their crop.

Based on our (non-) harvesting rule, we can roughly state that problems start to occur when total rainfall in the period 20-August to 4-November is larger than 300 mm. At 350 mm, the percentage not harvested area at a regional level is estimated to be more than 20% on the clay soils.

Table 3
Return interval of wet start of season based on the rainsum planting rule.



threshold (doy) ->		120	140
		Return interval (years)	
historical	1960-2009	5	25
	1960-1989	4	15
	1976-2005	6	30
Scenarios 2050	LW	4	30
	LS	4	30
	HS	4	10
	HW	4	30

A return interval of 5 for threshold day of year 120 means that this threshold (planting date) is exceeded on average once in every 5 years. Red shading indicates a more than ±25% change in frequency relative to historical reference period 1976–2005.

3.4. *Frequency past and future*

How often did these extremes occur in the past? How meaningful are such frequencies based on sparse meteorological data and might these frequencies change due to global climate change? These questions are answered in the following sections.

3.4.1. *Wet start of season*

We used the rainsum rule to calculate the frequencies of planting dates exceeding two thresholds: DOY 120 for start of planting problems and DOY 140 threshold for severely late plantings. During 1960–2009 simulated planting dates were later than 120 in 10 out of 50 years (average once in 5, Table 3) and later than 140 in 2 years (1965 and 1983). The average frequency was relatively high during 1960–1989 (120 exceeded once in 4 years) and relatively low in 1976–2005 (120 exceeded once in 6 years), see Table 3. Applying the same rule to the longest available time series suggests that also over the last 100 years, the period 1960–1989 had a relatively high incidence of this extreme (Fig. 6).

Climate change scenarios indicate no change or increased frequency of this extreme (Table 3). Calculations on changes in frequencies are very sensitive to the planting rule used. According to the dry days planting rule there will be no change in frequencies of late plantings (data not shown) while according to the rainsum rule, frequencies of late planting will increase from one in 6 years around 1990 (1976–2005) to one in 4 years around 2050 (Table 3, red colouring). Calculations on changes in frequencies are also sensitive to the reference period used, relative to the period 1960–1989 there is no change in frequency.

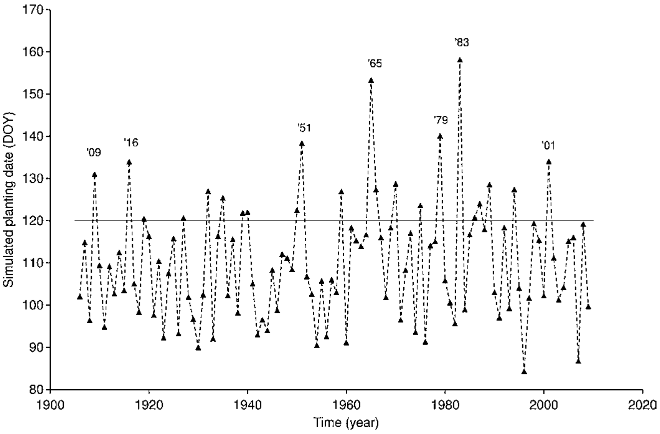


Fig. 6. Potato planting dates simulated with the rainsum planting rule with long-term weather data of De Bilt weather station (the longest available time series for The Netherlands). Solid horizontal line indicates a planting date of 120, numbers indicate years of extremely late planting.

Table 4
Return interval of wet end of season.

station	Start KNMI series	historical return interval (years)				future return interval for exceeding the 350mm threshold F350							
		1976-2005		1974-2003		compared with 1976 - 2005				compared with 1974 - 2003			
		F300	F350	F300	F350	LW	LS	HS	HW	LW	LS	HS	HW
Valkenburg (Z.-Holland)	1972	8	30	8	15	30	30	15	30	30	30	15	30
De Kooy (N.-Holland)	1957	8	30	6	15	10	15	8	30	10	15	8	30
Schiphol (N. -Holland)	1971	15	30	30	30	15	30	15	30	15	30	15	30
De Bilt (Utrecht)	1906	15	30	15	30	30	30	30	30	30	30	30	30
Soesterberg (Utrecht)	1974	30	30	30	30	30	30	30	30	30	30	30	30
Leeuwarden (Friesland)	1974	15	>30	30	>30	30	30	15	30	30	30	15	30
Eelde Groningen)	1957	15	30	15	30	30	30	30	30	30	30	30	30
Twenthe (Overijssel)	1974	30	30	30	30	30	30	30	30	30	30	30	30
Vlissingen (Zeeland, Westen part of N.-Brabant)	1957	30	>30	15	30	30	30	30	30	30	30	30	30
Rotterdam (Z.-Holland)	1974	10	30	8	15	10	15	10	30	10	15	10	30
Volkel (Noord-Brabant)	1974	30	30	30	30	30	30	30	30	30	30	30	30
Maastricht (Limburg)	1957	30	>30	30	>30	30	>30	30	>30	30	>30	30	>30
Average		20	30	21	26	25	27	23	30	25	27	23	30

The table shows the return interval for years in which the rainfall sum over the period 20 August till 4 November is greater than 300 mm (F300, start of harvesting problems) and greater than 350 mm (F350, serious problems). F300 = 8 means that the event occurred on average once in 8 years. LW, LS, HW and HS are the downscaled KNMI climate change scenarios. Green shading means the extreme occurs >25% less often (e.g. from once in 15 to once in 30 years), red shading means >25% more frequently (e.g. from once in 30 to once in 10 years). We compare future frequencies (around 2050, simulated weather data 2036–2065) with two historical (reference) periods: 1976–2005 and 1974–2003.

3.4.2. *Wet end of season*

The analysis of historical weather records showed that 1998 had the highest amount of rain (average 399 mm) in the period 20 August–4 November and was above the threshold of 300 mm for the whole country. The second largest rainfall sum over this period occurred in the year 1974 in which the part of The Netherlands along the North Sea Coast received on average 378 mm. This year is known in Dutch history as the year in which the army was employed to help farmers in their potato harvesting operations, adding credibility to our definition of this weather extreme. We analysed spatial and temporal variability in the occurrence of this extreme. Spatially, we find that the North Sea coast has a higher frequency (lower return interval) than inland regions.

Climate change scenarios showed either no change in frequency, or an increase in frequency of this extreme (Table 4). Sensitivity analysis showed quite different historical return intervals after just shifting the start date of the reference period by 2 years (comparing 1974–2003 with 1976–2005). The uncertainty about the historical (reference) frequencies also affects statements about changes in frequency (Table 4). For the station with the longest time series (De Bilt) we find that the 350 mm threshold was exceeded only once (in 1998), hence the return interval for this threshold could not be calculated. Limited data availability makes further reconstructions impossible (see the first column of Table 4 with start year of records of the listed official KNMI stations). Whether the 1998 event is a consequence of ongoing climate change and will occur more often in the near future is unclear. Our sensitivity analysis shows the problem of using 30 years historical weather data as input for generating future climate scenarios; 30 years is simply too short a period for making statements on the frequency of extremes like the 1998 wet end of season.

4. Discussion

4.1. *Main findings*

Our results show that the two extremes with highest impact on potato yields over the course of a period of 50 years were a wet start of the growing season and wet end of the growing season. We do not know if these two extremes are also the highest impact extremes in other potato growing areas of the world. While our methods are generic, the findings are likely to be specific to the agro-meteorological conditions in The Netherlands. We were able to translate the qualitative definitions of the extremes into quantitative definitions. The quantitative definition of the wet start extreme was based on point data in the province of Flevoland. We expect the definition of this extreme to be valid for other major production areas in The Netherlands, since the majority (ca. 70%) of Dutch ware potatoes are grown in similar soils (clay) with similarly high ground water levels. Both for planting and for harvesting we may expect problems to be larger on the more poorly drained clay soils. Indeed, we did not find extremely late plantings in starch potatoes on sand/reclaimed peat soils in the North East of The Netherlands (based on planting dates reported in Steenhuizen et al., 2000) while van de Neut et al. (1995) reported similar late-planting induced yield losses caused by a wet start in De Hoekse Waard, a potato growing area on clay soils in the province Zuid-Holland. For the wet end of season extreme we used regional data and derived different definitions for different parts of the country, related to soil type. Our analysis of harvesting problems (Fig. 4) clearly showed that harvesting problems were larger on the clay than on the sand soils.

Subsequently the definitions of the extremes were combined with historical and future weather data. Climate change scenarios showed either no change or increase in frequency of the two extremes identified here. Statements on frequency change were dependent on which historical period we used as a reference. We found that the period 1960–1989 had a relatively high frequency of the wet start of season extreme, the period thereafter had a lower frequency and scenarios suggest an increase in frequency relative to the current period, back to frequency of the period 1960–1989. The wet end of season is a more rare extreme than the wet start. We found that available historical weather time series were too short to accurately calculate the historical frequency of this extreme. Statements on change in frequencies of the extremes under scenarios of climate change are highly uncertain. The main causes of uncertainty are (1) too short historical records, (2) climate change projections of precipitation are much more uncertain than those for temperature (Lobell et al., 2008), also in The Netherlands (van den Hurk et al., 2006), and (3) high spatial resolution simulations of total rainfall for the identified periods (>50 days) are difficult, considering the chaotic nature of the climate system and incomplete data and understanding of hydrological cycles (Knapp et al., 2008; Maraun et al., 2010).

The impact of extremes is evidently large in those years in which they occur (Figs. 2–4). Their relative impact averaged over a period of several years is highly uncertain, strongly sensitive to choice of the period over which yields and impact of extremes are calculated and hampered by lack of data availability. For instance, the historical, relative impact of end of season rain on Dutch ware potato production would be twice as high if we were to calculate it over the period 1974–2003 (with the 1974 and 1998 extreme) instead of the period 1976–2005 (only the 1998 extreme, Table 4). The relative impact would be even higher if we were to calculate it over a shorter period (e.g. 1990–2000). Likewise, any statement on future impact is contingent on highly uncertain projections of future rainfall.

4.2. Previous studies on climate change impact on potato production

A question that arises is whether previous studies on potato have included the two extremes in their climate change impact studies. Previous studies on potato have shown the importance of planting date as a yield determining management decision and as an adaptation option to climate change (Rosenzweig et al., 1996; Davies et al., 1997; Wolf, 2002; Hijmans, 2003). Peiris et al. (1996) noted workability and trafficability of the land as a possible issue that was not included in the models they used. It suggests that the trafficability related weather extremes identified in this paper may also be an issue in other environments. Haverkort and Verhagen (2008) called for more empirical data on this topic: “planting time experiments or comparing years of early accessibility to the field with late accessibility resulting in varying length of the growing season”. Effects of changing planting date have also been investigated experimentally for potato, though not in the context of climate change (Roy and Jaiswal, 1998; Opoku-Ameyaw and Harris, 2001; Hospers-Brands et al., 2008; Hassanpanah et al., 2009; Roshani et al., 2009). We found no empirical research on what rules farmers apply to select their planting dates and harvesting dates and we found no studies in which the accuracy of a potato growth simulation models was tested in case of late planting. Although simulations show that earlier planting is an interesting management option under climate change to raise yields, it remains to be tested whether earlier planting is practically possible in terms of soil water conditions and trafficability.

4.3. Validity and agro-hydrological modelling

The approach used in this paper is highly empirical, but it is more than just a data mining exercise: metadata and agronomic insight played an important role in identifying the extremes. Our study helped to identify weather extremes and highlight the causalities that link the extremes to their ultimate impact on yield. Strengths and limitations of our work are its sole reliance on meteorological variables defining a weather extreme. We have shown that it is possible, with a limited number of weather variables, to define factors that have a great impact on crop yield. However we know that weather is but one of the factors affecting crop yields. The impact of the same amount of rain will be different in a better drained soil. As we have shown in the regional analysis of harvesting problems, the impact and threshold may be different depending on soil type. We did not investigate the relation between rainfall, soil water holding capacity and drainage rates in a more extensive way because sufficiently accurate data on a regional scale are lacking for such an analysis.

There is scope for more mechanistic and empirical research on the interaction between rainfall, drainage and planting/harvesting problems. At the field level, a more mechanistic understanding of soil hydrology is already incorporated in many models (e.g. WOFOST, van Diepen et al., 1989; APSIM, Keating et al., 2003). Some of these models also contain planting rules such as planting a crop only if sufficient water is available (Keating et al., 2003; Donatelli et al., 2009). The presence of such rules in models does not guarantee that these rules accurately reflect farmers' decision making. Very few researchers have studied actual sowing dates and established direct relationships between choice of sowing date, weather and soil moisture content (rare exceptions are Hammer et al., 1987; van de Neut et al., 1995).

Hydrology, soil types and cultivars differ within and across regions. Where high resolution data (in space and time) are lacking, as is almost invariably the case, we must accept a lower precision. This is apparent in our study on the relation between wet end of season and harvesting problems. Early-, mid- and late cultivars are all grown in each region studied. Our bi-linear models can therefore not be directly applied at the field level. The critical period of prolonged rain might be shorter for a single cultivar (e.g. mid-August till end of September for an early cultivar) than for the mixture of cultivars in a region, while the critical period of rain might be shorter on soils with poorer drainage. Unfortunately, a lack of data did not allow us to answer such questions.

4.4. Further research

Historical reconstructions such as those presented here can reveal knowledge gaps relevant in the understanding of important weather variables for agricultural production. Our compilation of data (Appendix A, Fig. 7) revealed a worrying trend for The Netherlands: since 1990 there has been a large drop in freely available well documented data. It seems that the current trend is to invest less and less in the actual measurements, collection and publication of data. Our study shows that data and metadata are invaluable to understand climate–management interactions. Furthermore, the data of experimental stations that were previously published in reports are currently being published through web pages and with less background information on the experiments. If these web pages are not sustained then in the long run data will be lost for ever. If experimental farms are closed without recognition of the importance of their archives, potentially very valuable data will inevitably be lost. We call for more historical reconstructions, not only of weather data (e.g. www.met-acre.org/) but also impact data (in this study crop yields) and background information, metadata which is essential for retracing the chain of events from weather extreme to impact. The extremes identified here were identified specifically for one crop and one country. Our approach can be applied to a wider range of crops and regions. Eventually this might lead to meta-datasets, in which high impact weather extremes for climatic gradients are described. In this way, information on weather extremes identified in one climatic region can reveal new threats for another region: a new and an on-going challenge for science.

5. Conclusions

We have identified the weather extremes that were responsible for the largest negative yield anomalies in ware potato in the province of Flevoland in the last 50 years: (1) a wet start of the season delays planting which in turn reduces yield and (2) a wet end of the season that inhibits harvesting operations. Quantitative meteorological definitions were developed and there is scope for linking these definitions to existing crop growth models and soil hydrology. Climate change scenarios indicated either no change or increased frequency of these extreme events. We have shown that statements on changes in frequency are uncertain, due to lack of long (>30 years) historical weather data and due to uncertainty in climate change projections in terms of rainfall. The challenges are for

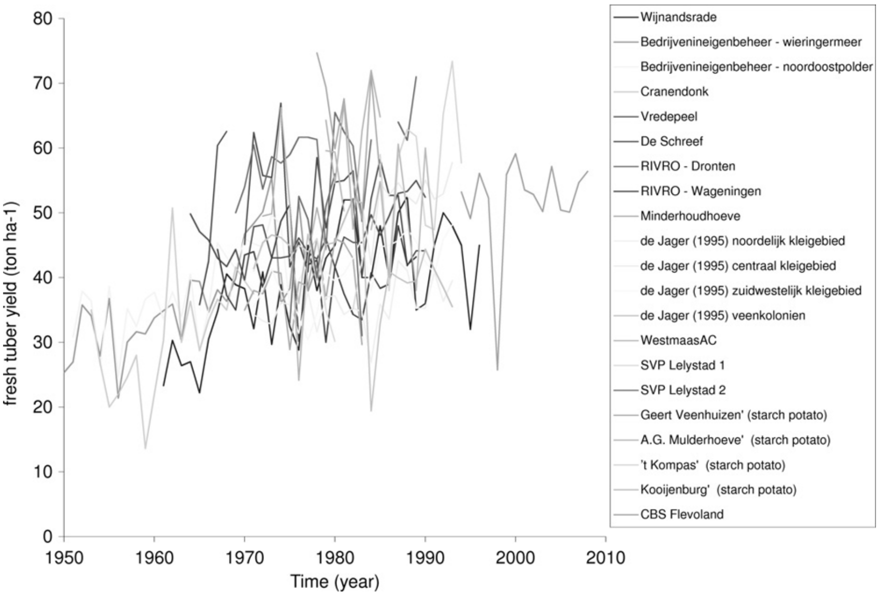


Fig. 7. List of all time series of ware potato yields compiled from references listed in Appendix A.

agronomists to use the same approach to investigate extremes in other parts of the world, for meteorologists to develop forecasting skill for these extremes and for climate change impact modellers to include effects of extreme events in their models. Ultimately such research can contribute to improved risk management.

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Appendix A.

Time series of potato yield data available from the library of Wageningen University.

The figure and table with references lists time series of 8 years or more. Some of the references provide data of more than one farm or region. The references include both regional statistics and references to reports of experimental farms, with experiments conducted at different plots (Fig. 7).

Table with references to time series.

Crop	Dataset	From	To	Reference
Seed potato	Bedrijven in eigen beheer (Noordoostpolder and Wieringermeer)	1951	1978	Lalkens, R.H., 1985. Bedrijven in eigen beheer, 1950–1978: documentatierapport bij publikatie 3.132. Den haag: L.E.I., 18 p.
Seed potato	De Jager	1970	1992	Akkerbouw 1975–1995, [door] J.H. Jager, 1995, Periodieke rapportage/Landbouw-Economisch Instituut (LEI-DLO), Afdeling Landbouw (ISSN 0923-7143; nr. 5-93)
Seed potato	Central Bureau of Statistics (CBS) per province for all crops. Five categories of potatoes: 1 Ware potatoes on clay 2 Ware potatoes on sand/reclaimed peat 3 Seed potatoes on clay 4 Seed potatoes on sand/reclaimed peat 5 Starch potatoes	1994	Now	http://statline.cbs.nl/statweb/
Starch potato	‘t Kompas’	1985	1999	Steenhuizen, J.W., Haren, R.J.F. van, Metselaar, K., Begeman, J.R., Wijnholds, K.H., 2000. Proefveld- en praktijkgegevens betreffende de aardappelteelt voor de zetmeelindustrie ten behoeve van modellering: groeicurves van zetmeelaardappelrassen op de noordelijke zand- en veenkoloniale gronden (1973–1999). Wageningen: Plant Research International http://www.library.wur.nl/WebQuery/edepot/120249
Starch potato	‘A.G. Mulderhoeve’	1979	1985	Steenhuizen et al. (2000). Same as above
Starch potato	‘Kooijenburg’	1979	1999	Steenhuizen et al. (2000). Same as above
Starch potato	proefboerderij ‘Geert Veenhuizen’	1973	1985	Steenhuizen et al. (2000). Same as above

Appendix A (*Continued*)

Crop	Dataset	From	To	Reference
Starch potato	Central Bureau of Statistics (CBS) per province for all crops. Five categories of potatoes: 1 Ware potatoes on clay 2 Ware potatoes on sand/reclaimed peat 3 Seed potatoes on clay 4 Seed potatoes on sand/reclaimed peat 5 Starch potatoes	1994	Now	http://statline.cbs.nl/statweb/
Ware potato	Bedrijven in eigen beheer	1950	1978	Lalkens (1985). See above
Ware potato	Cranendonk	1953	1971	Verslag proefboerderij van de Noord-Brabantsche christelijke boerenbond "Cranendonck" te Maarheeze
Ware potato	De Jager (regional data, 4 major clay regions in NL)	1970	1992	Jager, J.H., 1995. Akkerbouw 1975–1995. Landbouw-Economisch Instituut (LEI-DLO), Afdeling Landbouw (ISSN 0923-7143; nr. 5-93)
Ware potato	De Schreef	1965	1990	Hoekstra, O., Lamers, J.G., 1993: 28 jaar De Schreef. Proefstation voor de Akkerbouw en de Groenteteelt in de Vollegrond, publikatie nr 67, Lelystad.
Ware potato	Minderhoudhoeve	1970	1983	Proefbedrijf Ir. A.P. Minderhoudhoeve, Landbouwhogeschool, Jaarverslag 1977
Ware potato	RIVRO Dronten	1967	1989	Verslag van de proefboerderijen in Wageningen en Dronten over 1967, Verslag van de proefboerderij en proeftuin te Wageningen en de proefboerderij te Dronten over 1989, Rijksinstituut voor het Rassenonderzoek van Cultuurgewassen RIVRO Wageningen
Ware potato	RIVRO Wageningen	1967	1989	Verslag van de proefboerderijen in Wageningen en Dronten over 1967, Verslag van de proefboerderij en proeftuin te Wageningen en de proefboerderij te Dronten over 1989, Rijksinstituut voor het Rassenonderzoek van Cultuurgewassen RIVRO Wageningen, Omvat uitgebreide informatie: rassen, zaai data, omschrijving van het weer, kaart van de percelen, voorvrucht, etc.
Ware potato	Stichting voor Plantenveredeling S.V.P.	1974	1983	van de Weg, M. en Glerum, A.J.,1975–1983, Jaarverslag over de proefbedrijven te wageningen en Lelystad. Stichting voor Plantenveredeling S.V.P., NN38181
Ware potato	Vredepeel	1964	1990	"Van onderzoek naar voorlichting 1991: Onderzoeksresultaten van de proefboerderij de vredepeel voor de akkerbouw op de z.o. zandgronden", page 14 in 1984 report: 1964–1984 + page 24 in report 1991 report: 1970-1991
Ware potato	Westmaas	1972	1979	Lumkes, L.M.; Ovaa, I.; Preuter, H., 1983. Acht jaar grondbewerkingssystemen-onderzoek te Westmaas. Lelystad: PAGV, 23 p.
Ware potato	Wijnandsrade	1959	1996	Van Onderzoek naar voorlichting, yyyy. Onderzoeksresultaten van de proefboerderij wijnandsrade. Bibliotheek PPO Lelystad, code V230C/1988, Bibliotheek Wageningen, code UB MAG NN21321, Bibliotheek Wageningen, code UB MAG NN21321
Ware potato	Central Bureau of Statistics (CBS) per province for all crops. Five categories of potatoes: 1 Ware potatoes on clay 2 Ware potatoes on sand/reclaimed peat 3 Seed potatoes on clay 4 Seed potatoes on sand/reclaimed peat 5 Starch potatoes	1994	Now	http://statline.cbs.nl/statweb/

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