MEAN ANNUAL YIELD REDUCTIONS OF POTATOES DUE TO WATER DEFICITS FOR DUTCH WEATHER CONDITIONS

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Abstract

In The Netherlands drought causes occasional reductions in yield and quality of potatoes, especially on sandy soils. The mean annual yield loss determines the investments that can be made to prevent the losses. The mean annual loss is determined by the water deficit and the yield reduction per mm water deficit.

Experiments which compared well-watered controls with transient drought treatments showed that the average yield reduction per mm water deficit amounted to 117 kg tubers ha^{-1} on a fresh weight basis and to 36 kg ha^{-1} on a dry weight basis.

The water deficit is determined by the precipitation deficit integrated from 1 May to 1 September, and the net amount of water that the crop can extract from the soil during that period. From the distribution function of precipitation deficits, mean annual water deficits can be calculated. In this way mean annual reductions in tuber yield (fresh weight) were estimated to range from 8.6 t h^{-1} for zero mm soil water to 1.1 t ha^{-1} for 140 mm soil water; corresponding figures on a dry weight basis are 2.7 and 0.3 t ha^{-1}.

1. Introduction

Quantitative information on crops and weather is increasingly used to support farming decisions. Such decisions can be at the operational level of day-to-day crop management or at the strategic level of decisions that influence farming operations for more than one growing season. An example of a decision at the operational level is the timing of irrigation, whereas buying irrigation equipment is a strategic decision. At both levels the quality of the decision may be improved by using quantitative information on the crop, the weather variables and their interactions.

Although water shortage is not a major constraint to crop productivity in the Netherlands, occasional droughts cause appreciable losses of yield and quality, especially on sandy soils. For farmers it is important to have insight into the mean annual losses of yield that they incur. The average loss and the price per unit produce determine the amount of capital that they can invest in measures to prevent the losses.

In this contribution we present preliminary calculations on the mean annual reduction in yield of potatoes due to water deficits. The calculations are based on the distribution function of the precipitation deficit during the growing season, the quantity of soil water, and estimates of the yield reduction per mm water deficit.

The estimates on yield reductions are derived from a series of experiments at CABO which examined the impact of transient drought on potatoes. The measurements included photosynthesis, transpiration and stomatal conductance (Bodlaender et al., 1986, Vos and Oyarzún, 1987), leaf water relations (Vos, 1986), and periodic analysis of crop growth and development.

2. The effect of transient period of drought on potato yields

2.1. The design of the experiments and some data on the impact of drought

Plants were grown in containers with dimensions 1.33 m by 1.50 m and a soil depth of circa 0.4 m, placed under a permanent, transparent shelter roof. The outer rows of containers were excluded from the measurements. On bright days longitudinal segments of the roofs were usually opened. Evaporimeters indicated that the evaporative demand underneath the shelter amounted to circa 70 % to 80 % of the rate outside the shelter, mainly due to the reduction in incident radiation.

Water was supplied by a sub-irrigation system. Water use was calculated from recordings of water supply and from gravimetric sampling of soil moisture content. Crop transpiration represents the largest part of the total amount of water used, but some direct evaporation from the soil is also involved, especially in the beginning of the growing season. Therefore, the term 'water use' is a synonym of total evapotranspiration in this paper.

An important criterion in choosing the cultivars (Table 1) was difference in drought resistance: in the Dutch list of varieties, Kennebec is classified in the category with the highest degree of drought resistance, Bintje in the second one, and Saturna in the category with the poorest degree of drought resistance.

In each experiment the controls were watered throughout the growing season to maintain optimum soil moisture conditions. In the 1985 experiment drought stress was imposed by withholding water completely for a certain period. In other words: the degree of stress increased with time. In 1986, in contrast, soil water was first depleted till the appearance of symptoms of drought. From that point onwards the treatments were given half the quantity of water that was given to the controls (2 - 3 irrigations per week). As a result stomatal conductance oscillated between circa 80 % and 20 % of the values of the controls throughout the period of treatment (measurements with a Li Cor 1600 steady state porometer). Although 'limiting availability of water' is more adequate for the treatment in 1986, we shall also use the terms 'drought' and 'dry period' when referring to that experiment.

The periods with drought stress (reduced stomatal conductance, inhibition of expansion growth, wilting) lasted for about two to four weeks and occurred between 50 and 90 days after planting (Table 1); after the stress period the plants were given ample water again till the final harvest (recovery period). The final harvest was made at 118 days after planting in 1985 and at 131 days in 1986.

The relative green area at the end of the dry period is included in Table 1 as an index of the impact of the drought treatment. This parameter ranged between 50 % and 70 %. In 1985 drought decreased green leaf area mainly through accelerated senescence. The dry period occurred earlier in 1986 and then the inhibition of expansion growth was the prime reason for the reduction in green area.

2.2 Crop growth and water use for different water regimes

In accordance with earlier studies (e.g. de Wit, 1958) we found a linear relation between total dry matter production (roots partially excluded) and seasonal water use (Fig. 1); the data points appeared to fall on a single line irrespective of cultivar, treatment and season.

In the 1985 experiment very little tuber growth occurred during the relatively short period of severe stress (Fig. 2A), whereas in 1986 the treatment affected the rate of tuber growth less, but for a longer period than in 1985 (Fig. 2B). In the recovery period the growth rate was usually somewhat smaller in treatments than in controls, but Fig. 2A shows a case where the growth rate of the tubers of the treated crop even exceeded the growth rate of the controls during the recovery period. Furthermore, Fig. 2 indicates that our analysis pertains to a fairly high yield level (50 to 75 tons ha^{-1} fresh tubers), but it should be realized that these numbers are extrapolated from well-nursed and comparatively small units. The initial tuber bulking rate of the controls was similar in both seasons. Fig. 2 indicates earlier senescence and a lower yield level in 1985, compared to 1986. These differences in crop performance between seasons arose from differences in nitrogen regime.

The relative yield (% of controls) of the treated crops varied between 73 % and 87 % on a fresh weight basis, and between 67 % and 86 % on a dry weight basis (Table 2). The smaller impact of drought when yields are expressed on a fresh weight basis (except for cv. Kennebec) is due to the comparatively low dry matter content of tubers from transiently stressed plants at the final harvest (Table 2). Transient drought had a small effect on dry matter partitioning: the harvest index was only slightly lower for treated plants than for controls (Table 2).

When evaluated over the entire growing season, the treated plants showed higher water-use efficiencies (WUE, amount of plant material produced per unit amount of water used) than controls; this held for total dry matter, tuber dry matter, and fresh tubers (Table 3). This increase in efficiency is brought about by a larger decline in transpiration than in photosynthesis during drought (Bodlaender et al., 1986; Vos and Oyarzún, 1987). Secondly, a reduction in direct evaporation from dry soil may be involved.

2.3. Yield reductions per mm deficit in water use

We adopted an empirical method to calculate the reduction in tuber production per mm water deficit. The reduction factors were calculated with the formula:

$$(Y_c - Y_t)/(W_c - W_t) \qquad (1)$$

where Y is the final tuber yield (kg ha^{-1}), W the seasonal water use (mm); the subscripts c and t denote control and treatment, respectively. Assuming that the controls used water at the potential rate, these factors estimate the yield reduction that is incurred for each mm water that is in short supply to meet the potential seasonal evapotranspiration. Expressed on a fresh weight basis the average production loss per mm evapotranspiration deficit was 117 kg tubers ha^{-1} (range 85 to 150; Table 4); on a dry weight basis the average value was 36.4 kg ha^{-1} (range 22.8 to 46.0). Both characteristics are included because potatoes for human consumption are sold on a fresh weight basis, whereas the dry matter yield of tubers determines the financial returns of potatoes for starch production. The variation in these data is partly attributable to the fact that numerator and denominator of Eqn 1 are subtractions of two about equally large figures, each of which is subject to variation.

As expected, the reduction in tuber yield per mm water deficit is lower than the productivity per mm water use (Table 3), especially for fresh tubers.

3. Distribution functions of water deficits

The precipitation deficit (PD) is defined as the difference between the amount of precipitation, integrated over a certain period, and the potential evapotranspiration of crops, integrated over the same period. The latter is set equal to 0.8 E_o, where E_o is the 'Penman' open water evaporation as calculated at the Royal Netherlands Meteorological Institute, KNMI (de Bruin, 1979; Buishand and Velds, 1980). PD is a stochastic variable for which a normal distribution can be assumed.

The growing season for potatoes starts early May and extends till early September for potatoes for consumption and till October or later for potatoes for starch production. Distribution functions of PD are available for these periods (de Bruin, 1979). We shall make calculations for the period 1 May - 1 September. For that period the long-term mean PD at De Bilt is 71 mm, with a standard deviation of 96 mm. These figures are reasonably representative for The Netherlands. (A PD of 71 mm means that cumulative potential evapotranspiration exceeds rainfall with 71 mm.)

For reference it is noted that at De Bilt the mean annual rainfall amounts to 778 mm, while the mean annual E_o amounts to 673 mm. For the period from 1 May to 1 September the values are 271 mm and 439 mm, respectively (de Bruin, 1979).

We shall use the term 'water deficit' (WD) for the amount of water (mm) that is in short supply to sustain potential evapotranspiration; it is defined by:

$$WD = PD - SW \qquad (2)$$

where SW is the net amount of water that the crop can extract from the soil during the growing season. This amount depends on many factors such as the texture of the different soil horizons, the rooting depth, drainage out of the rooted zone and capillary rise into the rooted zone during the season. When the current analysis is applied at a particular farm, SW must be estimated. However, we shall proceed with a general analysis, assuming that a crop can rely on amounts of soil water varying from zero to 140 mm (steps of 20 mm).

The distributions of the water deficits are assumed to be similar to the distribution of PD. The mean of the water deficit is found by subtracting the amount of soil water from precipitation deficit (Eqn2). For instance, for 60 mm soil water, the distribution function has a mean of 11 mm and a standard deviation of 96 mm.

Mean seasonal water deficits can be calculated from the distribution functions of the water deficits with the table of the normal distribution. The first step is to find the probability of occurrence of water deficits (in a proportion of the seasons there are no deficits). The second step is to find the mean value of these deficits. The last step is to calculate the weighted mean seasonal deficit. For example, for 60 mm soil water there is a probability of 0.55 for the occurrence of water deficits, the mean of these deficits is 66 mm. In other words: in 55 out of 100 years there are water deficits with a mean of 66 mm. Therefore, the mean seasonal deficit is equal to (0.55 * 66 + 0.45 * 0) = 36 mm. The mean seasonal deficit for the period between 1 May and 1 September declines from 74 mm to 10 mm as SW increases from zero to 140 mm (Fig. 3).

4. The calculation of yield losses

The average yield reduction per mm water deficit amounts to 117 kg tubers ha^{-1} on a fresh weight basis and to 36.4 kg ha^{-1} on a dry weight basis (Table 3). The multiplication of the mean seasonal water deficits with these yield reduction factors gives estimates of the mean annual reductions in tuber yield (Fig. 3). In this way the mean losses (fresh weight) were estimated to decline from 8.6 to 1.1 metric tons ha^{-1} yr^{-1} for amounts of available soil water increasing from zero to 140 mm. Similarly, losses ranged between 2.7 and 0.3 tons ha^{-1} yr^{-1} on a dry weight basis.

When the physical losses are multiplied with the average price per unit one arrives at estimates of the annual average of the expenses that can be made to prevent losses due to drought. However, such an economical analysis is beyond the scope of this paper.

5. Discussion

The reliability of the calculated yield losses depends on the reliability of the assumptions that were made. The assumption that the seasonal evapotranspiration of potato crops equals 0.8 E_o (E_o as calculated at KNMI) is an approximation, but is based on experimental data (e.g. Hellings, 1979).

The extrapolation of the yield reduction per unit reduction in water use to field conditions is justified only if WUE in our experimental system does not differ from WUE under average field conditions. Such differences in WUE can result from a difference in the average water vapour pressure deficit and from a difference in the fraction that direct evaporation from the soil makes up of total water use. However, the current value for efficiency of water use (total dry matter) of controls agrees with results from field experiments (Hellings et al., 1982; Nieuwenhuis and Palland, 1982).

We assumed a linear relation between yield reduction and crop water deficit. In general this assumption is fair for two reasons: firstly, the relation between seasonal water use and total production is fairly linear (Fig. 1), and secondly drought has usually little effect on the harvest index, except perhaps for droughts late in the growing season (cf e.g. de Wit, 1958; Shalhevet et al., 1983.).

The decrease in tuber dry matter content after transient stress affects the reduction in fresh tuber yield per mm water deficit substantially. This decrease in dry matter content occurred when ample water became available after the stress period. When the stress period extends till the final harvest, the dry matter content of tubers from stressed plants will be higher than from controls, and as a consequence the average yield reduction factor will be larger than 117 kg ha^{-1} mm^{-1}. The effects of drought stress on the dry matter content are not important for starch potatoes because total dry tuber yield rather than fresh weight determines the financial yield.

In the current experiments the final harvests were made about three weeks earlier than in agricultural practice. This may affect the applicability of the current yield reduction factors to some extent. For instance, we do not know if the decrease in dry matter content of the tubers after transient drought will persist till late in the season.

The growing period of potatoes for starch production extends till October. When September is included in the calculations, the mean annual water deficits would increase with 10 mm at zero soil water; with 7 mm at 40 mm soil water and with 1 mm at 140 mm soil water. However, during the month September the potential evapotranspiration rate of a potato crop is probably often lower than 0.8 E_o and therefore the conclusions are not materially changed when the data of the month September are included in the calculations.

Buishand (1982) pointed out that analyses that are based on the distribution function of cumulative, seasonal precipitation deficits tend to underestimate the mean seasonal water deficits due to the irregular distribution of rainfall within seasons. For instance, a season with no rainfall in May and June and abundant rainfall in July and August can result in a seasonal, cumulative PD close to zero; yet, water deficit and drought losses will have occured early in the season. Therefore, estimates of mean seasonal water deficits and yield reductions can be improved by using actual data on rainfall and evapotranspiration per decade from at least 30 years.

We left the effects of water deficits on quality beyond the scope of this paper. However, for a complete analysis such effects must be quantified. Here, we only mention some important aspects. Irrigation at the beginning of the tuber growth stage is an effective precaution against scab. Drought and high temperatures often coincide. Through the maintenance of full ground cover, irrigation can be an effective mean to keep the soil temperature below the threshold for induction of secondary growth. When tuber size distribution is adversely affected by water deficits, the financial returns can decrease much more than in proportion to the decrease in physical yield.

Another aspect of the strategic decision on investments is the acceptability of occasional large losses: the farmer may be prepared to accept a somewhat lower mean annual income caused by investments in irrigation equipment if rare seasons with a low income are avoided in this way.

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Table 1. - Some characteristics of the experiments and treatments (DAP is days after planting).

Season	Cultivar	Planting date	Period of drought (DAP)	Relative green leaf area at the end of the dry period (% of controls)
1985	Bintje	18 April	73 - 90	47
1985	Saturna	18 April	73 - 90	59
1985	Kennebec	18 April	73 - 90	55
1986	Bintje	10 April	50 - 83	68
1986	Saturna	10 April	50 - 83	60

Table 2. - Effects of transient drought on relative tuber yields (per cent of controls). Dry matter content of the tubers (g kg^{-1}), and harvest indices of controls (C) and transient drought treatments (T). All the data are from the final harvests, i.e. 118 and 131 days after planting in 1985 and 1986, respectively.

Season	Cultivar	Relative yield		Dry matter content		Harvest index	
		fresh	dry	C	T	C	T
1985	Bintje	87	77	226	202	0.84	0.80
1985	Saturna	73	67	256	234	0.82	0.77
1985	Kennebec	87	86	203	200	0.77	0.76
1986	Bintje	82	76	212	198	0.79	0.76
1986	Saturna	85	76	242	217	0.73	0.71
mean		83	76	228	210	0.79	0.76

Table 3. - Average water use efficiencies (n = 5) for total dry matter, tuber dry matter and fresh tubers in kg plant material ha^{-1} mm^{-1} water used for controls (C) and treatments (T). Data from the final harvests.

	Total dry matter		Tuber dry matter		Fresh tubers	
	C	T	C	T	C	T
mean	56.2	62.1	44.4	47.3	196	227
SE	1.1	1.6	1.9	1.9	12	14

Table 4. - Reduction in tuber yield per mm water deficit ($kg\ ha^{-1}\ mm^{-1}$)

Season	Cultivar	Fresh weight	Dry weight
1985	Bintje	100	38.9
1985	Saturna	145	46.0
1985	Kennebec	104	22.8
1986	Bintje	150	41.9
1986	Saturna	85	32.6
mean		117	36.4

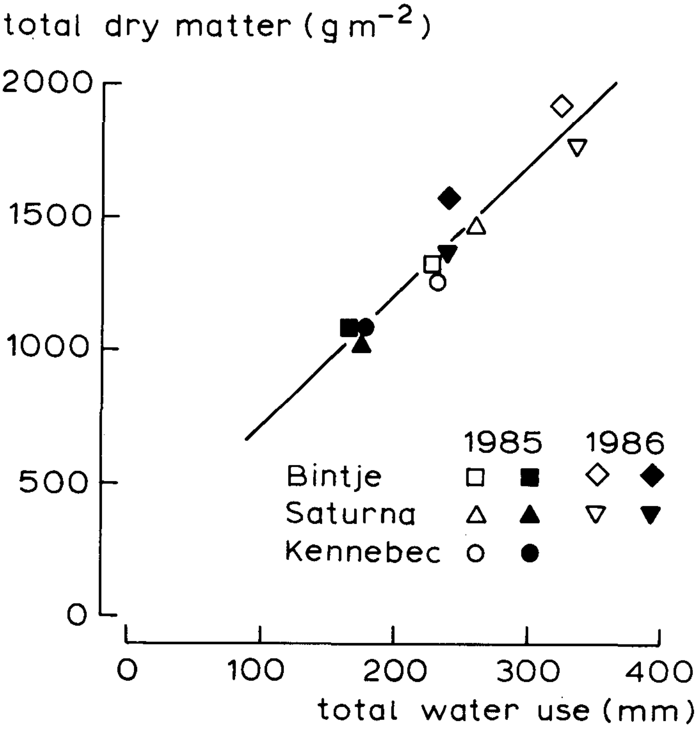

Figure 1 - Seasonal total dry matter production as a function of seasonal water use. Open symbols: controls, closed symbols: transient drought treatments. The regression equation for the full drawn line is: $Y = 4.85$ (SE 0.50)$X + 237$ (SE 121), $n = 10$, $r = 0.96$.

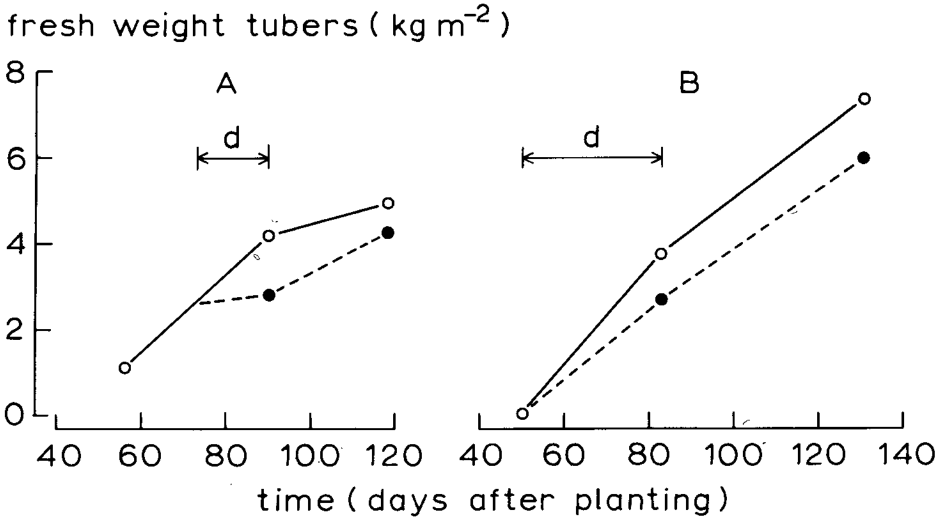

Figure 2 - Changes with time in tuber fresh weight. A: Bintje 1985; B: Bintje 1986. Open symbols: controls; closed symbols: transient drought treatments; the time interval designated with 'd' is the drought period.

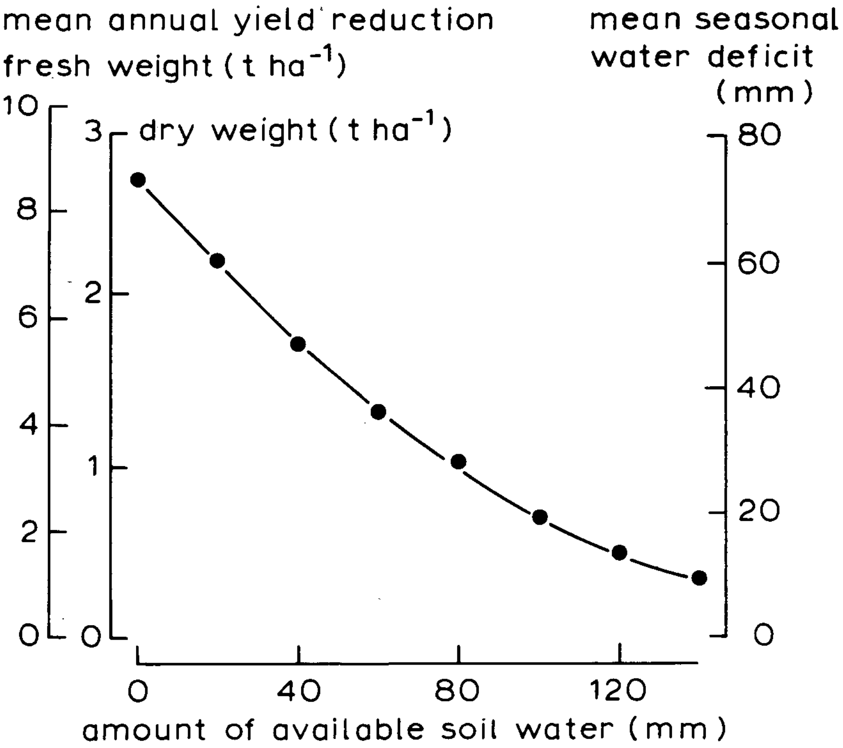

Figure 3 - The calculated mean seasonal water deficit (right-hand ordinate) and the mean annual yield reductions (left-hand ordinates) as a function of the amount of available soil water.