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A Robust Potato Model: LINTUL-POTATO-DSS

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Abstract In 1994, LINTUL-POTATO was published, a comprehensive model of potato development and growth. The mechanistic model simulated early crop processes (emergence and leaf expansion) and light interception until extinction, through leaf layers. Photosynthesis and respiration in a previous crop growth model—SUCROS—were substituted by a temperature-dependent light use efficiency. Leaf senescence at initial crop stages was simulated by allowing a longevity per daily leaf class formed, and crop senescence started when all daily dry matter production was allocated to the tubers, leaving none for the foliage. The model performed well in, e.g., ideotyping studies. For other studies such as benchmarking production environments, agro-ecological zoning, climatic hazards, climate change, and yield gap analysis, the need was felt to develop from the original LINTUL-POTATO, a derivative LINTUL-POTATO-DSS with fewer equations—reducing the potential sources of error in calculations—and fewer parameters. This reduces the number of input parameters as well as the amount of data required that for many reasons are not available or not reliable. In LINTUL-POTATO-DSS calculating potential yields, initial crop development depends on a fixed temperature sum for ground cover development from 0% at emergence to 100%. Light use efficiency is temperature dependent. Dry matter distribution to the

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tubers starts at tuber initiation and linearly increases up to a fixed harvest index which is reached at crop end. Crop end is input of the model: it is assumed that the crop cycle determined by maturity matches the length of the available frost-free and or heat-free cropping season. LINTUL-POTATO-DSS includes novel calculations to explore tuber quality characteristics such as tuber size distribution and dry matter concentration depending on crop environment and management.

Introduction

LINTUL-POTATO-1.0

Although Alberda (1962) considered potato when comparing actual and potential yields of crops and De Wit (1964) also modeled photosynthesis of potato, the first comprehensive potato crop model was published by Ng and Loomis (1984). It made use of the SUCROS model (Van Keulen et al. 1982) that calculates potential growth from light extinction in the canopy, photosynthesis, respiration, and dry matter allocation. Later, the WOFOST model (Van Diepen et al. 1989) took soil and water relations into account, allowing a more accurate simulation of actual yields. SUBSTOR (Ritchie et al. 1995) was developed for ideotyping, agrozoning, and decision support as part of some 30 different crop models. The original LINTUL-POTATO model was developed in the early 1990s by Kooman and Haverkort (1994). The objectives of this paper are to describe the change of the LINTUL potato model from a scientific tool to a tool that is used by the potato industry for yield and quality forecasting, for yield gap analysis, and assessing weather and climate hazards.

LINTUL-POTATO was based on models describing dry matter accumulation as a function of light (solar radiation) interception and light use efficiency by Spitters (1990) and Spitters and Schapendonk (1990). Dry matter allocation to the various plant organs is modeled by assuming a temperature-dependent crop development. LINTUL-POTATO aimed to explain dry matter production and distribution of potato crops under field conditions varying in photoperiod and temperature for use in ideotyping and agrozoning (Haverkort and Kooman 1997).

In LINTUL-POTATO, crop development starts at planting. The seed tuber is planted at an indicated depth and the moment of emergence depends on the temperature-dependent sprout growth rate with a maximum value of 1 mm $(°Cd)^{-1}$. Also, light use efficiency is temperature dependent. The base temperature for crop development is 2.2 °C. The model assumes that the early phases of crop development are temperature driven as they only involve metabolic processes (mobilizing carbon from the mother tuber to the emerging sprout) and to leaf expansion well before canopy closure. It is assumed that the role of the mother tuber as deliverer of energy stops when the leaf area index (LAI) exceeds 0.75. To simulate crop senescence, the leaves are divided into cohorts according to the day in which they were formed and die or become ineffective when exceeding a cumulative temperature sum defined as their longevity, when they have more than a threshold number of leaves above them, or when daily growth is all

allocated to the tubers leaving none for the foliage. The model assumes an LAI-dependent proportion of intercepted photosynthetically active and also total solar radiation of the incident radiation. Newly formed dry matter is allocated over stems, leaves, and tubers. Tuber initiation depends on maturity type, day length, and temperature: shorter photoperiods and higher temperatures reduce the time between crop emergence and tuber initiation.

After tuber initiation, the tuber growth rate is temperature dependent and increases until its rate equals the daily LUE-dependent growth rate. LINTUL-POTATO does not take root biomass into consideration as root mass—being difficult to assess—was not measured in the experiments on which the parameterization was based. The model is written in the simulation language FORTRAN and contains 38 parameters and 21 equations. The temperature, variety, and day-length-dependent parameter values were obtained from crop analysis experiments carried out in 1991 and 1992 in Rwanda at two altitudes (short photoperiod, varying temperature regimes), in Tunisia in winter, spring, and autumn (varying photoperiods and temperature regimes) and the Netherlands (long photoperiod and a temperate season). The parameterized model was then validated against independent experimental datasets with various varieties from the Netherlands, Hawaii, Peru, the Philippines, Tunisia, and Israel (Kooman 1995).

LINTUL-POTATO-DSS

For studies in which crop production needs to be calculated to compare the influence of environmental conditions such as benchmarking, different years or agrozones, or to explore climatic hazards and climate change, a less mechanistic and less complex but more robust—e.g., less sensitive to minor weather effects—model has been derived from LINTUL-POTATO: LINTUL-POTATO-DSS. In this model, a number of adaptations are incorporated based on numerous trials analyzing growth, mainly from the PhD theses of Haverkort (1985), Kooman (1995), and Van Delden (2001) and further fine-tuned with data from various surveys.

Emergence and Crop Development

Van Delden et al. (2000) studied the early crop development and calculated a conservative—valid across growing conditions and varieties—temperature-dependent relative leaf extension rate of 0.013 cm^2 cm^{-2} $(°Cd)^{-1}$ under optimal temperatures until an LAI value of 0.75 is reached and a conservative specific leaf area of 270 cm^2 g^{-1}. Another adaptation or simplification was to replace an extinction coefficient, which depends on increased extinction of light within the canopy at higher LAI values, with a direct conversion of LAI into the proportion of intercepted solar radiation by green foliage (Haverkort et al. 1991). Between LAI values of 0 and 3, the relationship is linear, with no radiation intercepted at LAI=0 and 100% radiation intercepted at an LAI of 3 and above.

In LINTUL-POTATO-DSS, the base temperature for the various processes is 0 °C, more properly Kelvin degree should be used but in crop growth models, this is not the general habit. The model uses the following input data: daily maximum and minimum temperature (°C), solar radiation (MJ m^{-2}), precipitation (mm), and evapotranspiration

(mm). The model is run with daily data, and in case only monthly values are available, it uses interpolated values as a substitute. Monthly accumulated rainfall data, however, are converted to daily data by equally distributing rainfall over the number of rainy days, and rainy days are stochastically distributed over the month. In this situation, the monthly number of rainy days needs to be added as input. All other model input data is shown in Table 1. The base temperature for, e.g., sprout growth, is 0 °C, and the sprout growth rate equals 0.7 mm (°Cd)$^{-1}$. This proves to predict actual emergence dates well where temperatures in spring increase gradually (Van Delden et al. 2000), as is the case in temperate maritime climates. However, in locations with a cold continental winter and heavy frosts, spring temperatures usually increase swiftly, while the soil temperature often lacks behind due to the still frozen undersoil. In such conditions, actual soil temperatures need to be inserted or—if unavailable—the average day-night temperature should be used in LINTUL-POTATO-DSS, but with a reduced "sprout growth rate" as to match the modeled and actual time between planting and emergence.

The model assumes that the length of the crop cycle of the variety planted (crop earliness or lateness) in a certain environment matches the length of the available growing season when temperatures are not too high or too low for potato crop growth. When year-round potatoes can be grown, more planting and harvest dates are inserted. The crop partitions dry matter to tubers and foliage such as to arrive at a HI value of 0.75 at maturity. Inserting an earlier harvest date leads to lower calculated yields. To take a lower HI value into account when the crop is harvested earlier, in LINTUL-POTATO-DSS, the HI in the model is linearly correlated to thermal time after tuber initiation: HI is assumed to have a value of 0, for a number of days after emergence (Kooman and Haverkort 1994), which is shorter for earlier varieties, higher temperatures, and shorter photoperiods, and reaches 0.75 at crop end. Crop end is the moment when the crop is mature or haulms are killed close to maturity. The modeler inserts the date of haulm killing or assumed date of crop maturity (crop death). This is not necessarily the harvest date, as crops in, e.g., the Netherlands are harvested a few weeks after haulm killing and, in e.g., some parts of Africa, Argentina, and Australia often many weeks or even months after complete crop senescence (Caldiz 2007).

Crop Ecological Parameters

The time between emergence and 100% ground cover in LINTUL-POTATO-1.0 was made dependent on temperature until LAI equals 0.75. In LINTUL-POTATO-DSS, the temperature dependence is stretched to the LAI value of 3 representing 100% ground cover: the value of 650 °Cd between the day of emergence and the day of canopy closure best matches the actual value in crops not subjected to biotic and abiotic stress, well supplied with minerals and water and planted at a density of four plants m^{-2} as calculated from the best performing field trials carried out as described by Haverkort (1985) and Kooman (1995).

Water Relations

To simulate water-limited yield using LINTUL-POTATO, Stol et al. (1991), Franke et al. (2011), and Verhagen et al. (1998) calculated the daily crop

Table 1 Input parameters required for LINTUL-POTATO-DSS (values shown are examples only)

INPUT DATA description	Value	Explanation and range
Month of planting	4	Value between 1 and 12 (Jan–Dec)
Day of month of planting (1–31)	1	Value between 1 and 31
Planting depth (cm)	17.5	In centimeters from tuber to hill top, used to calculate emergence date
Sprout growth rate (mm $(°Cd)^{-1}$)	0.7	
Month of tuber number assessment	7	When destructive sample is taken from representative crop sample: value between 1 and 12 (Jan–Dec)
Day of tuber number assessment	15	When destructive sample is taken from representative crop sample: value between 1 and 31
Number of tubers/10 kg fresh mass	150	
Month of haulm killing	9	When foliage is desiccated a few weeks prior to harvest: value between 1 and 12 (Jan–Dec)
Day of haulm killing	15	When foliage is desiccated a few weeks prior to harvest: value between 1 and 31
Month of crop end	9	Date when crop matures (senesces) naturally, maturity type dependent: value between 1 and 12 (Jan–Dec)
Day of crop end	15	Date when crop matures (senesces) naturally, maturity type dependent: value between 1 and 31
Day of tuber initiation after emergence	15	5–20 days after emergence, maturity type dependent
Rooting depth (cm)	50	Depth of soil layer with roots
Texture (% clay and silt)	5	For water-holding capacity estimation
DM concentration of tubers (%)	21	Expected or measured
Area under irrigation (%)	100	0 or 100 for a field, intermediate for a region
Harvest index (%)	75	At crop end for all crops
Degree-days emergence—100% crop cover	650	Initial crop development
LUE (global solar radiation) (g MJ^{-1} radiation intercepted)	1.25	Light use efficiency
Min. temperature for photosynthesis ($T_{average}$)	3	LUE=0 if $T_{average}$ <3 °C
Min. temp. optimal photosynthesis ($T_{average}$)	15	LUE is at optimal value of 1.25 g MJ^{-1}
Max. temp. optimal photosynthesis ($T_{average}$)	20	LUE is at optimal value of 1.25 g MJ^{-1}
Max. temp. photosynthesis ($T_{average}$)	28	LUE=0 if $T_{average}$ >28 °C
Optional for approximation of dry matter concentration		
Dry matter of the tuber at tuber initiation		
Amount of nitrogen applied above or below average	11%	
Amount of potassium applied above or below average	+50 kg −40 kg	
Amount of water received above or below average	−100 mm	
Percentage clay	%	Explanation, see text

evaporation from Penman-Monteith grass reference transpiration (ETo) and a crop-specific coefficient (using the daily maximum and minimum temperatures, relative humidity, wind speed, solar radiation as input parameters), crop canopy cover, rainfall, and soil evaporation (calculated according to Ritchie, 1972). Water availability was calculated from soil water-holding capacity and precipitation and a water balance dependent on precipitation, drainage, and evapotranspiration.

Where LINTUL-POTATO calculates potential crop yield unlimited by water or nutrient availability nor reduction by biotic factors, LINTUL-POTATO-DSS calculates attainable yields under water-limiting conditions. Moisture stress reduces LUE, and the photosynthesis rate is proportional to the ratio of actual to potential evapotranspiration. The repercussion of lack of water for crop daily growth is thus calculated, as shown in Eq. 1:

$$Yatt = Ypot \times \frac{Wav}{ETP} \tag{1}$$

where Yatt=attainable yield increment per day, Ypot=potential yield increment per day, ETP=daily evapotranspiration, and Wav=the daily available water from rain and irrigation, its maximum value is that of ETP. Water availability further depends on rooting depth and water-holding capacity and other soil properties. Silt plus clay content of the soil are input parameters used to estimate soil water-holding characteristics such as field water capacity (FWC) and wilting point (WP) according to Bennie and Hensley (2001). Plant available water (PAW) is the amount of water between FWC and WP in mm water m^{-1} soil depth. It is assumed that only 50% of PAW is freely available for plant uptake. Plant stress develops when more than this amount is depleted from the root zone. The cumulative seasonal rainfall and soil water reserve determine the total amount of water available for crop use. Only 80% of the rainfall is assumed to infiltrate the soil and is available for crop use.

The water deficit factor (WDF) approach to quantify water stress described above can be an oversimplification of reality. A single stress factor calculated for the entire season cannot work well for rain-fed conditions in subtropical and Mediterranean areas, where rainfall is often very poorly distributed over the season. Yields are often higher in a season with lower, but well-distributed rainfall than in one with high, but poorly distributed rainfall. Therefore, the shortage of plant available water is better calculated—when daily rainfall and ETP data are available—with a "tipping bucket" (Van Keulen 1975) approach. A water balance of the rooted soil volume is then included. The balance accounts for the input "rain and irrigation" and the output "evapotranspiration and drainage." At time of planting, the soil water balance is assumed to be at field capacity. If not, the difference between the actual availability and field capacity has to be accounted for in the irrigation need. Daily inputs of rain are leveled with losses due to evapotranspiration. When rain exceeds the soil water content at field capacity, the surplus drains. On the other hand, irrigation deficit and water stress starts to accumulate when the plant available soil water content is depleted for 50% by evapotranspiration (Van Keulen 1975).

Tuber Quality Characteristics

Tuber Size Distribution

The number of tubers per unit area—contrary to yield—so far cannot be predicted with any accuracy. The number of tubers can be influenced by management factors (Struik et al. 1990), e.g., it can be increased by increasing the number of seed tubers per unit area, larger seed tuber size, and by ample availability of soil water at tuber initiation. Furthermore, the number of tubers formed per plant depends on the number of eyes per seed tuber, the proportion of sprouting eyes, number of emerging main and lateral stems per sprout, the number of main and lateral stolons, and the proportion of stolon ends yielding tubers (Struik et al. 1990). Final tuber number also depends on the proportion of tubers resorbed. All these factors are a result of interaction between variety, seed tuber physiology, and ambient soil and climatic conditions. To date, these interactions have not been elucidated or quantified. Tuber size prediction at crop end therefore requires an assessment of tuber number. This can be done once tuber number has been established, which is assumed to be at two third of the time between planting and crop end. The number of tubers per 10-kg sample at the time of assessment, coupled to the calculated final yield, can be used to calculate the number of tubers per 10 kg tuber yield at crop end, according to Eq. 2:

$$Nce = Nta \ \times \ \frac{Yad}{Yce} \qquad (2)$$

where Nce=tuber count per 10 kg at crop end, Nta=tuber number per 10 kg sample at the date of tuber number assessment, Yad=yield of tubers at date of tuber number assessment, and Yce=yield of tubers as calculated by LINTUL-POTATO-DSS at the date of crop end. The tuber count per 10 kg—often used by the industry—is a measure of the tuber size/width distribution, often also assessed with grids of varying sizes, e.g., <28, 28–35, 35–50, 50–70, and >70 mm. For different length to width ratio (L/W) categories of tuber shapes, a relationship between Nce and size distribution needs to be stablished in order to accurately estimate final tuber size distribution. Round tubers with a L/W value of 1 have higher mass proportions in the larger tuber size classes at similar Nce values than long-shaped tubers, e.g., L/W=1.8.

If so desired, the tuber size, Wtav, may also be expressed as the average tuber weight derived from the 10 kg tuber count, Nce, as shown in Eq. 3.

$$Wtav = \ \frac{10 \ kg}{Nce} \qquad (3)$$

Tuber Dry Matter Concentration

The tuber dry matter concentration (DMC) expressed as percentage dry matter usually is inferred from the specific gravity (Wilson and Lindsay 1969). Starch is heavier than water, so this is usually measured by weighing 5 kg of tubers under water. Specific gravity closely correlates with percentage of tuber dry matter as determined by oven

drying cut potato tuber parts. In the text below, specific gravity data from literature were transformed into dry matter percentage of potatoes (Wilson and Lindsay 1969).

We assume that when tubers are initiated, they have the same DMC as the stolons they are derived from. The DMC of stolons, stems, and leaves closely approaches 11% (Haverkort, 1985) and at maturity often varies between 16 and 26%, depending on the variety, environmental conditions, and crop management. LINTUL-POTATO-DSS calculates intermediate DMC values by interpolating linearly between 11% at tuber initiation (coinciding with HI=0) and the expected DMC given as input when the crop is harvested at maturity. The expected DMC is inserted by the user of LINTUL-POTATO-DSS, based on long-term observations of this parameter for the specific variety. A linear relationship is assumed as both DMC and HI follow a sigmoid pattern. This value can be used to estimate fresh crop yields at harvests earlier than crop end, e.g., at the tuber number per 10 kg count and at premature seed crop haulm killing. In Eq. 4,

$$Tdmc = a \times HI + 11\% \qquad (4)$$

where a is the slope, i.e., the increment of Tdmc % with each 0.01 increase of HI.

The HI varies between 0 at tuber initiation to 0.75 at crop end. The value of a depends on the expected Tdmc at crop end and may vary between 6, leading to a Tdmc of 15.5%, and 20, resulting in a Tdmc value of 26%. When for example the relation factor $a=15$, Tdmc=11% at tuber initiation and at crop end, it is $(15\times0.75)+11=11.25+11=22.25\%$.

Unlike total and tuber dry matter yields that can be simulated and predicted with accuracy, tuber dry matter concentration so far cannot be predicted closer than within a range known for a certain variety-environment-management combination. An approximation of a deviation from the average dry matter combination (average recorded by the grower based on long term experience with average conditions) may be established by taking nitrogen and potassium fertilization, water availability, temperature during the growing season, and soil sandiness into account. For each of these factors, only one example was taken from a large body of literature, which seems only limited to these five factors, to show its effect on tuber dry matter concentration according to Eq. 4.

Increased nitrogen fertilizer doses usually lead to lower dry matter concentrations. From results of experiments in Australia with increasing N doses ranging between 68 and 230 kg of N applied per hectare, the relationship in Eq. 5, based on data of Victoria (2010) could be established:

$$Tdmc = 25.0 - 0.0254 NITapp \qquad (5)$$

where Tdmc is the tuber dry matter concentration (%) and NITapp is the amount of nitrogen (kg N ha^{-1}) applied to the crop. Similarly, muriate of potassium (KCl) applications cause a decrease of the tuber dry matter concentration. The same source reports an absolute decrease of Tdmc with K_{app} applied kg ha^{-1}, between 62 and 312 kg K_2O ha^{-1}, according to Eq. 6, based on data of Victoria (2010):

$$Tdmc = 24.3 - 0.0340 Kapp \qquad (6)$$

Growing potatoes in increasingly wet soil conditions also tends to negatively influence the tuber dry matter concentration. Equation 7 is an example of experiments where crops were supplied with amounts of irrigation water, Wapp in mm per season, varying from 250 to 600 mm in Australia, according to Eq. 7, based on data of Hegney (2001):

$$Tdmc = 22.9 - 0.0117 Wapp \qquad (7)$$

Two environmental factors are also known to substantially reduce Tdmc: higher average temperatures during the growing season and lighter, i.e., more sandy soils. Haverkort and Harris (1986) showed that the same potato varieties and seed origin grown simultaneously at altitudes ranging from 2350 to 1350 m in Rwanda with average day temperatures over the growing season, TEMPmean, ranging from 15 to 22 °C, showed a decreasing Tdmc as shown in Eq. 8 (Haverkort and Harris 1986):

$$Tdmc = 28.0 - 0.450 TEMPmean \qquad (8)$$

Haverkort, unpublished data, found that lighter soils with a lower proportion of clay (Pclay), expressed as volumetric percentage of all soil particles, are associated with lower dry matter concentrations in a range of 5 to 35% clay according to Eq. 9 (derived from unpublished data Haverkort):

$$Tdmc = 18.2 + 0.0847 Pclay \qquad (9)$$

Similar to tuber number, the tuber dry matter concentration cannot be approached with certainty by model calculations. Tuber dry matter concentration may be assessed at the moment of tuber number assessment and, when deviating from a long-term average, a higher or lower concentration may be expected. Currently, the best approach may be to assume an average Tdmc from experience for a given variety, environment, and crop management and calculate an expected deviation based on deviating water and fertilizer supply, weather conditions, and soil type according to Eqs. 5, 6, 7, 8, and 9 leading to Eq. 10 as a follow up of Eq. 4.

$$
\begin{aligned}
Tdmc = a \times HI + 11.0 \ & + 0.0254 \,(\text{NITav} -- \text{NITact}) \\
& + 0.034 \,(\text{Kav} -- \text{Kact}) \\
& + 0.0117 \,(\text{Wav} -- \text{Wact}) \qquad (10) \\
& + 0.45 \,(\text{TEMPav} -- \text{TEMPact}) \\
& + 0.084 \,(\text{Pclay-av} -- \text{Pclay-act})
\end{aligned}
$$

When all parameter values are within the average range, no deviation from amount of nitrogen, potassium, and water made available to the crop with average temperatures and clay content, Tdmc=a×HI+11.0 % (Eq. 4) will be the average tuber dry matter value expected for this crop.

Additionally, LINTUL-POTATO-DSS can be used to study the effect of CO_2 on light use efficiency as shown by Haverkort et al. (2013) who explored the effect of climate change in different agroecological zones in South Africa. A higher CO_2

concentration in the air is associated with a higher light use efficiency. Haverkort et al. (2013) established the following equation:

$$LUE = 1.25 + ((ACC\text{-}360) \times 0.001875) \tag{11}$$

where LUE is the light use efficiency (g MJ^{-1}) and ACC is the actual atmospheric CO_2 concentration (ppm). The light use efficiency at 550 ppm as expected in 2050 will lead to a 28% increase of LUE valid in 2000 with an atmospheric CO_2 concentration of 360 ppm.

Validation of LINTUL-POTATO-DSS

Kooman (1995) parameterized LINTUL-POTATO-1.0 with field experiments with various early and late maturing varieties each in the Netherlands' rainy summer, in the Mediterranean autumn, and spring seasons and in equatorial mid-elevations and highlands. To validate the parameterized model, he subsequently compared model performance with independent results, not used to parameterize the model, from variety, planting date, shading, altitude, and seed tuber age trials in the Netherlands, Hawaii, Israel, the Philippines, Peru, and Tunisia reported in literature.

Figure 1 shows the comparison of the observed and simulated data calculated with both versions of LINTUL-POTATO. The LINTUL-POTATO-DSS model output overestimates observed data by 6% on average, which gave points closer to the $y=x$ line than the original model, which overestimates observed data with 14% and thus showing an improvement of performance over the LINTUL-POTATO-1.0 version. The mean absolute error (MAE) as well as the root mean squared error (RMSE) between observed and simulated decreased from 0.063 to 0.0596 (MAE) and 43.7 to 41.8 (RMSE) for LINTUL-POTATO-1.0 to LINTUL-POTATO-DSS, respectively, and the modeling efficiency improved from 0.37 to 0.46, indicating that the simulated values of LINTUL-POTATO-DSS compared to those of LINTUL-POTATO-1.0 describe the correlation in observed data better than the mean of the observations (Loague and
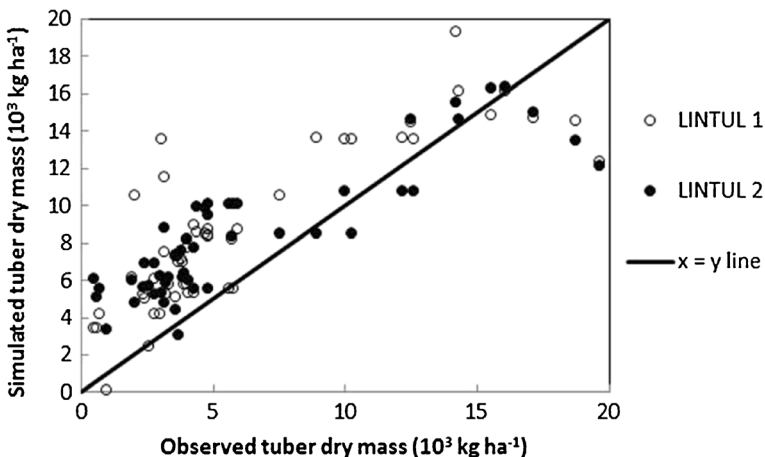
Fig. 1 Simulated versus observed tuber dry matter at final harvest for a series of experiments in different climates. *Drawn line*: simulated=observed

Green 1991). Both LINTUL versions simulated much higher values than observed when observed yields were low demonstrating that in general low yields result from inadequate management rather than from suboptimal growing conditions.

Output and Examples of Model Performance

For studies on benchmarking of production environments, agroecological zoning, climatic hazards and change, and comparison of actual/potential yields (Caldiz et al. 2001; Molahlehi et al. 2013), the need was felt to develop from the original LINTUL-POTATO-1.0 model a derivative LINTUL-POTATO-DSS with fewer equations—that would reduce the number and extend of the sources of error in calculations—and fewer parameters, thereby reducing the amount of input data required. LINTUL-POTATO-1.0 has 21 equations and 38 parameters for potential tuber dry matter yield calculations, whereas LINTUL-POTATO-DSS has only three rates: those of emergence, growth, through LUE, and distribution, through HI, and associated equations. Moreover, it is able to calculate water limited production. It uses two equations, one calculates water-holding capacity and another one yield related to relative water availability. Moreover, it estimates tuber quality characteristics such as tuber size and dry matter concentration. The simulation model LINTUL-POTATO-DSS calculates for instance output data as shown in Table 2.

Examples of the use of LINTUL-POTATO-DSS or closely resembling versions are shown by Franke et al. (2011) for yield gap analysis of different growers in the same growing production system in South Africa, by Haverkort et al. (2013) to explore the effect of climate change on potato yield and water use efficiency and by Haverkort et al. (2014) analyzing yield gaps in potato production systems and agroecologies in Chile. The ability of the model to correctly predict actual yields was shown by Machakaire et al. (2015) using the model to forecast yield and tuber size of processing potatoes in different South African environments.

Table 2 Some output data of LINTUL-POTATO-DSS (values shown serve as example only)

Output	Value	Explanation
Days between planting and emergence	28	Emergence: when 50% of the plants have emerged
Days from emergence to 100% ground cover	49	Initial crop canopy development
Days from 100% ground cover to haulm killing	90	Period of 100% light interception
DM tuber yield (t DM ha^{-1}) at haulm killing	16.8	Dry tuber yield at any day light interception is stopped
DM tuber yield (t DM ha^{-1}) at crop end	17.5	
Fresh tuber yield (t ha^{-1}) at haulm killing	78.9	Fresh tuber yield at any day when light interception is stopped
Fresh tuber yield (t ha^{-1}) at crop end	81.5	
Quality parameter: no. of tubers/10 kg fresh weight	88	Background for size distribution
Soil field capacity (mm water(m soil)$^{-1}$)	100	Upper limit of plant available water
Accumulated precipitation deficit (mm)	43	Cumulative PET minus plant available water
Irrigation need (mm)	18	Amount if irrigation water needed in addition to precipitation to meet crop water demand

Here follow two additional examples of the use of LINTUL-POTATO-DSS with illustrations: (a) the calculation of the effect of irrigation as of a predefined moment during the growing season when before none was applied and (b) prediction of final tuber size (distribution) some six weeks prior to final harvest.

Figure 2 shows the effect of irrigation—upper lines irrigated—of rain fed crops in the Netherlands, Lelystad area (Fig. 2a), and in South Africa, Bloemhof area at the border between the Free State and North West (Fig. 2b), both on sandy soils with 1% clay. In both areas, a certain year, 2003 in Lelystad and 2008 at Bloemhof, was chosen when crop yield was simulated with actual weather until mid-season with and without irrigation. Initially, there is no difference between the rainfed and irrigated crop—a single line—as the crops do not yet suffer from drought because of sufficient residual water in the soil profile. As of day 80 in the Netherlands and as of day 40 in South Africa, the nonirrigated crop total dry matter production stays behind. As of day 100 in the Netherlands and as of day 65 in South Africa, the model calculates total dry matter production in the so far either or not irrigated treatments with and without irrigation with the actual weather data of nine adjacent years. It is obvious that irrigated and rain-fed yields in the Netherlands are higher than in South Africa. It is also clear that the year to year variation in South Africa is much higher than that in the Netherlands and finally, that the impact of irrigation in South Africa is much higher than that in the Netherlands. Such LINTUL simulation exercises assist growers in making decisions for investment in irrigation equipment and to decide to irrigate or not during the growing season, especially when water supply is budgeted this may be an issue. Moreover, such work is important for yield estimations and the range of yields, e.g., for a McCain to estimate the supply they can expect (average), and what they can expect if weather conditions are going to be unfavourable.

An exercise of prediction of tuber size by LINTUL-POTATO-DSS is shown in Table 3. Ten-year weather data were taken from Lelystad, the Netherlands, and planting dates in LINTUL-POTATO-DSS were set at April 10. Yield was first calculated for August. As we did not have 10 kg tuber counts for these dates, we—for example, sake—assumed that the number was 150 for 2001 and proportional to yield in the other years. Then, using long-term average rain-fed weather conditions as input in the model calculated the final yield for each year. So, it also calculated the weight increase of the 10 kg present on August 1; hence, the new 10 kg tuber count was calculated. As a
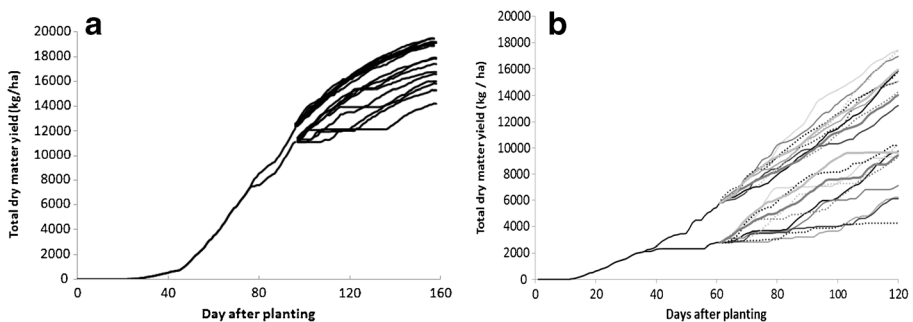
Fig. 2 Simulated total dry matter yield with LINTUL-POTATO-DSS with a single year real-time weather input with and without irrigation until mid-season, irrigation being responsible for the observed bifurcation. After mid-season, dry matter is calculated of both irrigated and nonirrigated treatments until crop end using weather data of nine adjacent years. **a** Lelystad, 2003; **b** Bloemhof, 2008

Table 3 Results of tuber count estimates at the end of the growing season when a presampling is done on August 1

Year	Simulated yield, August 1 (t ha^{-1})	Simulated yield, September 15 (t ha^{-1})	Number of tubers/10 kg	
			On August 1 (assumed)	Simulated at crop end on September 15
2001	39	74	150	79
2002	36	71	165	83
2003	35	70	167	84
2004	38	73	154	80
2005	35	70	167	84
2006	24	59	244	99
2007	42	77	139	76
2008	37	72	158	81
2009	41	78	143	75
2010	29	64	201	91
STDEV	5.48	7.28		16.75

hypothetical example, the model input is 18% dry matter on August 1 and 21% at crop end on September 15. Based on such prediction, growers, traders, or factories may set prices and predict raw material value. In years with high initial tuber counts such as 2006 with 244 tubers per 10 kg counted on August 1, the yield between sampling date —August 1—and at crop end more than doubled due to good growing conditions resulting in 99 tubers per 10 kg at crop end, till the highest in this 10-year series. This information is useful to gain insight into the crop value for an individual grower who may want to kill the crop earlier or later depending on the value of tuber size and for a processing factory in the area where it sources its raw material to pre-assess if total requirements will be met with the area contracted or if more raw material should be looked for in the open market.

Final Remarks

Over the last 20 years, LINTUL-POTATO underwent drastic changes resulting in fewer equations and parameters but with more empirical data. Due to these changes, the model became more robust and calculates or predicts yields closer to those observed. Moreover, the water relations assist in making the model useful in assessing water use efficiencies and irrigation needs. It has proven to be of use to ex ante assessments of potato areas before investing in potato processing facilities. Such investments greatly depend on variation in crop yields and water need among years and agrozones, and weather extremes such as droughts and heat waves. Also, the effect of climate change on yield, quality, and water use efficiency is easily evaluated, including the beneficial effect of increased ambient CO_2 levels on crop growth. The inclusion of relevant crop parameters such as average tuber size and dry matter concentration further make

LINTUL-POTATO-DSS a useful Decision Support tool for researchers and agronomists in the potato sector.

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