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The Canon of Potato Science: 46. Potato Crop Modelling

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What is it?

Potato crop performance can be described in terms of development and growth. Developmental stages are tuber initiation, tuber growth, maturity, dormancy, sprouting, emergence (after planting), development of leaves, stems and roots. Development is mainly determined by temperature and day length and is variety dependent. These factors determine the moment of organ initiation and the subsequent relative allocation of dry matter to them. Higher temperatures reduce the time between the various stages and shorter photoperiods lead to earlier tuber initiation, more dry matter allocated to the tubers – hence less to the foliage – and earlier maturing crops. Temperatures above the optimum for growth disfavour tuber growth and thus exert an influence on dry matter distribution.

Crop growth – the difference between assimilation and respiration – is determined by yield determining factors: the amount of photosynthetically active radiation and the carbon dioxide level in the air provided temperatures are in an optimal range and all resources such as water and minerals are in ample supply. Temperatures below optimum slow down assimilation processes and too high temperatures speed up respiration; both reducing growth. Carbon dioxide levels are the same everywhere in the world but gradually increase over the years thereby leading to higher intracellular CO_2 levels in the leaves which accelerates photosynthesis. The stomata need slightly less aperture because of higher carbon dioxide levels which leads to a reduction of transpiration and increased water-use efficiency.

At a higher level of aggregation than photosynthesis and respiration, growth may be described as the dry matter produced by the foliar apparatus following interception of photosynthetically active radiation (about half of global radiation).

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When resources that limit yield (such as water and nitrogen) are only available in suboptimal amounts, the rate and extent of canopy growth and the photosynthetic efficiency of the leaves are reduced. Yield reducing factors such as weeds, pests and diseases lead to competition for resources, reduction of foliage (Colorado beetle, late blight, bacterial diseases) or reduce the photosynthetic rate (viruses, early blight).

Modelling crop growth consists of schematically structuring all events that determine and influence development and growth of a crop as determined by Genotype, Environment and Management (G×E×M) and of quantifying the 'cause and effect relationships'. From plant physiological and crop ecological studies it appeared that many processes leading to a certain *state* have constant rates under similar conditions and when altered by changing environment this alteration also happens at fixed *rates*. Examples are conservative temperature dependent rates of sprout growth, leaf extension, rooting depth and respiration or water availability dependent rates of leaf extension and tuber dry matter concentration.

A not too complicated model of potato production may start with a tuber of a certain weight and number and length of sprouts planted at a certain depth. The plant emerges depending on soil temperature as sprouts grow at a rate of 0.7 mm per day degree (dd). The average air temperature after emergence determines the initial leaf extension rate as potato leaves expand at a rate of 0.013 $cm^2\ cm^{-2}\ dd^{-1}$. Initially leaf expansion is only temperature dependent as the leaf dry matter comes from the mother tuber. When planted at 4 plants per m^2, at a leaf area index of 1 m^2 leaf area per m^2 soil area (ground cover with green leaves then is 33%) temperature driven leaf expansion is replaced by dry matter accumulation following photosynthesis and the dry matter distribution over leaves, stems and roots. Fractional distribution initially is variety and temperature dependent and tuber initiation and subsequent partitioning of dry matter to the tubers further also depends on photoperiod. The length of the crop cycle depends on the tuber growth rate: the earlier all dry matter produced per day (source) is partitioned to the tubers (sink) the earlier the leaves will not receive any carbon and nitrogen and will die after a certain known number of day degrees. Relationships between most resource availabilities and their efficiency have been determined allowing the explanation and calculation of foliage efficacy and longevity.

Resource availability is also modelled through e.g., nitrogen routines (calculate nitrate availability from soil organic matter, (de)mineralization, leaching and volatization) or e.g., water availability from water-holding capacity, precipitation, drainage and evapotranspiration. For the whole crop simple routines have been developed shaped as

$$Y = R \times RUE \times HI : DMC$$

where Y=yield, R=amount of resource available, RUE=the efficiency of use of this resource, HI=harvest index (proportion of total dry matter produced ending up in the tuber) and DMC=dry matter concentration of the tuber.

Models explaining processes of crop development and growth and predicting of crop and resource performance depend very much on the accuracy and variety of trials carried out and the completeness of data collected from the crop and environment (soil and weather data). The ease of running these models depends on the simulation language used (e.g., FORTRAN) and the environment where the models and environmental data are stored and retrieved (e.g., DSSAT). Once a model is parameterized and quantified with existing data it has to be validated against an independent data set to validate its usefulness.

Why is it Important in Potato Science?

Models are important for potato science as they deliver a comprehensive framework of all processes, their mutual dependence and interrelations and their quantitative dependence on environmental factors. The first potato models in the seventies of the last century were able to explain potential yields based on soil and weather data. The first international potato modelling conference in the 1980s compared potato models from several groups using the same fixed soil and weather data set. It showed scientists which factors matter most and where gaps in knowledge existed. Especially yield limiting and reducing factors needed attention. In the second international potato modelling conference models of many such factors were presented, including weeds, late blight, water, nitrogen and aphids. Insight gained in these models triggered research into underlying processes down to cellular and genetic level. The enormous amount of detail and data of crop and environment presently also allow the development of a potato ontology which would have been impossible without the pioneering work of crop modellers to date.

Why is it Important for the Potato Industry?

Models initially were composed by scientists for scientists. The practical use, however, was evident soon after the beginning. It showed plant breeders for which traits plasticity exists (e.g., day length response) and none (e.g., water use efficiency) and also how expression of certain genes will contribute to yield, quality and adaptation of crops (genotyping). Models allowed the industry to look for sites where to establish new ventures by estimating timing, yields, hazards and water use efficiency in any given area in the world provided soil and weather data are available (agro-ecological zoning). Subsequent calculations of length of the growing season (frost and or heat free period) and matching this period with calculated length of the growth cycle (from planting to crop maturity) is helpful in selecting varieties for such new areas. Farmers, traders and processing factories use crop growth models to estimate expected yield in an area to be able to steer procurement and aid in establishing price policies. Finally, potato crop growth models are at the base of most decision support systems such as those guiding growers on irrigation and nitrogen supply management and dosing and timing of herbicides, pesticides (nematicides) and herbicides, thus contributing to an optimal use of resources. The third international potato modelling conference in 2004 therefore was dedicated to their use in decision support systems.

Scientific Developments

Crop growth modelling has become main stream in crop ecology and the development of decision support systems. Their use will become of increasing importance for data management in research and practice for the development of ontologies, data mining, queries and benchmarking systems. Therefore they continuously need to be refined, updated and better quantified. The presently available ones are also becoming of use in life cycle analysis especially becoming of importance in the discussion on resource use efficiency in the primary production of biomass for the biofuel industry. This creates a new series of crop growth models and of calculations with emphasis on energy use efficiency and carbon sequestration.

There is a drive on the other side of the spectrum to link various levels of aggregation starting at the level of the genome (gene sequencing, genomics, quantitative trait loci), functional genomics (gene expression, metabolomics, quantitative traits) and three-dimensional modelling allowing description and design of plants and crops for use in automation and robotization. The powerful sequencing apparatuses, enormous possibilities to store, organize and retrieve data coupled with elegant interpretation routines are likely to give continued impetus to modelling and simulation of development and growth of potato cells, organs, plants, crops and cropping systems.

Further Reading

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