Weather related risks in Belgian arable agriculture

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Abstract

Agricultural production risk is to a great extent determined by weather conditions. The research hypothesis was that adverse weather conditions during sensitive crop stages do not entirely explain low arable yields. The temporal overlap between weather conditions and crop stages in the arable cropping system was determined using a modelling framework that couples phenology to the soil water balance and crop growth. While climatic constraints have changed on average over time, block maxima of indicators during crop growth stages showed no trends except for minimum temperature related indicators owing to a dual shift in both phenology and weather conditions. Return periods were derived for adverse weather conditions such as frost, drought, heat and waterlogging, and for general weather conditions such as radiation, temperature, precipitation and the water balance using fitted statistical distributions for the period 1947-2012. Distributions fitted to detrended yields allowed relating weather conditions during the growing season to the lower and upper quintiles of the yield distributions. Weather conditions varied significantly between years, crops and growth stages. Results for winter wheat, winter barley, winter oilseed rape, grain maize, potato and sugar beet in Belgium demonstrated that the impact of single events on crop yields was difficult to capture, as yields integrated weather variability during the growing season and crops recovered from adverse weather conditions. The approach of combining physically based crop modelling with statistical distribution fitting to characterise the tail ends of both crop yields and weather conditions enabled to elicit effects of multiple adverse weather conditions and their relation to regional crop yields. The method helped quantify agricultural production risks and rate both weather and crop-based agricultural insurance.

Key words: adverse weather conditions, arable crop, yield, agricultural insurance, probability distribution, return period, Belgium

Highlights

- Crop-weather interactions were captured using a physically based crop modelling approach.
- Probability distributions enabled quantification of 20-year return values for weather events occurring during different stages of the growing season.
- Weather related stress varied significantly between years, crops and growth stages.
- The combination of multiple adverse weather conditions explained low arable yields, defined as the 20% lower tail of the yield distribution.

1. Introduction

Agricultural production is to a great extent determined by weather conditions. Managing weather related risks includes both on-farm measures and strategies to share the risk such as insurance schemes. Weather related risks are projected to increase in magnitude, frequency and duration under climate change (Field, 2012; WMO, 2011; Solomon et al. 2007). The perspective of this rising risk-exposure is exacerbated further by an overall reduction of direct income support from the CAP and more limits to aid received for crop damage (Council Regulation 73/2009, Commission Regulation 1857/2006). The condition that farmers can claim only 50% of the estimated damage if they are not privately insured against weather risks has triggered renewed interest in private agricultural insurances.

Agricultural insurance schemes across Europe range from single and combined to yield risk insurances, and depend largely upon the degree of government subsidies (Bielza Diaz-Caneja et al., 2009). In response to high risk and damage (Punge and Kunz, 2016), single risk insurance for hail is the most developed private insurance product available in all European countries (Mauelshagen, 2011), but there is gathering interest to include other meteorological triggers such as drought and frost, and offer a more comprehensive weather-based insurance cover. In general combined risk insurances are offered in regions with higher or multiple risks due to hail, rain, frost and wind (Bielza Diaz-Caneja et al., 2009). Combined risk insurance ranges from public and compulsory in Greece and Cyprus; private and partially subsidised in Portugal, Czech Republic, Slovakia, and Romania; to completely private in the Baltic States, Hungary and Bulgaria. Yield insurances guarantee the main risks affecting production, include systemic risks such as drought, and are available in a private partially subsidised system in Spain, Italy, Austria and France (Enjolras et al., 2012). In all European countries compensation for yield losses due to natural disasters is offered by public disaster funds; is subject to which risk caused the loss, the area affected and the magnitude of damage; and, invokes a clear trade-offs between providing catastrophic assistance and subsidising insurance premiums (van Asseldonk et al., 2013). In 2006 the total agricultural insurance premiums in EU-25 was 1,538 M€, with 32% subsidised by Member States (Bielza Diaz-Caneja et al., 2009). In comparison, the 2012 drought resulted in a $11,581 billion payment to farmers. The crop insurance market is less mature in Europe than in the U.S or Canada, where whole-farm income insurance and area yield or area revenue insurances exist. Knowledge gaps relate to the frequency and magnitude of adverse weather conditions and the resulting crop response.

Extreme weather events are meteorological phenomena that are at the extremes of the historical distribution, whereas severe weather refers to any dangerous meteorological phenomena with the potential to cause damage (WMO, 2011). Examples of extreme weather events include heat waves, droughts, storms and floods. Strong winds, hail, excessive precipitation, late spring frost and lightning (causing wildfires) are forms of severe weather. Extreme value theory provides a statistical framework to make inferences about the probability of extreme events beyond what has been observed (Coles, 2001; Beirlant et al., 2004; Dey and Yan, 2016). Insurance companies and disaster funds in Europe define extreme weather events in relation to agricultural damage as events equalling or exceeding a 20-year return value; a definition that points to adverse weather events from a meteorological point of view. Adverse weather events happen once or more in a lifetime, have lower return periods and have higher frequencies of occurrence during the observation interval as compared to extreme events. Following normality testing or transformation to normality, the cumulative frequency of adverse weather events may be approximated by the standard normal cumulative distribution function.

The degree of temporal overlap between adverse weather conditions and crop development leads to different crop performance responses. A significant advancement in crop phenology provides important evidence of the response to recent regional climate change (e.g. in Germany by Estrella et al., 2007), and ultimately influences crop yield. For example, during the 2003 heat wave a reduction of 30% was estimated in gross primary production of terrestrial ecosystems over Europe (Ciais et al., 2005), but winter cereal yields in Belgium and northern France were normal because wheat matured earlier thereby avoiding severe losses from drought and heat stress (Gobin, 2010; Peltonen-Sainio et al., 2010). Warming during spring and early summer accelerates canopy development and increases sugar beet yield (Jaggard et al., 2007). Evidence of negative impacts of advancing phenology is that premature plant development can result in exposure of vulnerable plant tissues and organs to for example late-season frosts (e.g. in US by Gu et al., 2007). Changes in planting date, emergence and seedling establishment could therefore cause positive or negative yield changes. Farmers' sowing dates, however, were found not to change significantly under warmer growing conditions of the last decades (Van Oort et al., 2012b; Jaggard et al., 2007). The impacts of adverse weather on crop yields necessitates a modelling approach that takes into account the progression of growth stages in the cropping calendar such that the occurrence of sensitive periods can be identified and related to adverse weather conditions.

Time windows considered for studying adverse weather impacts on crops range from the entire growing season to a few days around sensitive phenological stages such as flowering. Monthly to three-monthly temperature and precipitation anomalies during the growing season were found to relate significantly to crop yields of barley, wheat and maize, e.g. in the Czech Republic (Kolář et al., 2014) and in France (Ceglar et al., 2016). Sugar beet is susceptible to drought during foliage expansion (Richter et al., 2001) and wheat to hot temperatures around the flowering period (Wheeler et al., 2000). Based on these findings, crop modelling predicts that under future climate change, an increase in the frequency and magnitude of heat stress around the time of flowering, not drought, will increase the vulnerability of heat-sensitive wheat varieties in Europe (Semenov and Shewry, 2011). For grain maize, heat stress was found to reduce grain yield due to a decline in harvest Index induced by above optimal temperatures around flowering (Edreira and Otegui, 2012). The exceedance of critical thresholds during the growing season can result in crop damage as reviewed for temperature thresholds during different phenological phases and physiological processes of winter wheat (Porter and Gawith, 1999) and grain maize (Sanchez et al., 2014). A comprehensive review of weather conditions or events during different stages of the growing season and the relationship with arable crop yields is a prerequisite to understanding risks in agricultural production.

In Belgium weather-related events recorded in the last decades have captured the interest of the general public. In August 2003, record breaking temperatures exceeded 40°C in Belgium. Prolonged drought hit the 2007, 2010, 2011 and 2015 spring seasons causing crop damage. In May 2009 and June 2014, storms with lightning and hail resulted in crop damages across the country. In November 2010, excessive rainfall of up to 90 mm during 3 days triggered the worst flooding in 50 years. Based on claims to the disaster fund, the most important impacts on agriculture are from temperature (heat waves, frosts), precipitation (drought, waterlogging) and storms (wind, hail, flooding). Although most crops are vulnerable to hail, meteorological measurements are not readily available. Communications with the insurance and agriculture sectors revealed the need for analysing meteorological risks that impact crop yields to explore the feasibility of single risk, combined risk or index-based crop insurances. The research hypothesis is that adverse weather events during sensitive crop stages do not entirely explain low arable yields. The major objectives are to characterise adverse weather conditions; evaluate their occurrence during the cropping calendar and in particular in relation to sensitive crop stages; characterise low arable yields in terms of their distribution; and, assess the contribution of adverse weather conditions to low arable yields.

2. Materials and methods

2.1. Literature review of sensitive crop stages

A literature review of arable crop vulnerability to adverse weather conditions and events during different phenological stages showed that crop establishment, the transition from vegetative to reproductive growth (flowering time) and harvest were the most sensitive crop stages (Table 1). The focus was on identifying the most sensitive stages of the major arable crops that occur in Belgium: winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.), sugar beet (*Beta vulgaris* L.), late potato (*Solanum tuberosum* L.), grain maize (*Zea mays* L.) and winter oilseed rape (*Brassica napus* L.). The crop stages with a large impact on yields were related to the cropping calendar in Belgium featuring leaf development; mid-season stages around flowering, grain filling and tuber setting; and, harvest (Figure 1). Where possible relevant thresholds were provided for the different crop stages, and their impact on yield was documented (Table 1).

2.2. Assessment of the growing season and crop phenology of arable crops

Most arable crops are susceptible to adverse weather conditions during the entire length of the growing season. Inter-annual variability in potential growing season length was evaluated in potential heat units (ΣPHU in °Cdays) using fixed planting and harvesting dates and crop specific upper and lower threshold temperatures (Table 2). The inter-annual variability of crop phenological development necessitated the use of a crop growth model, *in casu* REGCROP (Gobin, 2012), to capture the dynamics of growth between the different years. The onset of crop phenological stages was controlled by thermal time (*cGDD*) using annual median planting dates and crop specific upper and lower threshold temperatures (Table 2; Gobin, 2010), and further refined with daylength and vernalisation responses to reflect winter crop development.

2.3. Agrometeorological modelling

Long-term daily weather records were obtained from the Belgian Royal Meteorological Institute for the period 1947-2012. The Ukkel time series are the longest available measurements for all meteorological variables measured at the same location and for the entire period. The Ukkel station (50°47′55′′ N, 4°21′29′′ E, 100m a.s.l.) is located in the major arable production area of Belgium. The meteorological records included daily rainfall (*P*); mean, minimum, maximum, dewpoint temperatures (*Tmean, Tmin, Tmax, Tdew*); solar radiation (*RAD*), wind speed (*u*) and relative humidity (*RH*). Quality control and homogeneity testing were provided for daily evapotranspiration and precipitation (Zamani et al., 2015), wind speed (Van de Vyver and Delcloo, 2011) and daily temperature (Van de Vyver, 2012).

Vapour pressure deficit (*VPD*) and potential evapotranspiration (*PET*) were calculated using the FAO Penman-Monteith equation (Allen et al., 1998). The soil water balance (θ_t, Eq.1) was calculated for a deep well developed soil with a rooting depth of 1.5 m, a plant available water holding capacity (θ_{FC} - θ_{WP}) of 200 mm/m and a saturated water content of 50 vol% (Gobin, 2010). Waterlogging (*WL*, Eq.2) and drought (*DR*, Eq.3) were evaluated on a daily basis prior to confining the soil moisture (Eq.4) between field capacity (θ_{FC}) and permanent wilting point (θ_{WP}). The actual evapotranspiration (AET_t) assumed a function of soil evaporation and plant transpiration with a feedback for soil moisture below the critical moisture level (θ_{CR}) (Gobin, 2010).

$$\theta_t = \theta_{t-1} + (P_t - L_t - AET_t).\Delta t \qquad \text{Eq. 1}$$

$$WL_t = \left(\frac{\theta_t - \theta_{FC}}{\theta_{SAT} - \theta_{FC}} \right) \quad for\,\theta_{t-i} > \theta_{FC} \qquad \text{Eq. 2}$$

$$DR_t = \frac{\theta_t - \theta_{WP}}{\theta_{CR} - \theta_{WP}} \quad for\,\theta_{t-i} < \theta_{CR} \qquad \text{Eq. 3}$$

$$\text{If } \theta_t > \theta_{FC} \text{ then } \theta_t = \theta_{FC} \text{ and } \theta_t < \theta_{WP} \text{ then } \theta_t = \theta_{WP} \qquad \text{Eq. 4}$$

Where θ_t is the soil moisture at daily time step Δt; θ_{CR} is the critical crop-specific moisture level; and θ_{SAT} is the saturated moisture level. Field access for planting/sowing and harvesting was derived from the water balance whereby hindered access was assumed from soil saturation onwards indicating waterlogging on agricultural fields.

2.4. Insurance relevant agrometeorological indicators

Three different types of insurances are considered for production risks: (1) private insurances; (2) public disaster fund; and, (3) crop insurances yield damage. Variation in adverse weather conditions, natural disasters and yields were further explored in relation to probability of occurrence and impact for each of the insurance types.

Private insurances are commonly used to manage weather risks, a market that is gaining interest. A frequency analysis of meteorological metrics was carried out during the entire growing season, as determined by cumulative growing degree days using annual median planting dates. Agrometeorological indicators were calculated for a time window of 14 days before and after the thermal date of the sensitive crop stage (Table 2, Figure 1)), as determined with a calibrated regional crop model (Gobin, 2010, 2012):

a. VPD_m: maximum vapour pressure deficit (in kPa)
b. $TMAX_m$: maximum temperature (in °C)
c. P_m: maximum rainfall (in mm)

d. U_m: maximum wind (in m/s)
e. *CDm*: maximum cumulative deficit (in mm; Eq. 1)
f. *Radm*: maximum radiation (in MJ/m²)
g. $ET0_m$: maximum reference evapotranspiration(in mm)

The public disaster fund in Belgium covers drought, frost and waterlogging due to excessive rain; heat was also considered. The following agrometeorological indicators were defined during the growing season:

a. *LFS*: Late frost, last day of killing frost in spring (where Tmin < -2°C)
b. *EFA*: Early frost, first day of killing frost in autumn (where Tmin < -2°C)
c. *TR*: total rainfall during ripening (in mm)
d. *WL*: waterlogging during planting/sowing and harvesting (in days; Eq. 2)
e. *DR*: dry days during ripening (in days; Eq. 3)
f. *Tmax>30°C*: number of heat days around flowering (in days)
g. *WD*: water deficit during the growing season and during harvest index built-up (in mm; Eq. 1)

WL, *DR*, *Tmax>30°C* were also evaluated in terms of percentage of days during the period.

2.5. Yield and weather conditions during the growing season

For most major commodity crops in the world crop insurance is available to reduce the risk exposures related to yield variability. A challenge remains to determine actual, mostly observed, loss and relate the loss to annual productivity. Most crop insurance products therefore use an underlying indicator to determine losses: weather related conditions during the growing season are common indicators. For state aid related to relief from natural disasters, the EC defined a reference of three-year average based on the preceding five-year period, excluding the highest and the lowest entry (EC, 2014).

The use of long term yield observations was explored to characterise regional yields and their distributions. The advantage of yield statistics is that they exist for the period 1947-2012 at the national level. Yield time series were detrended using linear regression (Peltonen-Sainio et al., 2010; Gobin, 2010), and subsequently translated to current yields (ny_t) by adding the residuals (e_t) to the median 2006-2012 yield ($y_{2006\text{-}2012}$) (Eq. 5).

$$ny_t = y_{2006-2012} + e_t \qquad \text{Eq. 5}$$

In addition to the indicators detailed above the following indicators were evaluated during the entire growing season: the sum of radiation (∑rad); the sum of heat units (∑PHU); the sum of precipitation (∑P); the sum of evapotranspiration (∑ET0); is the maximum cumulative precipitation deficit ($\sum(P\text{-}0.5ET0)_{mx}$); the maximum number of consecutive dry days (CDD_{mx}); the water balance deficit during selected months within the growing period (WD); the maximum number of consecutive rainy days (CRD_{mx}); and, the rainfall amount during the maximum number of consecutive rainy days ($ACRD_{mx}$).

2.6. Fitting return periods

Cumulative probability distributions were fitted to the agrometeorological indicators. A lognormal transformation was performed on the agrometeorological indicators related to the water balance. The Shapiro-Wilk test was implemented to test normality in the data at the 0.05 significance level.

Continuous mathematical equations were sought to fit the cumulative frequency, i.e. the frequency of non-exceedance $P\{X \leq x\}$, within the range of the observed data. The cumulative frequency was approximated by the standard normal cumulative distribution function (Φ) whereby x was translated by the mean (μ) and stretched by the standard deviation (σ). The parameters of the Gauss error function (*erf*) of sigmoid shape (Eq. 6) were estimated using a maximum likelihood approach.

$$F_n(x) = \emptyset\left(\frac{x-\mu}{\sigma}\right) = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \quad \text{Eq. 6}$$

Normal Q-Q plots were used to compare randomly generated independent standard normal data to the data, whereby linearity in the points suggested normal distribution. For comparison the empirical non-exceedance probability was approximated by a plotting position formula (Eq.7).

$$F_i = \frac{(r_i - b)}{(n+1-2b)} \quad \text{Eq. 7}$$

Where *F* is the probability associated with observation *i*, *r* is the rank number of the observation from highest to lowest, *n* is the number of observations and *b* is the slope between observations and years of occurrence. The slope enabled to weigh the contribution of each event to the computation of the non-exceedance probability.

Twenty-year return values were derived for the agro-meteorological indicators. The return period *T* (Eq. 8) associated with the return level x_T is defined as the average period of time between exceedances of x_T. The return value is on average exceeded once in T years and is derived from the mean, standard deviation and the inverse of the standard normal cumulative distribution functions (Eq. 8).

$$T = \frac{1}{1-F_X(x_T)} \text{ and } x_T = \mu + \sigma\emptyset^{-1}(1 - \frac{1}{T}) \quad \text{Eq. 8}$$

Cumulative probability distributions (Eq. 6) were fitted to the detrended yields to derive low and high yields, defined as the lower and upper quintiles of the distribution respectively.

3. Results

3.1. Phenology of arable crops

The flowering, tuber setting and maturity occurred significantly earlier during the growing season in the period 1988-2012 as compared to the period 1947-1987 (Figure 2). For the entire period 1947-

2012, the maturity date of winter wheat reached 1700 cumulative growing degree days (*cGDD*) between 16th July and 15th August with 95% confidence level. Winter barley reached 1450 *cGDD* between 26th June and 30th July and winter oilseed rape reached 1500 cGDD between 23th June and 30th July with 95% confidence level. The maturity date of potato reached 1350 cumulative growing degree days (*cGDD*) between 23rd August and 29th September with 95% confidence level. Maize reached 1300 *cGDD* between 8th September and 14th October displaying a large variability in maturity, while sugar beet matured at 1800 *cGDD* between 20th September and 28th October. There was a significant shift towards earlier maturity with on average 17 days for wheat and 16 days for both barley and winter oilseed rape. For the summer crops, the shifts were larger with 19 days for potato, 21 days for maize and 28 days for sugar beet (Figure 2). The shifts in maturity corresponded to 3.8 days per decade earlier for oilseed rape; 3.7 days per decade for sugar beet; 3.5 days per decade for wheat and barley; and, 3.1 days per decade for potato and grain maize.

3.2. Yield variability

The production area of Belgian arable crops was not related to yield, which confirmed that the effect of production area on yields could be excluded and that crop damages in Belgium did not lead to an underreported cropping area. Since long term yield data (1947-2012) were influenced by technological advances, yields for arable crops were detrended to detect inter-annual yield variation and low yields (Figure 3). The inter-annual yield variation had a range of 3.1 $t.ha^{-1}$ around the detrended mean of 8.6 $t.ha^{-1}$ for winter wheat; 2.2 $t.ha^{-1}$ around 8.1 $t.ha^{-1}$ for winter barley; and, 2.3 $t.ha^{-1}$ around 3.9 $t.ha^{-1}$ for winter rapeseed. Grain maize had a range of 4.3 $t.ha^{-1}$ with on average 11.7 $t.ha^{-1}$. Sugar beet had the largest range with 29.1 $t.ha^{-1}$ and a detrended mean of 47.3 $t.ha^{-1}$. Late potatoes yielded on average 75.3 $t.ha^{-1}$ and had a range of 18 $t.ha^{-1}$.

3.3. *Adverse weather conditions during sensitive crop stages*

The shift in phenological calendar had implications for the coincidence between adverse weather conditions and sensitive crop stages across the years. Crop stages considered were leaf development; and, flowering or tuber setting. The mean *VPDmax* during the sensitive stages of winter crops increased with 27% for winter oilseed rape, 50% for wheat and 77% for barley (Figure 4). For summer crops the increase in mean *VPDmax* was 40% for potato during tuber setting, 63% for sugar beet and 79% for grain maize. The increase in *VPDmax* was explained by higher *Tdew* and *Tmin* but not by *Tmax*. Only for grain maize and despite earlier flowering, the median *Tmax* increased with 2.4 °C from the period before 1988 to after 1987. Average rainfall during the sensitive crop stages decreased with 5 to 14% for winter cereals and winter oilseed rape, and even up to 34% during sugar beet establishment pointing at increasing dry spells during spring (Figure 4). The median peak rainfall (*Pmax*) did not change for winter crops and sugar beet, and decreased for potato. During maize flowering the peak rainfall increased with 30-70%, while the variability doubled. The variability in *Pmax* between the years during the period 1947-2012 indicated the presence of adverse weather conditions. The evapotranspiration (*ET0max*) and radiation (*RADmax*) was higher after 1987, and resulted in relative increases in cumulative moisture deficit (*CDmax* in Figure 4). Median wind speed tended to be lower during the last two decades (Figure 4).

A comparison of the six agrometeorological indicators between low and high yields for each of the six arable crops demonstrated a significantly lower radiation (*RADmax*) for low winter wheat yields ($p<0.05$) and winter barley yields ($p<0.01$). In addition, wind speeds (*Umax*) were significantly higher for low barley yields ($p<0.01$). Low winter oilseed rape yields were associated with higher values for *VPDmax*, *Umax* and *CDmax* at the 0.05 significance level. Maximum temperatures (*Tmax*) and cumulative moisture deficits (*CDmax*) were significantly higher for low potato yields at the 0.05 significance level. For sugar beet there were differences in *Tmax* and *CDmax* but these were not significant. Low grain maize yields had significantly lower *RADmax* ($p<0.01$) and lower evapotranspiration rates (*ET0max*; $p<0.05$).

3.4. Weather conditions during the growing season

A comparison of agrometeorological indicators between low and high yields (Table 3) clearly demonstrated significant differences for radiation with 19.5% higher radiation sums (Σrad) for high as compared to low maize yields; 17.6% higher values for winter wheat; 9.6% for winter oilseed rape; and, 9.3% for sugar beet. The sum of heat units (ΣPHU in Table 3) was significantly lower for high potato and winter barley yields suggesting a lower tolerance to heat, while significantly higher sums were found for high grain maize yields. Significantly lower rainfall amounts during the growing season (ΣP in Table 3) occurred for high winter wheat yields, whereas significantly higher rainfall during the growing season was found for high potato yields. The sum of evapotranspiration during the growing season ($\Sigma ET0$ in Table 3) was significantly higher for high maize yields, but lower for high potato yields and high barley yields, though the latter was not significant. The water balance, expressed as the maximum cumulative precipitation deficit during the growing season ($\sum(P\text{-}0.5ET0)_{\mathrm{mx}}$ in Table 3), displayed a lower deficit for high barley, potato and sugar beet yields; while higher precipitation deficits were found for high winter wheat yields. Further analysis showed significant differences between the water balance during different stages of the growing season. Relatively dry conditions in April-June were detected for winter wheat, winter oilseed rape and grain maize yields; for sugar beet this period was March-May. In contrast higher soil moisture conditions during March-May were found for high barley yields, while higher soil moisture conditions during June-August were observed for high potato yields. Further to the water balance the differences between low and high yields were investigated for the number of consecutive dry (CDD_{mx} in Table 3) and wet days (CRD_{mx} in Table 3) during the growing season, including the amount of rainfall during the period ($ACRD_{mx}$ in Table 3). In general, significantly lower amounts of rainfall during the maximum number of consecutive rainy days were associated with high yields for winter wheat, potato and sugar beet (Table 3). Significantly lower numbers of consecutive dry days during the growing season were observed for high yields of winter wheat, potato and grain maize (Table 3). Overall potato had the most meteorological indicators with significant differences between low and high yields.

3.5. Adverse weather conditions explain low arable yields

Low arable yields were explained by a combination or concatenation of adverse weather conditions during specific stages of the growing season. The implications of concatenated adverse weather conditions were demonstrated for low arable yields during recent decades.

Low wheat yields were associated with a combination of low radiation during the growing season (70% of low yields) and excess rainfall during late spring or early summer (55% of low yields) or wind and rain during panicle development (14% of low yields). Low wheat yields were also related to a combination of precipitation deficit during the growing season and high temperatures during flowering and maturing (36% of low yields). A very wet spring, low in sunshine, and a dry hot summer with heat spells interrupted by storms in July caused low winter wheat yields in 2001.

Low barley yields were related to spring drought (71% of low yields) in combination with high temperatures between flowering and maturity (64% of low yields) or with low temperatures during the vegetative stage (42% of low yields). Excessive rain and waterlogging during early spring (57% of low yields) combined with cold temperatures also explained lower barley yields. Frost in February 2003, drought during February-April and high temperatures in June resulted in the lowest winter barley yield.

Low potato yields were explained by combined drought and heat stress during tuber setting (79% of low yields). Waterlogging occurred in 43% of the years with low yields, and caused late planting, tuber damage or difficult harvest operations. In 2006, low temperatures in April, high rainfall in May and a heat wave in July followed by a cold and rainy August created unfavourable growth conditions for potatoes.

Low sugar beet yields were associated primarily with repeated waterlogging during the growing season (86% of low yields), and notably around seeding and germination (36%), leaf development (36%) and harvesting (36%). In 43% of the low yield cases heat and drought stress coincided during the summer. Cold temperatures and frosts contributed to 29% of the low yields. In 1998, late planting due to excess rain in April, heat stress in May, low radiation in July, and high rainfall during harvesting in September caused low sugar beet yields.

Low grain maize yields were associated with a combination of low radiation sums during the growing season (64% of low yields) and a cold and wet spring (79% of low yields) causing late planting and retarded biomass development. Late frost often aggravated this condition (36% of low yields). Drought and heat stress during flowering (21% of low yields) and waterlogging during harvest (29% of low yields) also contributed to low yields. A concatenation of wet and cold spring, excess rain during June and July, and wet conditions during harvest resulted in low yields in 2012.

Low winter rapeseed yields were primarily associated with low radiation sums during the growing season (57% of low yields), cold and wet conditions during pod formation and/or harvest (86% of low yields) and late frosts (21% of low yields). Drought, wind and heat around flowering or harvest occurred in 29% of low yields. Unfavourable conditions leading to low yields in 2006 comprised a concatenation of low temperatures in April, high rainfall in May and dry warm weather in July.

3.6. Return periods for adverse weather conditions

Trends in agrometeorological variables during different phenological phases of the six arable crops were expressed by the proportion of the variance in the indicator attributable to the variance in year (R^2). The maximum vapour pressure deficit showed a significant trend for WW (R^2=0.25), WB (R^2=0.37), SB (R^2=0.31) and GM (R^2=0.47); the maximum evapotranspiration showed a significant trend for GM (R^2=0.29). Variables showing a significant trend were detrended prior to fitting cumulative distribution functions. Return periods were derived for all agrometeorological variables and for the soil water balance during different phenological phases. The twenty-year return values were all within the range of observations. The modelled probabilities were compared to the empirical probabilities approximated by plotting positions, showing an excellent goodness-of-fit (Figure 5).

Return periods for the date of late harvest were calculated because late harvests resulted in higher risks of waterlogging for summer crops, and increased risks of drought or storms for winter crops (Table 4). The 20-year return value for early frost is 15th October, which is important for the establishment of winter crops (Figure 6). During autumn soils can be waterlogged for 75% of the sowing period hindering winter crop establishment (Table 4). The following spring, winter sown crops may experience heat stress during 70% of the flowering period based on the 20-year return value of vapour deficit (Figure 6). The 20 year return value for soil moisture deficit in a soil with 200 mm available water capacity is 168 mm for winter crops. Spring can be dry and without the winter soil moisture reserve water deficits during April-June have a 20 year return value of 301 mm.

The 20-year return value for late frost is 14th of May, which may affect the early stages of summer crops (Figure 6). Waterlogging in spring can occur for 73% of the time during sowing and/or crop establishment. The 20-year return value for heat stress in spring sown crops (*VPD*) is 73% of the time. The 20-year return value for soil moisture deficit between April and September which is relevant for summer crops is 494 mm for a soil with 200 mm available water capacity. The driest and most critical period are the months June to August when deficits have a 20 year return value of 336 mm. Other return values were established using the fitted distributions (Table 4).

4. Discussion

4.1. Weather impacts on crop performance

The REGCROP modelling framework captured quantified evidence of the shift of important crop growth stages due to changes in agrometeorological conditions in Belgium. This phenomenon is confirmed by other authors in near-by regions. Phenological phases of field crops in Germany have advanced significantly with up to 2.9 days for winter rye, 3.3 days for sugar beet and 1.7 days for maize per 10 years in the period 1961-2000 (Chmielewski et al., 2004) compared to between 3.1 and 3.8 days per decade in this study for the period 1947-2012.

The REGCROP modelling framework (Gobin, 2010) enabled quantification of agrometeorological variables that had impacts on crop growth and field activities such as planting and harvesting. The findings related to reported effects of weather on crop damage (Table 1). Winter wheat was found susceptible to high temperatures between anthesis and maturity (Semenov and Shewry, 2011), while drought hindered stem elongation and grain filling (Brisson et al., 2010). In relation to low winter cereal yields, the results in this study showed a combination of low radiation and high rainfall during the growing season, and low radiation during anthesis. Bingham et al. (2007) found that the amount of radiation intercepted per unit grain number during ear emergence, anthesis and the start of rapid grain filling affected mean grain weight (Bingham et al., 2007) and yield (Ceglar et al., 2016). Late frost occurrence was significantly higher for low wheat yields in Belgium ($p<0.05$), which suggested frost damage during stem elongation (Fuller et al., 2007; Table 1). The combined risk of frequent rainfall and wind, as reported in 2007, increased the risk of lodging (Creissen et al., 2016). Though waterlogging around anthesis caused yield losses of 34 to 92 % in wheat, and 40 to 79 % in barley (Romina et al., 2014), waterlogging in Belgium occurred mostly in spring and corresponded to stem elongation. Waterlogging during stem elongation was estimated to cause 2% yield loss per waterlogged day (Marti et al., 2015). Similar to the findings of Weymann et al. in Germany (2015), low winter oilseed rape yields were explained by low radiation during the growing season and by a combination of wind, heat and drought stress. Cold and wet conditions during the growing season, however, explained a larger portion of low yields in Belgium. Water supply played a critical role and related directly to nitrogen use efficiency and a strong vegetative growth during late autumn

(Hoffmann et al., 2015). This could explain the impact of late frost and waterlogging during spring in the low yields subsample.

Summer crop yields and weather analysis were also related to the reported findings of weather on crop damage (Table 1). Due to a shallow rooting system, potatoes were found very sensitive to waterlogging and heavy rainfall, particularly during planting and harvesting (Table 1; Van Oort et al, 2012a). Though waterlogging explained 43% of the low yields in Belgium, high temperatures and moisture deficit during the onset of tuber formation and also during yield formation accounted for the majority of low yields. Drought impact on overall growth and yield even at low stress levels was confirmed by Monneveux et al. (2013). Growth at elevated temperatures reduced tuber dry matter yield by 30% despite an increase in net foliar photosynthesis (Table 1; Hancock et al., 2014). Low sugar beet yields were attributed to waterlogging and late frost. Similarly, Choluj et al. (2004) found that sugar beet suffered from waterlogging, late frost and drought during early growth stages (Table 1). Drought influenced plant growth and final yield more during the early development stage of foliar expansion than at the end of the growing cycle (Shrestha et al., 2010), and resulted in significantly lower (sugar) yields (Choluj et al., 2004) in part due to foliage variation and radiation use (Richter et al., 2001). Drought and high temperatures during the early growth stages were not significantly related to low yields in Belgium, whereas low radiation was. Wet and waterlogged fields hindered harvests and caused tuber damage (Hanse et al., 2011). Being confined to a window between late April and mid-October, low grain maize yields in Belgium were associated with low radiation and low evapotranspiration during flowering, and overall low radiation and cold and wet conditions during the growing season. In France, temperature, global radiation and rainfall variability explained grain maize variability (Ceglar et al., 2016). Grain maize suffered from frequent rainfall and cold weather during the growing season and particularly during the early stages (Ying et al., 2002). Drought and heat stress during flowering resulted in a yield decline of up to 3000 kg.ha^{-1} (Roth et al., 2013), but these combined stresses could not always account for low maize yields in Belgium.

The adverse weather conditions during sensitive crop stages and during the entire growing season caused agricultural crop damages and yield anomalies, the occurrence of which was captured in aggregated regional statistics. The impact of single events on crop yields was difficult to establish, since yields integrated weather variability during the growing season. In some cases crops may recover, in other cases certain events may aggravate each other into an adverse impact.

4.2. Risk assessment and management

Crucial to the quantification of weather impacts is the farming calendar which follows the phenological crop cycle. The general agricultural performance of a crop can be derived from the succession of phenological stages in time as controlled by daylength and temperature, the farming calendar of cultivation practices, the generated biomass and yield. Extremes in these values may be a good indication of stress, part of which is of direct meteorological origin.

The growing season length, late spring and early autumn frosts, and solar radiation availability are typical climatic constraints (Maracchi et al., 2005) that have changed on average during the timeframe studied. Global increasing trends in maximum precipitation, temperature, drought and storm show amplification at the tails (e.g. Easterling et al., 2000). Block maxima of meteorological variables have not always followed the average trend as shown for one third of global rainfall stations (Westra et al., 2013). The block maxima presented in this study showed no trends in rainfall related indicators and a clear trend in minimum temperature related indicators such as vapour pressure deficit. Block maxima of temperature related indicators are dual from an agronomic point of view. In addition to a shift in occurrence of adverse temperature related events during the season, there is also the effect of faster crop development and a shift in crop phenological stages. Normal cumulative distribution functions were fitted to derive 20-year return values. For return values beyond the tail of the observations, GEV distributions provide a more robust solution (e.g. Van de Vyver and Delcloo, 2011; Van de Vyver, 2012).

Risk assessment in arable agriculture is an essential tool for farmers to anticipate, avoid and react to shocks. Risk assessment in terms of distribution, frequency and consequences underlie a risk management strategy. The probability of occurrence (likelihood) and the magnitude of impact (consequence) help risk assessment where risks with a high probability and serious impact are assessed high. Agricultural risk management policies focus on risks that cause significant damage to many farmers at the same time (Anton et al., 2013).

A combination of adverse weather conditions has serious implications for risk management and adaptation options (Trnka et al., 2014). The major arable crops in Belgium were found sensitive to different adverse weather conditions. In addition, their sensitive periods occurred during different times of the year. Since most arable crops are grown in rotation farmers faced different meteorological risks that were related to different crops each season. Crop rotations constitute an important measure to avoid meteorological risks in agriculture in addition to changing cultivars (White et al., 2011). Other measures at the field level include crop mixtures. For example, barley mixtures achieved yields comparable to the best performing monocultures whilst enhancing yield stability despite being subject to multiple predicted and unpredicted abiotic and biotic stresses including brown rust (*Puccinia hordei*) and lodging (Creissen et al., 2016). With reforms in the common agricultural policy, a change to less intensive production techniques may change the production risk farmers face.

4.3. Development of crop insurances

The occurrence of adverse weather events during sensitive stages does not entirely explain low arable yields; crops have the capability to recover from stress conditions and farmers can sometimes adopt strategies to overcome stress conditions, for example by applying supplementary irrigation. Therefore it is difficult for farmers to adequately insure themselves against yield and income losses, and at the same time insurance companies have difficulties to design profitable insurance schemes that farmers will purchase. Examples from European countries highlight the need for re-insurance schemes to lower risk (Bielza Diaz-Caneja et al., 2009), particularly when large claims are filed.

A common method used to reduce the financial consequences of high risks is to buy insurance and pay a premium for someone else to take the risk. Subsidised insurance is one way of providing disaster assistance but it tends to crowd out the development of private insurance markets and has not been successful in preventing additional ad hoc assistance after the event (van Asseldonk et al., 2013). For example, the Belgian national disaster fund identifies 20-year return values of frost, drought, heat and waterlogging due to excess rainfall as critical for damage claims; the damages, however, are established in terms of yields that deviate from the normal. Increasing climatic and market risks as well as policy reforms (e.g. changes in the direct payments system) recently increased the demand for new insurance schemes that cover more than single risks in agriculture (Bielza Diaz-Caneja et al., 2009).

Long term seasonal forecasts of agrometeorological conditions would be beneficial for both farmers and insurance companies to assist in risk assessment, but these forecasts are currently not reliable enough for commercial purposes (Calanca et al., 2011). The next best option is to establish relevant agrometeorological indicators that provide insights into the potential risks for farmers of more frequent adverse weather conditions. To this extent, remote sensing based indicators offer opportunities for the vast and diverse global insurance markets (de Leeuw et al., 2014). Current applications for the public claim-based insurance systems are confined to crop damage and flood and fire risk assessment, whereas the private industry offers remotely sensed index insurances with thresholds implemented on NDVI distributions. Insurance companies need to couple these probability based risk functions and modelling results to an insurance pricing model in order to establish profitable insurance premiums.

5. Conclusion

Phenological calendars of arable crops advanced with up to 4 days per decade during the period 1947-2012 and this had implications for the coincidence between adverse weather conditions and crop development stages. In addition, a shift occurred in maximum values and distributions for vapour pressure deficit, wind, reference evapotranspiration, cumulative moisture deficit, precipitation and radiation between the periods before and after 1988. The growing season length, frost-free period, and solar radiation availability are climatic constraints that have changed on average during the timeframe studied. With the exception of minimum temperature and derived indicators, block maxima have not followed the average trend owing to a shift in both phenology and weather conditions. This dual shift necessitated a modelling approach of combining physically based crop modelling with statistical distribution fitting for assessing meteorological risks for arable crops.

The governmental disaster fund and private insurance sector are interested in expressing adverse weather conditions in terms of 20-year return values. Damage claims, however, are expressed in crop yield loss. A methodology based on yield detrending and fitting distributions to characterise low and high yields at the lower and upper quintile of the distribution, allowed for relating long-term yields to meteorological conditions during the growing season and contrasting adverse weather conditions between low and high yields. Inter-annual yield variability was related to adverse weather conditions during sensitive crop stages and during the growing season. Water (drought and waterlogging) and temperature (frost and heat) stress resulted in low Belgian arable yields when they occurred either in concatenation or in combination with adverse weather conditions such as low radiation during the growing season.

6. Acknowledgements

The author acknowledges funding from Belspo contract SD/RI/03A. Two anonymous reviewers contributed substantially to the manuscript in its present form.

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Tables

Table 1 Critical thresholds for phenological stages in arable crops

Table 2 Crop characteristics of six major arable crops in Belgium

Table 3 Agrometeorological return level values for 5, 10, 20 and 30 year return periods.

Table 4 Comparison of meteorological metrics during the growing season for low and high arable crop yields, defined as 20% and 80% probability of occurrence respectively. *p*-values *<0.05; **<0.01; *** <0.001; ns not significant.

Table 1 Critical meteorological thresholds for different phenological stages in arable crops

Crop	Weather event	Phenological Stage	Reported damage	Reference
Winter Wheat	Heat (>30-33°C)	Anthesis	Reduced grain number & size	Barlow et al., 2015; Semenov and Shewry, 2011
	Heat (>33-37°C)	Grain filling	Yield loss	Porter & Gawith, 1999
	Frost (<-2°C)	Anthesis	100% yield loss	Barlow et al., 2015
		Stem elongation	100% yield loss	Fuller et al., 2007
		Flag leaf - Anthesis	13-33% yield loss	Whaley et al., 2004
	Low radiation	Anthesis	Yield loss	Ceglar et al., 2016
		Grain filling	Yield loss	Sun et al., 2015
	Waterlogging	Stem elongation	Yield loss of 2%.wlday^{-1}	Marti et al., 2015
	Waterlogging	Anthesis	34-92% yield loss	Romina et al., 2014
	Wind (>5 m.s^{-1}) + Rain (> 7mm)	Flag leaf to maturity	10-90% yield loss	Berry et al., 2004
	Drought	Stem elongation	Yield loss	Brisson et al., 2010
		Grain filling	Yield loss	Brisson et al., 2010
	Tmin: -17.2°C Tmax: 47.5°C	All stages	100% yield loss	Porter & Gawith, 1999
Winter Barley	Waterlogging	Anthesis	40-79% yield loss	Romina et al., 2014
	Radiation	Anthesis	Grain weight	Bingham et al., 2007
	Wind & rain	grain filling	40% yield loss	Creissen et al., 2016
	Tmin: -17.3°C Tmax: 47°C	All stages	100% yield loss	Prasil et al., 2007
Winter Oilseed Rape	Heat	Flowering	Yield loss	Weymann et al., 2015
	Drought	Flowering	Yield loss	Weymann et al., 2015
	Low Radiation	Flowering to pod	Yield loss	Weymann et al., 2015
	Temperature	Pod development	Yield loss	Hoffmann et al., 2015
Potato	Waterlogging	Planting	-25% yield loss	Van Oort et al., 2012a
		Harvesting	-50% yield loss	Van Oort et al., 2012a
	Drought	Emergence	Yield loss	Monneveux et al., 2013
		Tuber formation	Yield loss	Monneveux et al., 2013
	Heat (>30°C)	Tuber formation	-30% DM yield, low HI, small tubers	Hancock et al., 2014
Sugar Beet	Waterlogging	Foliage expansion	Yield loss	
	Frost (<-4°C)	Foliage expansion	Yield loss	
	Drought	Foliage expansion	16-52% yield loss	Choluj et al., 2004
	Drought	Foliage expansion	15% yield loss	Richter et al., 2001
		Early senescence	7% yield loss	Hanse et al., 2011
Grain Maize	Heat (>33°C)	Anthesis	4-6 Mg.ha^{-1} grain loss	Edreira and Otegui, 2012
		Anthesis		Gabaldón-Leal et al., 2016
	Frost (< -2°C)	Entire season	Yield loss	Sanchez et al., 2014
	Low radiation	Anthesis (JA)	Yield loss	Ceglar et al., 2016 Ying et al., 2002
	Drought	(pre)-Anthesis	Yield loss	Roth et al., 2013
	Tmin: -1.7°C Tmax: 46°C	All stages	100% yield loss	Birch et al., 1998

Table 2 Crop characteristics of six major arable crops in Belgium (Gobin, 2012).

Crop Variable	Definition	Unit	Wheat	Barley	Potato	Sugar beet	Oilseed Rape	Maize
T_b	Base temperature	°C	4	4	7	6	5	8
T_u	Upper temperature	°C	25	25	30	30	25	30
plant	Plant date	Date	15/10	15/10	09/04	09/04	15/09	01/05
harvest	Harvest date	Date	01/08	15/07	30/09	15/10	15/07	30/09
*Sensitive Stage**	Thermal units	°C	850	800	700	250	800	850
cGDD	cumulative GDD	°C	1700	1450	1350	1800	1500	1300

* for most crops the sensitive stage occurs around flowering, for potato it coincides with tuber initiation and for sugar beet the most sensitive stage is the early leaf stage.

Table 3 Comparison of meteorological metrics during the growing season for low and high arable crop yields, defined as 20% and 80% probability of occurrence respectively. *p*-values *<0.05; **<0.01; *** <0.001; ns not significant.

Crop	Yield	∑rad MJ/m²		∑PHU mm		∑P mm		∑ET0 mm		∑(P-0.5ET0)$_{mx}$ mm		WD mm		CRD$_{mx}$ days		ACRD$_{mx}$ mm		CDD$_{mx}$ days	
Winter Wheat	low	2647 ± 261		1710 ± 198		692 ± 142		556 ± 97		-42 ± 24		-97 ± 101	AMJ	8.9 ± 2.0		77.2 ± 24.3		22.1 ± 6.9	
	high	3111 ± 383	***	1701 ± 137	ns	574 ± 135	*	570 ± 56	ns	-55 ± 24	ns	-156 ± 71	*	8.7 ± 2.6	ns	61.6 ± 19.2	*	18.4 ± 5.8	*
Winter Barley	low	2497 ± 290		1548 ± 146		618 ± 100		523 ± 96		-55 ± 24		-120 ± 67	MAM	8.8 ± 2.1		68.6 ± 20.1		19.2 ± 5.6	
	high	2445 ± 232	ns	1410 ± 137	*	610 ± 112	ns	475 ± 50	ns	-37 ± 10	*	-78 ± 62	*	9.0 ± 2.3	ns	65.0 ± 19.1	ns	18.9 ± 6.8	ns
Oilseed Rape	low	2621 ± 168		1479 ± 127		684 ± 134		512 ± 69		-41 ± 21		-88 ± 53	AMJ	9.8 ± 2.7		65.0 ± 17.8		19.6 ± 4.7	
	high	2871 ± 408	*	1478 ± 146	ns	680 ± 150	ns	541 ± 98	ns	-42 ± 14	ns	-159 ± 94	*	8.4 ± 2.0	*	69.0 ± 18.3	ns	18.2 ± 5.5	ns
Potato	low	2584 ± 294		1470 ± 148		317 ± 75		576 ± 80		-65 ± 28		-213 ± 147	JJA	7.5 ± 3.4		64.6 ± 28.4		22.3 ± 6.7	
	high	2485 ± 249	ns	1349 ± 128	*	376 ± 55	*	520 ± 59	*	-33 ± 08	**	-101 ± 066	*	6.7 ± 2.0	ns	52.2 ± 18.8	*	16.6 ± 6.2	**
Sugar beet	low	2808 ± 362		1759 ± 182		415 ± 111		578 ± 59		-45 ± 21		-31 ± 50	MAM	8.2 ± 2.8		68.8 ± 19.8		19.9 ± 6.5	
	high	3069 ± 355	*	1790 ± 112	ns	430 ± 098	ns	589 ± 98	ns	-38 ± 16	ns	-111 ± 59	***	6.7 ± 1.9	*	57.2 ± 16.1	*	16.6 ± 4.8	ns
Grain Maize	low	2224 ± 155		1204 ± 116		360 ± 78		465 ± 66		-40 ± 23		-101 ± 85	AMJ	6.9 ± 2.6		57.1 ± 19.1		17.8 ± 7.5	
	high	2658 ± 319	***	1302 ± 110	*	365 ± 58	ns	510 ± 44	*	-42 ± 12	ns	-169 ± 55	*	7.4 ± 2.5	ns	62.5 ± 20.9	ns	14.4 ± 3.3	*

∑rad is sum of radiation; ∑PHU is sum of heat units; ∑P is sum of precipitation; ∑ET0 is sum of evapotranspiration; ∑(P-0.5ET0)$_{mx}$ is the maximum cumulative precipitation deficit; CDD$_{mx}$ is the maximum number of consecutive dry days; WD is the water balance deficit during sensitive months; CRD$_{mx}$ is the maximum number of consecutive rainy days; ACRD$_{mx}$ is the rainfall amount during the maximum number of consecutive rainy days.

Table 4 Agrometeorological return level values for 5, 10, 20 and 30 year return periods.

	Winter crops				Summer crops			
Risk Indicator	5y	10y	20y	30y	5y	10y	20y	30y
Date of late harvest	11/08	16/08	20/08	22/08	21/09	27/09	02/10	04/10
Date of early & late frost	28/10	21/10	15/10	12/10	29/04	7/05	14/05	17/05
Waterlogging at sowing/planting (% of period)	74	83	90	94	59	65	71	73
Tmax > 30°C during flowering (% of period)	31	40	49	55	50	58	65	69
Total rain during HI built-up* (mm)	235	260	281	292	282	312	336	349
Dry days during HI built-up* (% of period)	47	56	64	68	68	78	87	91
Water deficit during season (mm)	77	128	168	188	326	409	494	545
Water deficit during HI built-up* (mm)	219	264	301	320	204	250	287	307

* HI is harvest index.

Figures

Figure 1 Cropping calendar and occurrence of sensitive crop stages during the growing season being planting (p), sowing (s), leaf development (g), flowering (f), tuber setting (t) and harvesting (h).

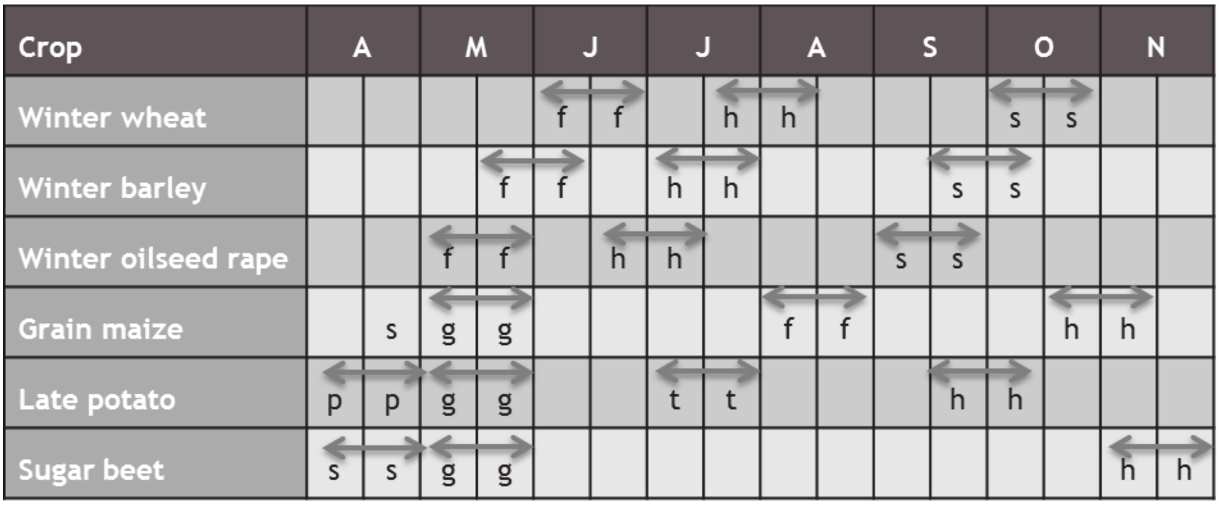
Figure 2 Shift in crop phenological stages during the periods 1946-1987 and 1988-2012. Selected stages are early vegetative stage of sugar beet (SB), flowering of winter wheat (WW), winter barley (WB), grain maize (GM) and winter oilseed rape (OS); and, tuber initiation of late potato (PB). Solid box lines represent median and lower and upper quartiles, while whiskers represent ± 1.5 the interquartile range and dots represent outliers.

Figure 3 Yield distributions of six major arable crops in Belgium. Detrending was based on linear regression and subsequent conversion to the 2006-2012 average yield.

Figure 4 Boxplots of block maxima during selected crop stages (see Figure 2) before 1988 and after 1987. VPD (kPa) is vapour pressure deficit; U (m.s-1) is wind speed; ET0 (mm) is evapotranspiration, CD (mm) is cumulative moisture deficit, P (mm) is daily rainfall, and RAD (MJ.m-^{2}) is solar radiation. Solid box lines represent median and lower and upper quartiles, while whiskers represent ± 1.5 the interquartile range and dots represent outliers.

Figure 5 Probability of non-exceedance (Fn(x)) for date of early frost, days for waterlogging in fall, days of heat stress and water balance deficit (in mm, drought) in winter crops and date of late frost, days for waterlogging in spring, days for heat stress and water balance deficit (in mm, drought) in summer crops. Full lines reflect the modelled distributions.

Figure 6 Modelled versus empirical plotting positions for heat (Tmax>30°C), rainfall during harvest index (HI) built-up, and water deficit during harvest built-up for winter and summer crops.



Crop	A		M		J		J		A		S		O		N	
Winter wheat					f	f		h	h				s	s		
Winter barley				f	f		h	h				s	s			
Winter oilseed rape			f	f		h	h				s	s				
Grain maize		s	g	g					f	f				h	h	
Late potato	p	p	g	g			t	t				h	h			
Sugar beet	s	s	g	g											h	h

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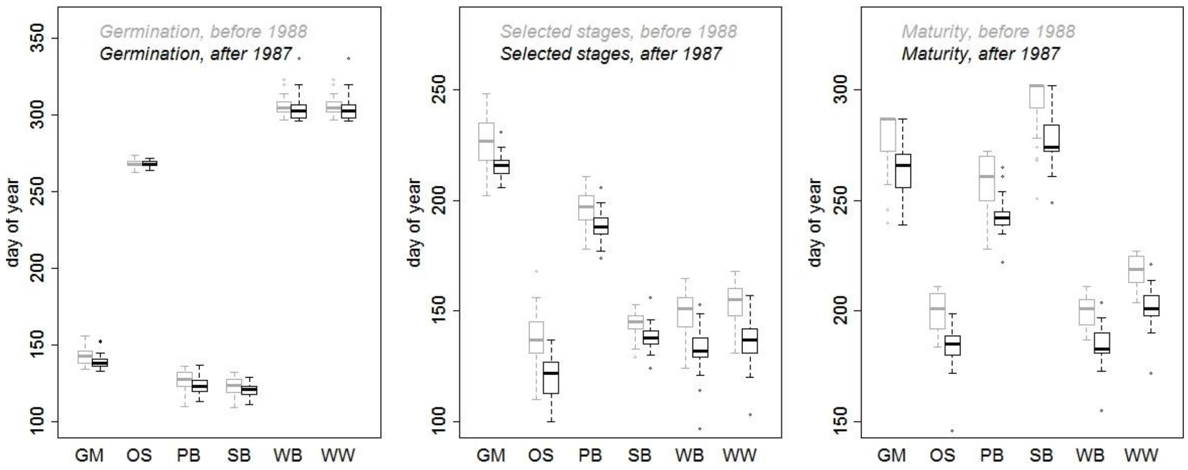

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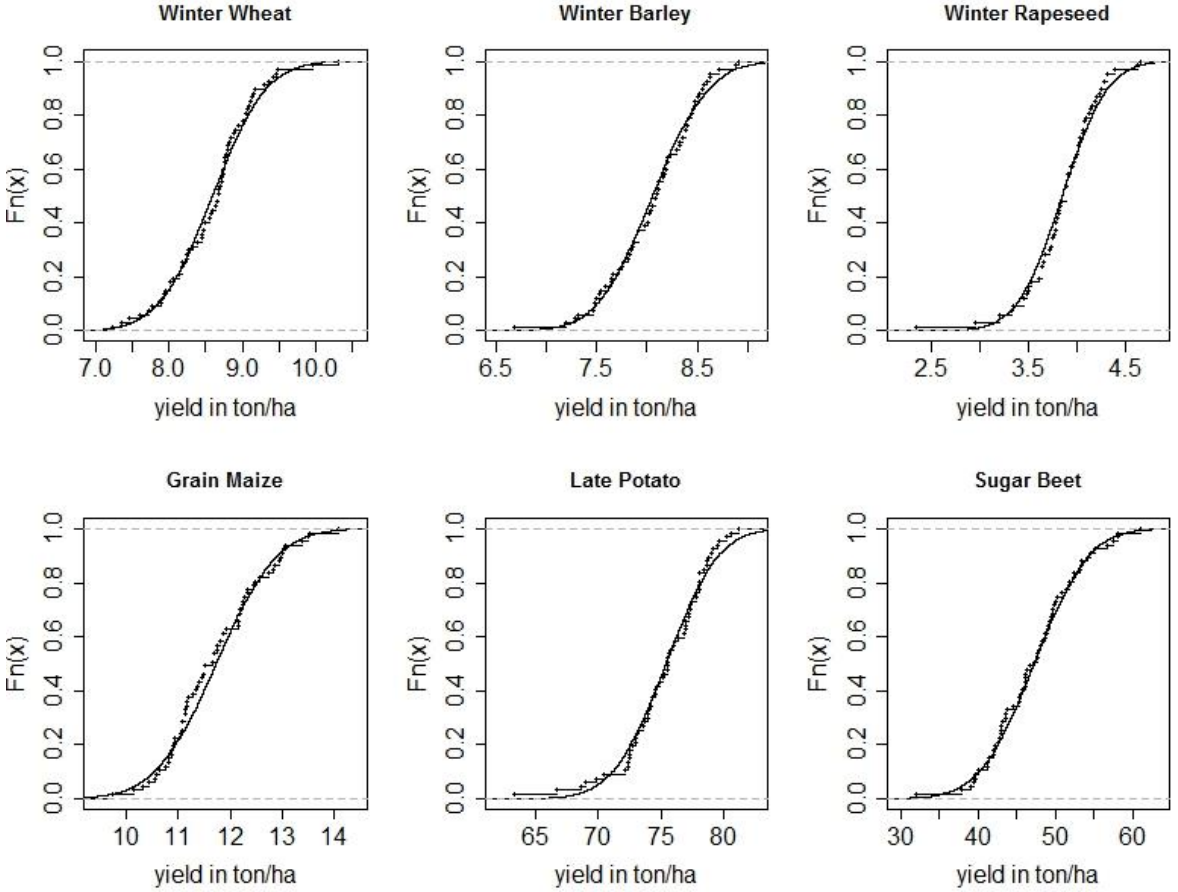

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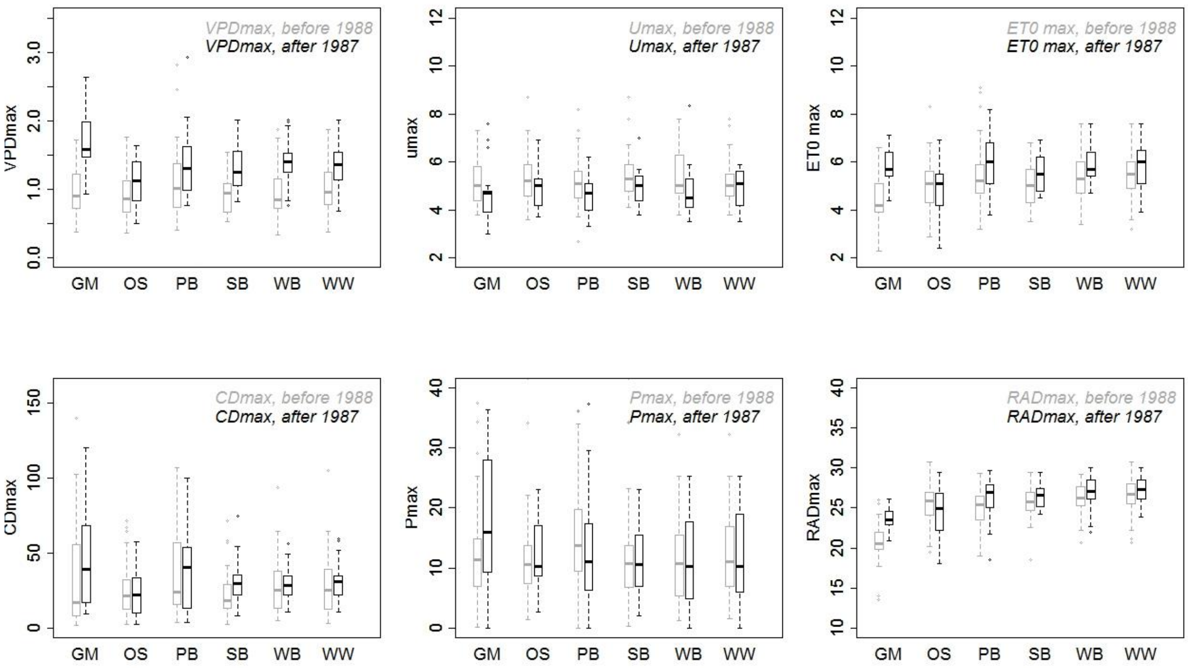

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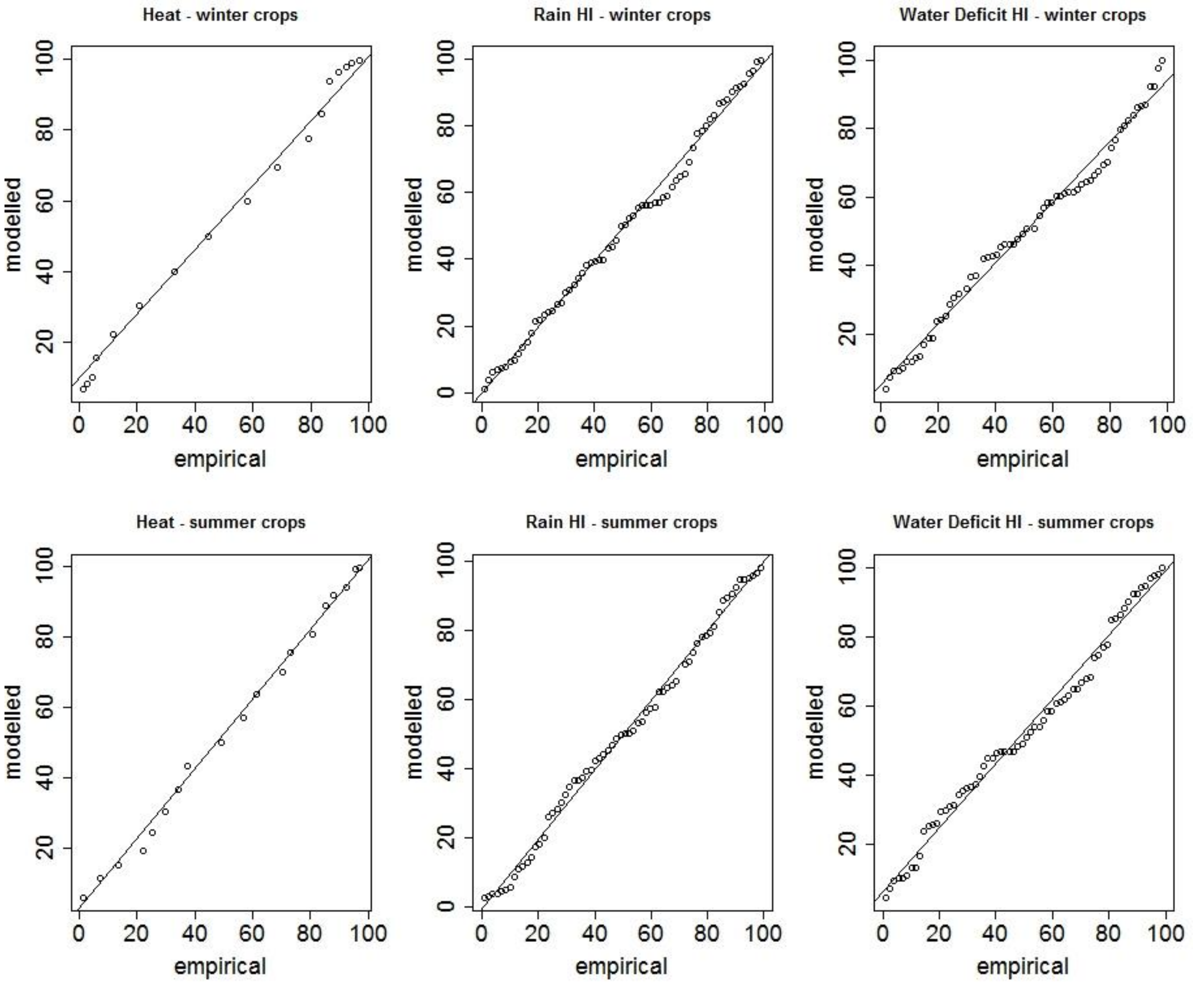

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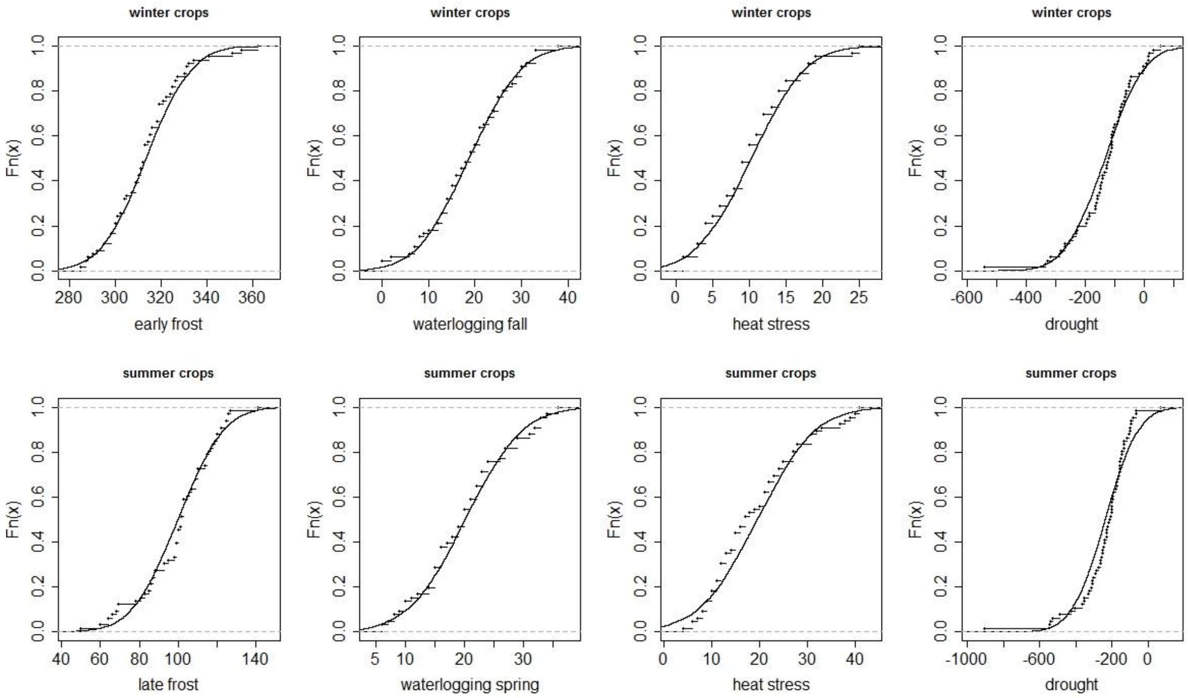

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