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Recent weather extremes and their impact on crop yields of the Netherlands

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ABSTRACT

We assessed impacts of recent weather extremes on yields of major food and feed crops in the Netherlands. Impacts on the arable crops potato, sugar beet, onion and winter wheat were analysed in 12 regions. Impacts on the forage crop yields grass and maize were analysed for 6 regions. This study shows impacts of weather extremes on crop yields, mediated by soil and agricultural management (irrigation, fungicides, etc). We show that two large scale weather extremes had a major impact on crop yields. The 1998 extremely wet harvesting period had a major negative impact on all tuber crops (potato, sugar beet, onion). The 2018 extremely dry summer period had a major negative impact on grass and onion. One region was found to be particularly sensitive to drought, which seems to be related to this province having poor access to irrigation. Much larger negative impact of drought in this one region shows that impact of extremes can be strongly mitigated by agricultural management (irrigation). Therefore, should access to irrigation decline in the future, impact of drought would be larger than reported here. Our analysis contributes to a deeper quantitative understanding of which weather extremes actually affect crop production and subsequently benefits the quest for adaptation options.

1. Introduction

There is a growing concern over climate change increasing the frequency of weather extremes and their impact on agricultural production (Beniston et al., 2007; Katz and Brown, 1992; Lesk et al., 2016). It is easy to quantify weather extremes as rare weather events, much harder to quantify their impact (Beillouin et al., 2020; Katz and Brown, 1992; Lesk et al., 2016; Vogel et al., 2019; Yan et al., 2022). Three approaches are used to quantify impact of weather extremes on agricultural production: crop growth modelling (e.g. see (Barlow et al., 2015; Gobin, 2010, 2018)), empirical approaches (e.g. see (Lanning et al., 2011; Troy et al., 2015; van Oort et al., 2012a)) and analyses based on expert knowledge (e.g. see (Schaap et al., 2011; Schaap et al., 2013)). Impact depends not only on the weather extreme itself, but also on crop, soil and agricultural management. Examples of agricultural management mitigating impact are drainage and irrigation, which can lead to a de-coupling of the relation between weather extremes and crop yield anomalies (Troy et al., 2015). Without information on actual agricultural management, modelling outcomes remain quite uncertain. Actual yields are the aggregated outcome of combined effects of weather extreme, crop, soil and management. The chain of events ultimately causing yield anomalies may be hard to retrace from yield data alone.

The year 2018 was extremely dry throughout Europe (Beillouin et al., 2020), also in the Netherlands (Sluijter et al., 2018). Impacts of this drought have never been analysed at higher spatial resolutions. Here, we build on a previous study where we identified key weather extremes' impact on potato yields in the Netherlands (van Oort et al., 2012a). Using 60 years of weather data, farm data and regional yield data we identified two weather extremes responsible for major ware potato yield anomalies in those 60 years: (1) an extremely wet start of the growing season causing delayed planting and (2) an extremely wet harvesting period causing harvest problems. The dataset used in this previous study was biased due to farm data originating mainly from one region (Flevoland) with good irrigation access. Limited farm data were available from the previous record large scale drought of 1976. The recent extreme drought offers a renewed opportunity for investigating impact of drought on crop yields. Compared with our previous study (van Oort et al., 2012a), we broaden the scope by analysing the impact of 4 types of weather extremes (wet planting period, wet growing period, dry growing period, wet harvesting period). We extend the analysis to all major crops of the Netherlands (Fig. 1). The crops considered together represent 88% of Dutch crop area of 2019: grass

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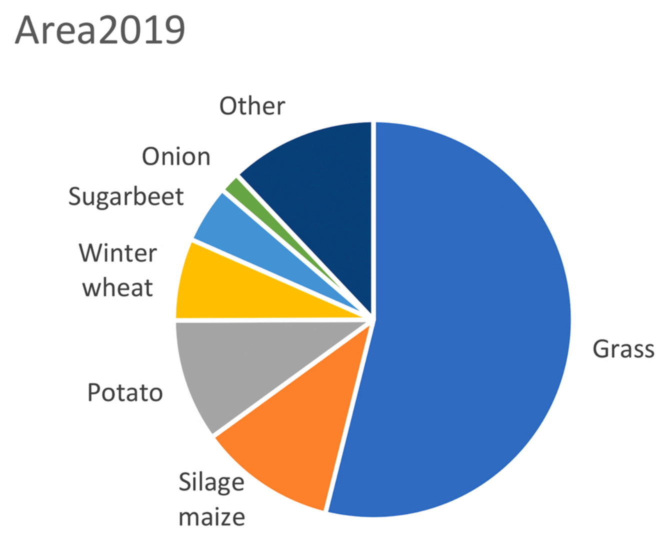

Fig. 1. Agricultural land use in the Netherlands 2019.
Source: Central Bureau of Statistics (CBS, 2022b).

(54%), silage maize (11%), potatoes (10%: ware: 5%, seed 3%, starch 3%), winter wheat (7%), sugar beet (5%) and onion (2%). Economically the crops we analysed are also the most important crops in the Netherlands (Schaap et al., 2013).

The objective of this paper is to contribute to the scientific basis for better climate risk management by better understanding weather extremes' impact on crop yields. We analyse impact of four weather extremes on crop yield anomalies for major crops of the Netherlands. The hypotheses are that (1) the four weather extremes can, but do not necessarily, have a large negative impact on crop yields and (2) actual negative impact can be moderated by farm management, crop traits and soil and landscape position. We test the first hypotheses using weather data and crop yield data. Quantitative data for testing the second hypothesis are unavailable at a large scale. Therefore, we reflect on this second hypothesis using agronomic knowledge of field crop cultivation in the Netherlands.

2. Material and methods

2.1. Data

2.1.1. Weather data

Daily precipitation and potential evapotranspiration (ET_0) were collected from the Dutch weather service (KNMI, 2022a), for 11 KNMI weather stations across the Netherlands (Table 1, Figs. 2, 3). ET_0 values are calculated by KNMI using the 'Makkink' method (Makkink, 1957). The precipitation deficit was calculated as ET_0 minus precipitation.

Table 1
Weather stations and linked FADN and CBS regions.

Weather stations			Linked regions	
Name	Code	First year[$]	FADN	CBS
De Kooy	235	1965	Clay	Noord-Holland
De Bilt	260	1960		Utrecht
Lelystad	269	1992	Clay	Flevoland
Leeuwarden	270	1988	Peat	Friesland
Deelen	275	1988	Sand Central	Gelderland
Eelde	280	1965	Sand North	Groningen
Eelde	280	1965	Sand North	Drenthe
Twenthe	290	1988		Overijssel
Vlissingen	310	1964	Clay	Zeeland
Rotterdam	344	1988	Peat	Zuid-Holland
Eindhoven	370	1985	Sand South	Noord-Brabant
Maastricht	380	1965	Loss	Limburg

[$] first year for which both rainfall and ET0 data are available. Some stations have longer time series for temperature. For some stations incomplete rain and ET0 timeseries are available for earlier years, the years listed in this table are the first year from which onwards to now complete rainfall and ET0 data are available.

2.1.2. Crop data

2.1.2.1. Arable crops. The arable crops included in our study are ware, seed and starch potatoes, sugar beet, onion and winter wheat. Arable crop yields are available from the Central Bureau of Statistics (CBS, 2022a) at the provincial level (Table 2, Fig. 2). CBS determines planted area (ha), harvested area (ha) and yield (kg/ha) through annual surveys. Yield in the CBS definition refers to the yield of those fields from which crops were actually harvested. This approach obscures harvesting problems (van Oort et al., 2012a), because for the fields that were planted but not harvested, the yield was zero. We first calculated production as yield x harvested area and then yield as total production / planted area. Dividing by 'planted area' does account for losses from not-harvested fields. For onion, quality losses may become apparent after harvesting, during storage. CBS reports onion yields before (without) and after (with) quality losses. We used the latter in our calculations.

2.1.2.2. Forage crops. CBS does not report forage crop yields at the provincial level. The lowest available spatial scale for the yield of forage crops is the FADN dataset (Roskam et al., 2020), with 6 regions (Fig. 3). From this database, we extracted the total dry matter yield (kg/ha) of grass and forage maize, between 1998 and 2020. The production of harvested forage maize is determined by measurements of on-farm silage stocks, corrected for conservation losses. A similar approach is used to determine the production of cut grassland. The production of grazed grassland is calculated as the difference between the energy demand for milk production, growth and maintenance, and the energy supply by grass silage, maize silage and concentrates. The production of grass is calculated as the sum of cut and grazed grass. The yields of grass and maize are calculated by dividing the production by the respective areas (Aarts et al., 2008; Duijnen et al., 2021). A possible issue with the FADN data is that year 2000 is missing. Results for the arable crops showed no weather extremes or crop extremes in the year 2000. We therefore expect no problems in our analysis from missing FADN crop data in year 2000.

2.2. Extremes

We defined thresholds for weather variables and crop yields as the upper or lower 5% percentile of all observations. Any observations above the upper or below the lower threshold where classified as extreme. Clearly, large interannual variation exists also within this "normal" and within this "extreme", see for example Fig. 4. With such variability one could state there is no such thing as "normal" weather or a "normal" crop yield. For lack of better wording, we use the words "normal" here for the upper 95% and "extreme" for the lower 5% of observed values.

2.2.1. Weather extremes

Searching for high impact weather extremes has been compared with looking for a needle in a haystack: an infinite number of definitions of extremes are possible, many of which have no noticeable impact on crop yields. We used a priori agronomic knowledge to focus on four types of weather extremes for key periods with agronomic importance and proven high impact (Table 3). We selected a wet planting period (van Oort et al., 2012a), a wet harvesting period (van Oort et al., 2012a), a dry growing period (Beillouin et al., 2020; Gobin, 2010, 2018) and a wet growing period. Although there is less empirical evidence for the impact of a wet growing season, there are good reasons to include it in our

Fig. 2. Dutch Provinces and linked KNMI weather stations.

analysis. One may expect increased nutrient leaching, lower radiation levels associated with persistent c

Table 3 were calculated from 5 stations with complete time series between 1965 and 2021 and a good spatial distribution (De Kooy, De Bilt, Eelde, Vlissingen and Maastricht), covering North, Centre, East, West and South of the country (Fig. 1).

The same set of weather extremes was applied to all crops. Admittedly differences in planting period exist between crops and between regions (van Oort et al., 2012b). Growing periods and harvesting periods are also different between crops and between cultivars. Roughly the crops considered here all have the same growing period. Grass has a longer growing period from March/April to October/November. Winter wheat is sown in October and harvested in July. At 52 degrees latitude irradiance in the Netherlands shows strong seasonal effects with irradiance being intermediate in spring and high in summer. Our definition of the growing period as being May-Aug covers that part of the (longer) growing period of grass and winter wheat in which highest irradiance and thus highest growth are to be expected.

Cases where two weather extremes occurred in the same year and region were very rare and did not affect the outcomes of our analyses. We address this issue in the interpretation of the results.

2.2.2. *Crop yield extremes*

To allow for comparison among crops and regions we normalise the data by dividing yields for all region-year-crop combinations by the normally expected crop yield for that region. The relative yield (RY) for crop c in region r in year t was calculated as:

$$RY_{c,r}(t) = \frac{Y_{a,c,r}(t)}{\widehat{Y}_{c,r}(t)} - 1 \qquad (1)$$

Where $Y_{a,c,r}(t)$ is actual (observed) crop yield and $\widehat{Y}_{c,r}(t)$ is expected yield, obtained through linear regression of $Y_{a,c,r}(t)$ on t, and thus accounting for possible trends in yields. Breeding and technological advances may have led to yield increases over time (Fischer et al., 2014; Schils et al., 2020). The trend correction accounts for these developments, allowing us to single out the effect of weather extremes on crop yields.

When yields $Y_{a,c,r}(t)$ are normal, $Y_{a,c,r}(t)$ equals $\widehat{Y}_{c,r}(t)$ in which case the relative yield RY is zero. A negative RY indicates that yields $Y_{a,c,r}(t)$ are lower than expected. For instance, an RY of -0.2 means yields are 20% lower than normal. We considered a relative yield below the 5th percentile as a crop yield extreme, indicating the 5% lowest relative crop

Fig. 3. FADN regions and linked KNMI weather stations.

Table 2
Overview of collected crop yield data.

Crop	Source	n	Regions	Years	Remarks
Potato Ware	CBS	324	12	27	
Potato Seed	CBS	314	11	27	Less data for Utrecht: 17 years
Potato Starch	CBS	54	2	27	
Sugar beet	CBS	324	12	27	
Onion	CBS	308	11	26	Less data for Utrecht: 17 years
Winter wheat	CBS	324	12	27	
Grass	FADN	168	6	20	No data for year 2000. Clay: 3 stations; Peat: 2 stations
Silage maize	FADN	171	6	20	No data for year 2000. Clay: 3 stations; Peat: 2 stations

yields for each crop. Percentiles were calculated from regions with the same length of timeseries, excluding three regions with incomplete timeseries: ‘Loss’ (FADN), ‘Sand South’ (FADN) and ‘Utrecht’ (CBS).

2.2.3. *Weather and crop yield extremes*

For each crop and each weather extreme, we grouped the relation between the occurrence of weather extreme and the occurrence of crop yield extreme in four possible categories:

- W_1C_1: Co-occurrence of weather extreme and crop yield extreme
- W_1C_0: Occurrence of weather extreme with a normal crop yield
- W_0C_1: Occurrence of crop yield extreme with normal weather
- W_0C_0: Co-occurrence of normal weather and normal yield

From these 4 categories we calculated the following conditional probabilities:

$$p(W_1|C_1) = W_1C_1 / (W_0C_1 + W_1C_1) \tag{2}$$

$$p(C_1|W_0) = W_0C_1 / (W_0\mathbf{C}_1 + W_0C_0) \tag{3}$$

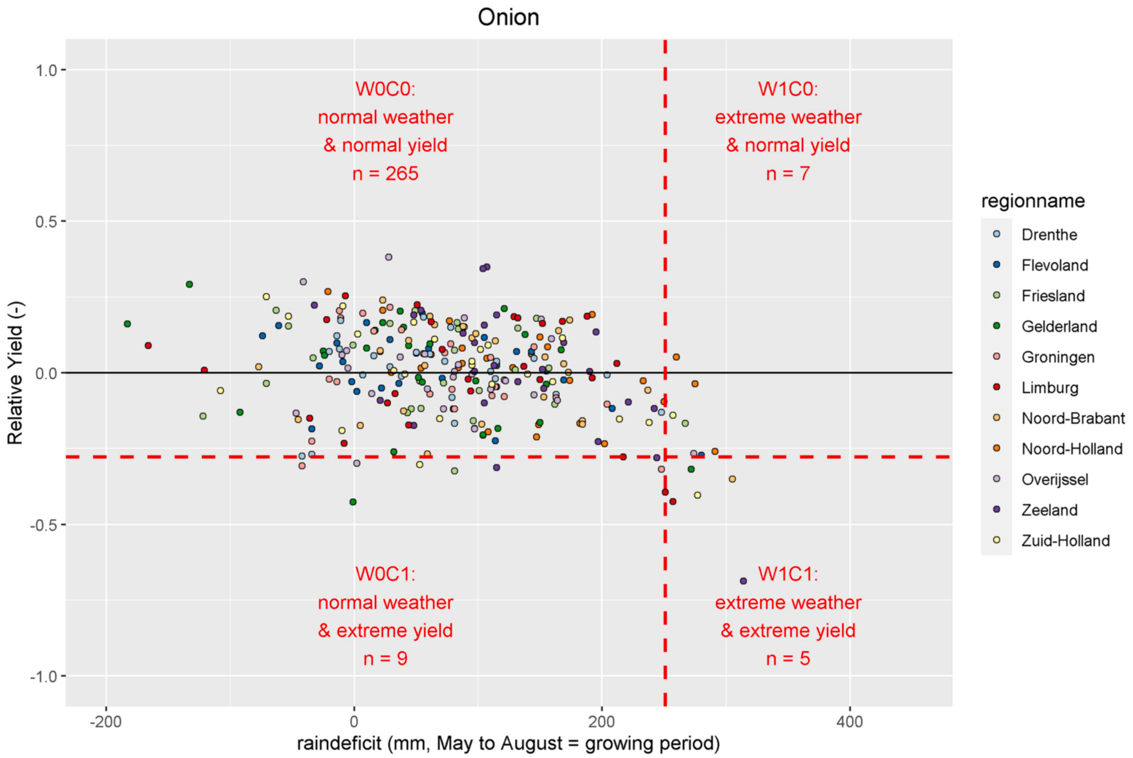

Fig. 4. Relative yields in relation to sum of precipitation deficit during the growing period for the onion crop. x-axis: Sum of precipitation deficit between 1 May and 31 Aug (mm); y-axis: relative yield (Eq. (1)). Horizontal dashed red line corresponds with 5th percentile of relative crop yields as defined per crop in table Fig. 6. Vertical dashed red line corresponds with 95th percentile of the sum of precipitation deficit as defined in Table 3. Horizontal solid black line corresponds with mean relative yield.

Table 3
Weather extremes and their 5th and 95th percentile threshold values.

Weather extreme	Weather variable	Period	5th (mm)	Median (mm)	95th (mm)
Wet planting period	Sum of precipitation$^{@}$	16 Mar – 5 May		77	138
Wet growing period	Sum of precipitation deficit$^{\$}$	1 May – 31 Aug	-59	97	
Dry growing period	Sum of precipitation deficit$^{\$}$	1 May – 31 Aug		97	251
Wet harvest period	Sum of precipitation$^{@}$	20 Aug – 4 Nov		177	299

[@] For consistency with our previous study, we use the same definitions of these two extremes here as in (van Oort et al., 2012a).

[$] The Dutch weather service (KNMI) calculates the precipitation deficit over the period 1 April – 1 Oct (KNMI, 2022b). Here we calculate it over a shorter period that better matches the growing period of crops. The positive median precipitation deficit $\sum(ET_0\text{-rain})$ of 97 mm indicates the Dutch growing season normally has a precipitation deficit. The 95th percentile of 251 mm indicates precipitation deficit was 251/97 = 2.6x higher than the median in the upper 5% of cases out of 285 total cases (5 stations x 57 years).

$$p(C_1|W_1) = W_1C_1 \,/\, (W_1C_1 + W_1C_0) \tag{4}$$

Where $p(W_1|C_1)$ is the probability of a weather extreme given a crop extreme. $p(C_1|W_0)$ is the probability of a crop yield extreme under normal weather conditions; we can think of this as the baseline risk. $p(C_1|W_1)$ is the probability of a crop yield extreme, given that a weather extreme occurs.

This concept is illustrated in Fig. 4 for the occurrence of onion crop yield extremes and the 'dry growing period' extreme. There are 286 region x year combinations with the following distribution: $W_1C_1 = 5$, $W_1C_0 = 7$, $W_0C_1 = 9$ and $W_0C_0 = 265$. The crop yield extreme occurs $C_1 = 5 + 9 = 14$ times. Of these 14 cases, $W_1C_1 = 5$ cases were with an extremely dry growing period. Thus (Eq. (2)) 5/14 = 36% of the onion crop yield anomalies seem to be caused by the 'dry growing period' extreme type. In a similar vein, one could calculate how much of the remaining 9 onion crop yield anomalies are associated with the other 3 weather extremes listed in Table 3. Further on in the paper we will show that another $W_1C_1 = 5$ cases were with an extremely wet harvesting period, thus in total (5 +5)/14 = 72% of the onion yield anomalies are associated with these two extremes. The baseline risk of an onion yield anomaly, under 'normal' weather conditions is $p(C_1|W_0) = 100\%$ x 9 /(9 +265) = 3% (Eq. (3)). An extremely dry growing period leads to the risk of crop failure increasing to: $p(C_1|W_1) = 100\%$ x 5 /(5 +7) = 42% (Eq. (4)).

The classification into quadrants simplifies the analysis. Quantitative values for the magnitude of the extremes in the quadrants W_1C_0, W_0C_1 and W_1C_1 are presented in the 'Supplementary Material Main' and 'Supplementary Material Co-occurrence of Crop and Weather Extremes'. For example in the W_1C_1 quadrant in Fig. 4 we can see for the 'Zeeland' dot a rainfall deficit of 314 mm (3.2x higher than normal) and the onion relative yield is $RY = -0.687$ (68.7% lower yield than normal).

3. Results

3.1. Weather extremes: frequency in time

Fig. 5 shows the frequency of the 4 extremes over time for the 5 stations with long time series (1965–2021). It is difficult to detect trends from these figures. Rather these figures suggest 57 years of weather data per station is still too short for detecting trends in rare weather conditions. For the extreme Dry growing period, two years stand out as years

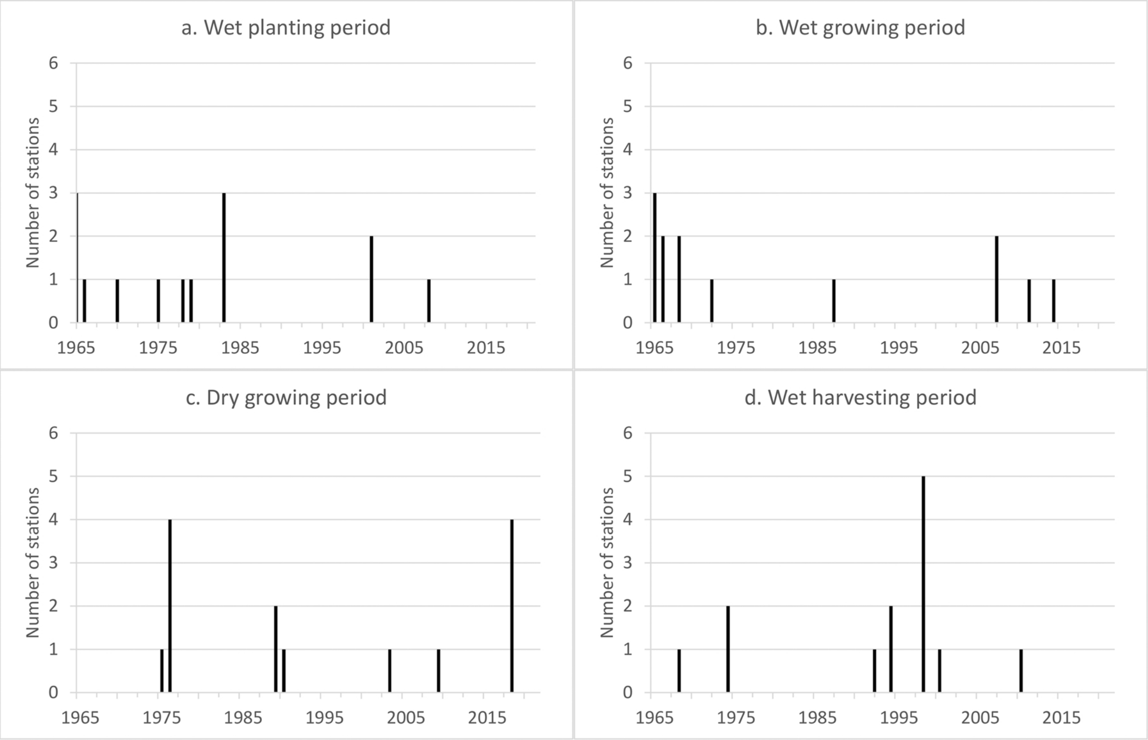

Fig. 5. Frequency of weather extremes in 5 stations with long timeseries (1965–2021).

in which the extreme occurred in large parts of the country (4 out of 5 stations): years 1976 and 2018 were extremely dry (Fig. 5c). The extreme Wet harvesting period (Fig. 5d) occurred in 1998 throughout the country, while in 1974 it occurred in 2 stations in the Western part of the country. To the older Dutch agronomists, 1974 is known as the year with severe harvesting problems as fields were too wet for machinery to operate in. Therefore, conscript soldiers were ordered to help harvesting (Fig. S1 in 'Supplementary Material Main').

3.2. *Crop yield extremes*

A crop yield is considered extreme if relative yield *RY* (Eq. (1)) is below the lower 5% of all observed *RY*. For onion, relative yields at the 5% threshold are 28% lower than normal (see Fig. 4 for an illustration). Fig. 6 shows these 5% thresholds for the crops considered in this study. High values in this figure indicate stronger negative yield variations, i.e. more vulnerable crops. Lower 5% *RY* are worst for onion (−28%), followed by ware potato (−21%) indicating these crops are most fragile. *RY* are best for sugar beet (−15%), silage maize (−13%) and winter wheat (−14%) indicating these crops are most robust.

3.3. *Weather extremes x yield anomalies*

3.3.1. *Yield anomalies explained by two weather extremes*

For arable crops, except winter wheat, there was a strong co-occurrence of extreme crop yields and two weather extremes (Fig. 7; see 'Supplementary Material Co-occurrence of Crop and Weather Extremes' for further quantitative data). Out of 60 cases with extremely low arable crop yields, 42 (70%) co-occurred with one of the two weather extremes 'extremely dry growing period' and 'extremely wet harvesting period (Fig. 7). For ware potato, 13% of extremely low crop yields were explained by extreme drought and 73% by an extremely wet growing period, in total these two extremes explained 85% of the ware potato crop yield anomalies. In grass, 6 out of 7 (86%) extreme crop yield anomalies co-occurred with the weather extreme "extremely dry growing period". Variation in yield anomalies in winter wheat and silage

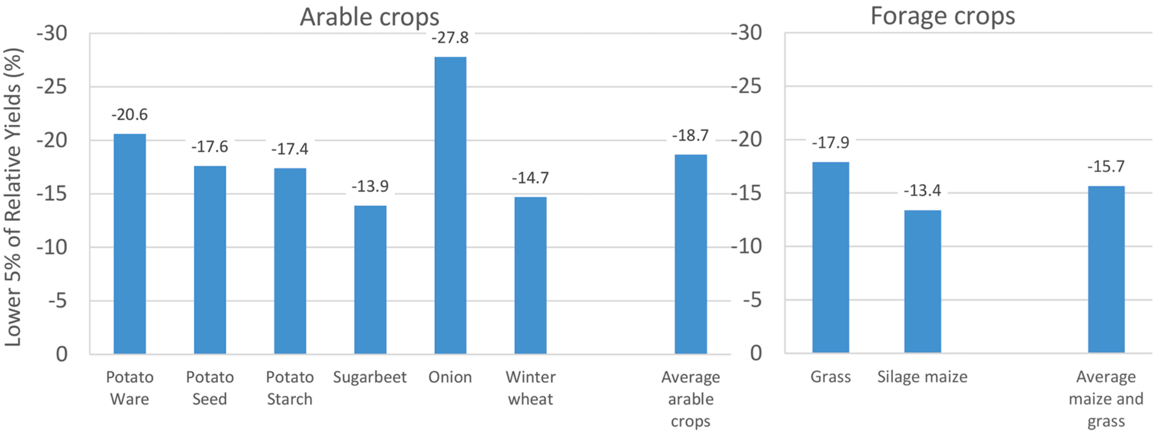

Fig. 6. Lower 5% of relative crop yields for arable and forage crops.

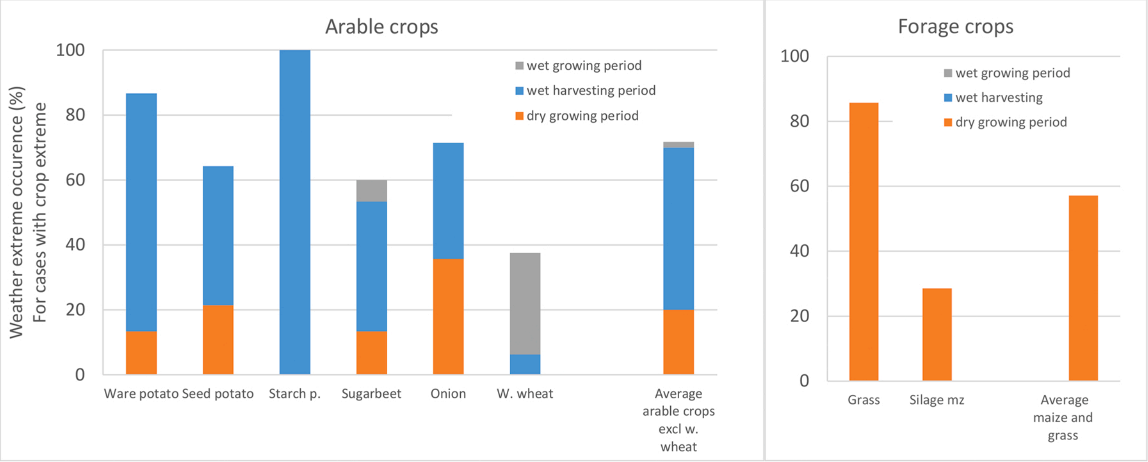

Fig. 7. Frequency of weather extreme types for cases where crop yields were extremely low.

maize was less well explained by the weather extremes.

3.3.2. *Crop sensitivities to weather extremes*

Fig. 8 shows how much the risk of crop failure increases with the occurrence of two weather extremes. In ware potato, the probability of an extremely low crop yield under normal conditions is $p(C_1|W_0) = 13/311 = 4\%$. Extreme drought increases the probability of crop failure to $p(C_1|W_1) = 2/13 = 15\%$. An extremely wet harvesting period increases the probability of crop failure to $p(C_1|W_1) = 11/20 = 55\%$. In Fig. 8 we can see which crops are most vulnerable to a particular extreme. Grass and onion are most sensitive to extreme drought during the growing period. Tuber crops (potato, onion, sugar beet) are most sensitive to extreme wet conditions during the harvesting period.

3.3.3. *Two large scale weather extremes*

3.3.3.1. Extremely dry summer of 2018. An extremely dry growing period occurred 13 times in 12 provinces x 27 years (13 out of $12 \times 27 = 324$ cases); more quantitative data can be found the Supplementary Material. Of these 13 cases, 10 cases were in 2018, indicating the extreme was a large scale extreme occurring throughout the country. The remaining 3 cases were in Zuid-Holland (1995) and Noord-Holland (2003, 2009). Drought was more severe in the 10 cases 2018 than in those other 3 cases. No yield anomalies were recorded in those 3 cases. The 2018 drought had a big impact on a range of crops in one or more provinces:

- 2 (out of 12) provinces experienced a ware potato yield anomaly (Overijssel, Zeeland)
- 4 (out of 12) experienced a seed potato anomaly (Limburg, Utrecht, Zeeland, Zuid-Holland)
- 0 (out of 2) experienced a starch potato yield anomaly
- 2 (out of 12) provinces experienced a sugar beet yield anomaly (Overijssel, Zeeland)
- 5 (out of 11) provinces experienced an onion yield anomaly (Gelderland, Limburg, Noord-Brabant, Zeeland, Zuid-Holland)
- 5 (out of 6) FADN regions experienced a grass yield anomaly. Relative yield in 'Sand South' was − 0.151, above the lower 5% of − 0.179 (Fig. 6)
- 0 (out of 6) FADN regions experienced a silage maize yield anomaly

From these analyses, the province of Zeeland stands out as the province in which impact of the 2018 drought was most severe (see also Fig. 4). Noord-Holland, a province with similar soil and weather as Zeeland, showed much smaller yield anomalies in 2018. The key difference between these two provinces is that Noord-Holland has good irrigation access (from the large IJsselmeer lake to the east of this province, Fig. 2), whereas Zeeland has poor access to irrigation, due to brackish groundwater and limited river/canal sweet water influx. Thus the comparison between these two similar provinces shows the great impact of irrigation mitigating negative impacts of drought.

The outcome of 0 silage maize yield anomalies came as a surprise. A (Dutch) report by (Haan et al., 2019) provides an elaborate analysis of the impacts of the 2018 drought on forage crop yields in a number of dairy farms. It suggests drought did impact both forage crops but also

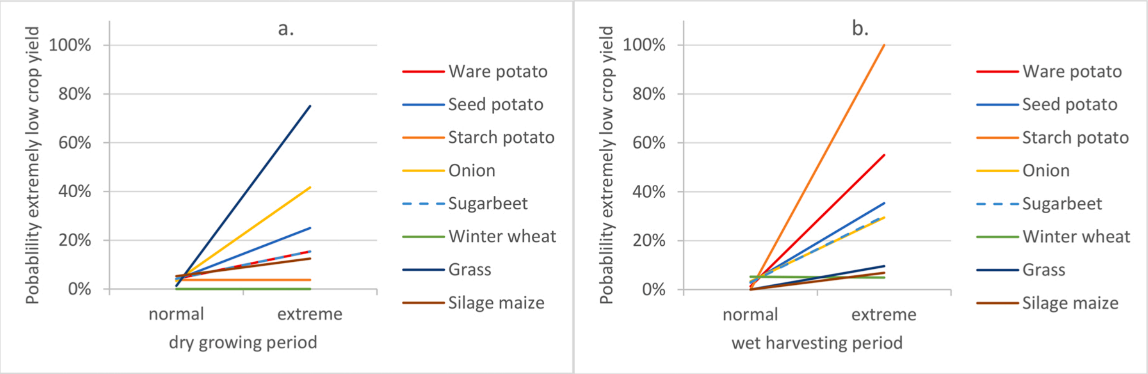

Fig. 8. Increased risk of extremely low crop yields for two particular weather extremes. Note in a the lines of sugar beet (dashed blue) and ware potato (red) overlap. Note in b the lines of sugar beet (dashed blue) and onion (yellow) overlap.

reports on irrigation applied in maize. Possibly the combination of irrigation and a deep rooting system has kept impacts on maize within limits.

3.3.3.2. Extremely wet harvesting period of 1998. An extremely wet harvesting period occurred 20 times in 12 provinces x 27 years. Of these 20 cases, 12 cases were in 1998, indicating the extreme was a large scale extreme occurring throughout the country. The 1998 wet harvesting period had a big impact on a range of crops in one or more provinces:

- 11 (out of 12) provinces experienced a ware potato yield anomaly
- 6 (out of 12) provinces experienced an seed potato anomaly
- 2 (out of 2) an extreme starch potato yield anomaly
- 5 (out of 12) provinces experienced an sugar beet yield anomaly
- 6 (out of 11) experienced an onion yield anomaly
- Forage crops had no yield anomalies in 1998

The extremely wet harvesting period of 1998 as measured by the rainsum was more extreme in the 12 cases occurring in 1998 than in the 8 other cases (‘Supplementary Material Main’, Table S2). Almost no extreme crop yield anomalies were found in those 8 remaining less severe cases. This finding is consistent with van Oort et al. (2012a) who reported a number of years and regions where rainfall sum during the harvesting period was just below the threshold above which excess rain causes irresolvable harvesting problems. The current study shows also other tuber crops (starch potato, seed potato, sugar beet, onion) are affected by this extreme.

4. Discussion

4.1. Main findings

Most of the crop yield anomalies in recent 27 years could be explained from two large scale weather extremes: the extreme wet harvesting period of 1998 and the extremely dry growing period of 2018. The same extremes also occurred more locally and less severely in a few other regions and years. For most crops, except for winter wheat and silage maize, we found a strong relation between occurrence of extreme crop yield anomalies and two weather extremes, the ‘dry growing period’ extreme and the ‘wet harvesting period’ extreme. Weather extreme impact may have been mitigated by crop traits, soil and agricultural management.

Crops can be ranked in terms of degree of yield variation. Yields of onion are most variable between years and regions, yields of silage maize, sugar beet and winter wheat are least variable (see also (Asseldonk et al., 2020)). This is reflected in the lower 5% percentile of relative yields shown in Fig. 6:

- least vulnerable: maize, sugar beet, winter wheat (Fig. 6: lower 5% relative yields: −14%)
- intermediate: grass, potato (Fig. 6: lower 5% relative yields: −17% to −20%)
- most vulnerable: onion (Fig. 6: lower 5% relative yields: −28%)

Correlation between occurrence of extremely low crop yields and weather extremes is stronger for the more vulnerable crops (Fig. 7 grass, potato, onion, 64%−100%) than for the less vulnerable crops (Fig. 7 Silage Maize, Sugar beet, Winter wheat, 20–53%). Perhaps not surprisingly, these 3 least vulnerable crops happen to be the crops with the deeper rooting system.

For the United States, Troy et al. (2015) found irrigation can strongly mitigate negative impacts of drought. Here we report a similar finding, where comparing two regions with similar weather and soil, one province (Noord-Holland) with good irrigation access suffered no crop yield anomalies from the 2018 drought. The province without irrigation access (Zeeland) suffered severe negative impact of the 2018 drought. Compared with other provinces Zeeland has both poor access to surface irrigation through influx from rivers and no access to groundwater irrigation because of shallow saline groundwater. Comparing crop sensitivity to weather extremes we find grass and onion to be most sensitive to a dry growing period (Fig. 8). Grass was even more sensitive than onion. We suspect the impact of drought in grass is still larger than in onion because onion is more likely to be irrigated than grass, as onion is a cash crop and grass a less profitable forage crop. Irrigation is costly and dairy farmers will be balancing the extra costs of irrigation against the extra costs of purchasing animal feed from other sources (Haan et al., 2019). When there is a severe drought period there can even be a ban on the irrigation of grassland, in particular in the sand regions.

An extremely wet harvesting period has impact on three potato cultures. Seed potato is relatively less sensitive to this extreme and starch potato is most sensitive. This sensitivity coincides with harvesting periods: seed potato is generally harvested earliest, starch potato is harvested latest out of the three potato types. Seed potatoes are often harvested already before the start of our (so defined) wet harvesting period of 20 Aug - 4 Nov. Starch potato seems extremely sensitive to the wet harvesting period extreme but it should be noted the number of observations for starch potato is small (2 regions only) and we caution against drawing too strong conclusions.

An interesting finding is that two other weather extremes analysed here showed no correlation with occurrence of crop anomalies. The “wet growing period” extreme was analysed as the reciprocal of the “dry growing period” extreme. Historically one could say the Great Irish Famine (Póirtéir, 1995) was caused at least partially by a wet growing period facilitating a major outbreak of the phytoptera disease in potato. Thus there was good reason to hypothesise a negative impact of this extreme, in any case for potato. Just as (Troy et al., 2015) indicated a decoupling of weather extreme and crop extremes due to irrigation, we speculate that fungicides against phytoptera might have caused a decoupling of the “wet growing period” extreme and anticipated potato yield anomalies. Another possible explanation for finding no impact of the “wet growing period” extreme is that the period over which we have been calculating it might not have been the most relevant period. We add further reflection on the definition of this extreme in Section 4.2.2 of the paper.

In a previous study we reported on impact of the “wet planting period” extreme impacting on potato yields for farms in the region Flevoland (van Oort et al., 2012a). In a later study for the whole of the Netherlands for the sugar beet crop, we found rainfall during the planting period to be less critical (van Oort et al., 2012b). Fig. S2 (‘Supplementary Material Main’) suggests this “wet planting period” extreme occurred less often in the period 1994–2020 considered in this paper and when it occurred the extreme was less severe than in the worst year of 1983. Possibly the data used in the current study were too sparse to fish out the effect of this weather extreme on crop yields. Or possibly more recent developments in terms of drainage facilities and changes in agricultural machineries may have reduced sensitivity to this extreme, compared with the year 1983 in which this extreme was shown to have large impact (van Oort et al., 2012b). More research on both wet extremes is desirable.

4.2. Uncertainties

4.2.1. Spatial and temporal bias

More weather extremes than those considered here have been defined by (Schaap et al., 2011, 2013) specifically for the Netherlands. They include extremes that generally occur on finer spatial scale (e.g. hail storms). Such small scale weather extremes can have a huge impact at the farm level that is averaged out when aggregating yield data to the regional level. The scale of the crop data used in this study may have created a bias towards more easily identifying impact of large scale weather extremes. It would be interesting to do further research those finer scale extremes at the farm or field scale. A wry conclusion of the work by (van Oort et al., 2012a) was that, as we are moving into an increasingly digitised age, less and less farm scale data are available. Farm scale data are available on platforms like FarmMaps (Kempenaar et al., 2021) but for legitimate reasons of privacy protection, such data are not always accessible to researchers.

Two large scale weather extremes were found to occur in recent 27 years and were shown to have a big impact on crop yields. 27 years is a short period for climate research and probably too short for research on weather extremes. Should we have conducted this same research 4 years ago, before the extreme drought of 2018, we might have come to the wrong conclusion that drought has limited impact. One cannot tell which other extremes will surface in years to come. This is an obvious limitation of the empirical approach presented here and could be an argument for more crop growth model-based explorations using weather data based on climate change scenarios. Accurate farm management data are essential for obtaining realistic outcomes from such model-based simulations of impact of extremes. Because as we have shown, impact of extremes is strongly moderated by farm management (such as irrigation and fungicides) in countries such as the Netherlands where all cropland is intensively managed.

4.2.2. *Unexplained crop yield extremes*

A large fraction (70%) of extreme crop yield anomalies for the arable crops could be explained from two weather extremes. Table S4 in the ‘Supporting Material Main’ lists the remaining 28 (30%) of cases of arable crop yield anomalies where the weather was “normal” i.e. none of our 4 weather extremes occurred. Having narrowed down these unexplained 30% of cases can guide further research. We found great diversity in year x region combinations with unexplained crop yield anomalies, which makes it difficult to fish out other weather extremes possibly overlooked in the current study. The most prominently recurring year is the year 2016, with extremely low yields for a number of crops in provinces Limburg, Noord-Brabant and Gelderland (7 out of total 28 unexplained yield anomalies). A quantitative analysis of rainfall data (not shown) suggests in two of these provinces (Limburg, Noord-Brabant) June 2016 was extremely wet, worse than in any of the other provinces and worse than in other years. We thus hypothesise a shorter intensively wet period during the growing period can cause severe crop yield loss. This hypothesis requires further quantitative refinement, following similar approaches as used in (van Oort et al., 2012a). For example, does a single extreme wet day already cause great damage? A wet week? Four wet weeks? And does it matter during which growth stage the extreme occurs? A solid scientific approach should also seek to falsify hypotheses. For example are there also region x year combinations with an extremely wet June without yield anomalies?

Thus the combination of agronomic knowledge and the listing of “unexplained” crop yield extremes provides new directions for further research. A combination of agronomic knowledge, sufficient data and statistical methods is necessary for developing new definitions of high impact weather extremes, i.e. weather extremes that cause large yield anomalies.

4.3. *Future societal demand for water and adaptation options*

The problem with a wet end of season (1998) is much less manageable than that of a dry growing period (2018). The problem with a large scale wet end of season (1998) is that if there is water everywhere, i.e. all the drainage canals and lakes are filled to the rim, then at a certain stage pumping away of excess water becomes simply impossible. Drought in that sense seems more manageable, one can irrigate. The comparison of drought impact without irrigation (Zeeland) and with irrigation (Noord-Holland) suggests that, should irrigation become more restricted in the future, drought impact would also become much more severe than now. Irrigation increased dramatically in the recent years in the Netherlands and is already quite costly (Asseldonk et al., 2020; Meer, 2021; Stokkers et al., 2022). Irrigation costs might further increase with rising energy prices or if water demand by other sectors in society increases. Meanwhile, in the longer run towards 2100 and beyond, rising sea levels due to climate change make pumping of sweet water out of polders into the sea increasingly expensive. A commonly contemplated resolution would be to have more natural reservoirs (i.e. inundated natural areas) that can also be used as a water buffer both in wet and in dry years (Prinsen et al., 2015). Conversion of agricultural land into such natural areas would, for the remaining farmers, improve their resilience to weather extremes. No farmer will happily sacrifice his/her land. Allocating existing agricultural area for nature and inundation is highly contentious in Dutch society and even more so among farmers. The future with regards to political decision making in this domain is highly uncertain.

Somewhat closer to the farmer are decisions at the water board level, especially those regarding groundwater level, which is controlled through a dense network of water control systems. There is always a tension between maintaining high groundwater levels which may act as a reservoir in case of dry summers and maintaining low groundwater levels for sake of trafficability and adverse effects of wet extremes for agriculture and society. Finding an optimum here in the face of year to year weather variability and hard to detect long term trends is difficult and subject of continuous debate within waterboards.

Farmers may have a number of adaptation options at hand to improve their resilience. These include increasing the efficiency of irrigation, improving soil quality for water infiltration and retention, and selecting crops and varieties for drought tolerance and rooting (e.g. De Boer et al., 2018, 2020; Deru et al., 2014, 2018; Hoekstra et al., 2018). Such adaption options have shown to be effective in case of moderate drought and wet conditions. To which extent such adaptation options can also be effective in case of extreme weather remains to be tested.

5. Conclusions

This paper identifies weather extremes which have in recent 27 years had a major impact on crop failures in the Netherlands. Impact was shown to be the combined effect of weather extremes in interaction with soil and agricultural management. Two large scale extremes dominate, the 2018 drought which caused severe yields losses in especially onion and grass and the 1998 wet harvesting period which caused severe yields losses in all the tuber crops (potato, sugar beet, onion).

CRediT authorship contribution statement

All authors contributed to all aspects of paper writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126662.

References

Aarts, H.F.M., Daatselaar, C.H.G., Holshof, G., 2008. Bemesting, meststofbenutting en opbrengst van productiegrasland en snijmais op melkveebedrijven. Plant Research International, Wageningen.

Asseldonk, Mv, Stokkers, R., Jager, J., Meer, Rvd, 2020. Economische effecten van droogte in 2018 en 2019: een regionale analyse akkerbouw en melkveehouderij. Wageningen Universty & Research, [Wageningen].

Barlow, K.M., Christy, B.P., O'Leary, G.J., Riffkin, P.A., Nuttall, J.G., 2015. Simulating the impact of extreme heat and frost events on wheat crop production: a review. Field Crop. Res. 171, 109–119. https://doi.org/10.1016/j.fcr.2014.11.010.

Beillouin, D., Schauberger, B., Bastos, A., Ciais, P., Makowski, D., 2020. Impact of extreme weather conditions on European crop production in 2018: random forest - yield anomalies. Philos. Trans. R Soc. B Biol. Sci. 375 (1810), 20190510. https://doi.org/10.1098/rstb.2019.0510.

Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylha, K., Koffi, B., Palutikof, J., Schoell, R., Semmler, T., Woth, K., 2007. Future extreme events in European climate: an exploration of regional climate model projections. Clim. Chang. 81, 71–95. https://doi.org/10.1007/s10584-006-9226-z.

CBS, 2022a. Akkerbouwgewassen; productie naar regio. ⟨https://opendata.cbs.nl/statline/#/CBS/nl/dataset/7100oogs/table?fromstatweb⟩. (Accessed 4 August 2022).

CBS, 2022b. Landbouw; vanaf 1851. ⟨https://opendata.cbs.nl/statline/#/CBS/nl/dataset/71904ned/table?ts=1649409420333⟩. (Accessed 4 August 2022).

De Boer, H.C., Deru, J.G.C., Van Eekeren, N., 2018. Sward lifting in compacted grassland: effects on soil structure, grass rooting and productivity. Soil Tillage Res. 184, 317–325. https://doi.org/10.1016/j.still.2018.07.013.

De Boer, H.C., Deru, J.G.C., Van Eekeren, N., 2020. Sward lifting in compacted grassland: contrasting effects on two different soils. Soil Tillage Res. 201, 104564 https://doi.org/10.1016/j.still.2019.104564.

Deru, J., Schilder, H., van der Schoot, J.R., van Eekeren, N., 2014. Genetic differences in root mass of Lolium perenne varieties under field conditions. Euphytica 199 (1–2), 223–232. https://doi.org/10.1007/s10681-014-1129-x.

Deru, J.G.C., Bloem, J., de Goede, R., Keidel, H., Kloen, H., Rutgers, M., van den Akker, J., Brussaard, L., van Eekeren, N., 2018. Soil ecology and ecosystem services of dairy and semi-natural grasslands on peat. Appl. Soil Ecol. 125, 26–34. https://doi.org/10.1016/j.apsoil.2017.12.011.

Duijnen, Rv, Blokland, P.W., Vrijhoef, A., Fraters, D., Doornewaard, G.J., Daatselaar, C.H.G., Duijnen, Rv, Blokland, P.W., Vrijhoef, A., Fraters, D., Doornewaard, G.J., Daatselaar, C.H.G., 2021. Landbouwpraktijk en waterkwaliteit op landbouwbedrijven aangemeld voor derogatie in 2019. Rijksinstituut voor Volksgezondheid en Milieu (RIVM), Bilthoven.

Fischer, T., Byerlee, D., Edmeades, G., 2014. Crop yields and global food security: will yield increase continue to feed the world?. Australian Centre for International Agricultural Research (ACIAR), Canberra, ACT, Australia.

Gobin, A., 2010. Modelling climate impacts on crop yields in Belgium. Clim. Res. 44 (1), 55–68. https://doi.org/10.3354/cr00925.

Gobin, A., 2018. Weather related risks in Belgian arable agriculture. Agric. Syst. 159, 225–236. https://doi.org/10.1016/j.agsy.2017.06.009.

Haan, Md, Verloop, K., Hilhorst, G., 2019. Droogte op Koeien & Kansen-bedrijven in 2018: praktijkervaringen. Wageningen Livestock Research, Wageningen.

Hoekstra, N.J., De Deyn, G.B., Xu, Y., Prinsen, R., Van Eekeren, N., 2018. Red clover varieties of Mattenklee type have higher production, protein yield and persistence than Ackerklee types in grass–clover mixtures. Grass Forage Sci. 73 (2), 297–308. https://doi.org/10.1111/gfs.12307.

Katz, R.W., Brown, B.G., 1992. Extreme events in a changing climate - variability is more important than averages. Clim. Chang. 21 (3), 289–302. https://doi.org/10.1007/bf00139728.

Kempenaar, C., Been, T.H., van Evert, F.K., Hoving, I.E., Kessel, G.J.T., Dantuma, W., Booij, J.A., Molendijk, L.P.G., Sijbrandij, F.D., van Boheemen, K., 2021. Decision support in the open service platform Akkerweb for precision agriculture. In: Proceedings of the ECPA2021 Conference.

KNMI, 2022a. Daggegevens van het weer in Nederland. ⟨https://www.knmi.nl/nederland-nu/klimatologie/daggegevens⟩. (Accessed 4 August 2022).

KNMI, 2022b. Historisch verloop neerslagtekort. ⟨https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten/historisch-neerslagtekort⟩. (Accessed 4 August 2022).

Lanning, S.B., Siebenmorgen, T.J., Counce, P.A., Ambardekar, A.A., Mauromoustakos, A., 2011. Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality. Field Crop Res. 124 (1), 132–136. https://doi.org/10.1016/j.fcr.2011.06.012.

Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529 (7584), 84–87. https://doi.org/10.1038/nature16467.

Makkink, G.F., 1957. Testing the Penman formula by means of lysimeters. J. Inst. Water Eng.

Meer, R.Wvd, 2021. Watergebruik in de land- en tuinbouw 2019.

Póirtéir, C., 1995. The Great Irish Famine. Mercier Press, Dublin.

Prinsen, G., Sperna Weiland, F., Ruijgh, E., 2015. The delta model for fresh water policy analysis in the Netherlands. Water Resour. Manag. Int. J. Publ. Eur. Water Resour. Assoc. (EWRA) 29 (2), 645–661. https://doi.org/10.1007/s11269-014-0880-z.

Roskam, J.L., Meer, R.Wvd, Veen, H.Bvd, 2020. Sample for the Dutch FADN 2017. Wageningen Economic Research, Wageningen.

Schaap, B.F., Blom-Zandstra, M., Hermans, C.M.L., Meerburg, B.G., Verhagen, J., 2011. Impact changes of climatic extremes on arable farming in the north of the Netherlands. Reg. Environ. Chang. 11 (3), 731–741. https://doi.org/10.1007/s10113-011-0205-1.

Schaap, B.F., Reidsma, P., Verhagen, A., Wolf, J., Ittersum, V.M.K., 2013. Participatory design of farm level adaptation to climate risks in an arable region in The Netherlands. Eur. J. Agron. 48 (7), 30–42.

Schils, R.L.M., Van den Berg, W., Van der Schoot, J.R., Groten, J.A.M., Rijk, B., Van de Ven, G.W.J., Van Middelkoop, J.C., Holshof, G., Van Ittersum, M.K., 2020. Disentangling genetic and non-genetic components of yield trends of Dutch forage crops in the Netherlands. Field Crop. Res. 249, 107755 https://doi.org/10.1016/j.fcr.2020.107755.

Sluijter, R., Plieger, M., Oldenborgh, G.Jv, Beersma, J., Vries, Hd, 2018. De droogte van 2018: een analyse op basis van het potentiële neerslagtekort. KNMI, De Bilt.

Stokkers, R., Jager, J., Asseldonk, M.A.P.Mv, 2022. Beregening in de Nederlandse landbouw op gewas- en regioniveau in de periode 2010–2019: analyses met het Bedrijveninformatienet. Wageningen Economic Research, Wageningen.

Troy, T.J., Kipgen, C., Pal, I., 2015. The impact of climate extremes and irrigation on US crop yields. Environ. Res. Lett. 10 (5), 054013 https://doi.org/10.1088/1748-9326/10/5/054013.

van Oort, P.A.J., Timmermans, B.G.H., Meinke, H., van Ittersum, M.K., 2012a. Key weather extremes affecting potato production in The Netherlands. Eur. J. Agron. 37 (1), 11–22 https://doi.org/DOI 10.1016/j.eja.2011.09.002.

van Oort, P.A.J., Timmermans, B.G.H., van Swaaij, A.C.P.M., 2012b. Why farmers' sowing dates hardly change when temperature rises. Eur. J. Agron. 40, 102–111 https://doi.org/DOI 10.1016/j.eja.2012.02.005.

Vogel, E., Donat, M.G., Alexander, L.V., Meinshausen, M., Ray, D.K., Karoly, D., Meinshausen, N., Frieler, K., 2019. The effects of climate extremes on global agricultural yields. Environ. Res. Lett. 14 (5), 054010 https://doi.org/10.1088/1748-9326/ab154b.

Yan, H., Harrison, M.T., Liu, K., Wang, B., Feng, P., Fahad, S., Meinke, H., Yang, R., Liu, D.L., Archontoulis, S., Huber, I., Tian, X., Man, J., Zhang, Y., Zhou, M., 2022. Crop traits enabling yield gains under more freq.uent extreme climatic events. Sci. Total Environ. 808, 152170 https://doi.org/10.1016/j.scitotenv.2021.152170.