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A Soil Temperature/Short-Wave Radiation Growth Model for Butterhead Lettuce Under Protected Cultivation in Flanders

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ABSTRACT

The objective of this study was to provide Flemish greenhouse farmers an accurate growth model for butterhead lettuce, based on two environmental parameters, i.e. soil temperature and short-wave radiation. During two consecutive years, a total of 27 growth experiments were followed up, whereby head fresh weight (at a 14 d interval), soil temperature at 10 cm depth (on a half-hour basis), and short-wave radiation (14 d summation) were measured. Separate Gompertz functions, with either radiation or soil temperature as input variable, accurately modelled growth; but via a combined approach, an almost perfect fit ($R^2 = 0.91$) between measured and simulated head fresh weight was obtained. This modelling approach provides lettuce growers a tool for the quantitative estimation of crop weight in relation to changes in soil temperature and short-wave radiation. Weather forecast (radiation) and managerial decisions (soil temperature), now serve as the input data of a scientifically based lettuce growth model.

Keywords: gompertz asymptotic functions, greenhouses, growth, *Lactuca sativa* L. var. *capitata* L., lettuce, short-wave radiation, simulation, soil temperature

INTRODUCTION

Growth and development of butterhead lettuce (*Lactuca sativa* L. var. *capitata* L.), grown with optimum water and nutrient supply and free of diseases and pests, are largely controlled by the effects of environmental factors, such as temperature, radiation, and day-length, upon plant growth, dry matter partitioning,

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and canopy structure and hence on the interactions between genotype and agronomic practices, such as sowing time and density (Hay and Walker, 1989). However, the complex nature of these effects makes it difficult to determine which are controlling growth in any particular circumstance (Tei et al., 1996a).

If one assumes vegetative lettuce development can be presented by the number of leaves (or plastochron index, i.e. the number of leaves $>$ 10 mm length) (Bensink, 1971), the data of Wurr et al. (1981) suggests that the early relative growth rate of a lettuce crop (i.e. the transplant till head initiation phase) can be positively related to root zone temperature. Although deleterious effects of suboptimal soil temperatures on early vegetative development have been ascribed to several physiological mechanisms, such as reduced root growth, nutrient uptake, water absorption, and hormone production in the roots, further crop research has revealed that temperature responses of leaf elongation at early growth stages are mainly due to divergences in shoot apical meristem temperatures, which in turn depend on soil temperature (Barlow et al., 1977; Coelho and Dale, 1980; Tinker, 1980; Steenhuizen, 1987; Engels and Marschner, 1990; Van Der Boon et al., 1990; White et al., 1991; Ben-Haj-Salah and Tardieu, 1995; Sayed, 1995; Ben-Haj-Salah and Tardieu, 1996; Bergh et al., 1998; Lafarge et al., 1998; Engels, 1999; Stone et al., 1999; Tardieu et al., 2000; Gavito et al., 2001; Reymond et al., 2003). However, to increase soil temperature in the early stages of the growing period, a somewhat higher air temperature is also required and it is therefore, not surprising to find leaf development or percentage soil cover to be determined by air temperature (Bensink, 1971; Bierhuizen et al., 1973; Bierhuizen and Feddes, 1973; Scaife et al., 1987; Harazono et al., 1988; Gysi, 1990; Brewster and Sutherland, 1993; Van Straten et al., 2000; Escobar-Gutiérrez and Burns, 2002).

Although a somewhat higher starting temperature favors elongation of the wrapping leaves, and hence enhances leaf photosynthetic capability, the formation of adaxial head leaves, characterized by a conspicuous surplus of mesophyll development relative to midrib elongation (Bensink, 1971; Barlow et al., 1977), is incompatible with high apical shoot meristem temperatures; therefore, soil temperature has to be somewhat lower. Furthermore, this relatively lower soil temperature, experienced by the lower leaves, lowers the respiration rate, thereby minimizing their negative contribution to the total photosynthesis (Kler et al., 1987; Cai and Dang, 2002).

These data are in accordance with Wurr et al. (1981) stating that soil temperature undoubtedly affects the growth and hearting of the crop, but that it does not appear to be the only factor of importance. As stated by Bensink (1971), Bierhuizen et al. (1973), Bierhuizen and Feddes (1973), Barlow et al. (1977), Gray and Steckel (1981), Glenn (1984), Roorda van Eysinga and Van der Meijs (1985), Kler et al. (1987), Goudriaan and Monteith (1990), Aikman and Benjamin (1994), Seginer and Ioslovich (1999), Sinclair and Muchow (1999), and Escobar-Gutiérrez and Burns (2002), final head weight is mainly influenced by radiation or light interception, which becomes the driving force for maximum relative growth rate during the head-filling phase. However, in accordance with soil temperature, it is often difficult to separate the effects of light and air temperature because it is difficult to assess to what extent each of these two environmental factors determines growth under field conditions.

Though there is modelling experience on short- and long-time control of lettuce growth based on light interception and/or soil temperature (Goudriaan and Monteith, 1990; Wurr and Fellows, 1991; Tei et al., 1996a; Tei et al., 1996b; Pietka, 1998a; Pietka, 1998b), a specific growth model for lettuce cultivated in Flanders (Belgium) does not exist. Belgian butterhead lettuce is characterized by a high on average crop weight of at least 400 g head^{-1} (FAO, 2002) and a yellowish to pale green color, making this product a high demand on foreign markets (France, Germany, etc.). Therefore, efficient managerial decisions on lettuce production are only possible if growth from transplant till marketable crop is fully understood. The principal aim of this work was to establish a quantitative relationship between the growth of protected butterhead lettuce and soil temperature and short-wave radiation.

MATERIALS AND METHODS

Field Experiments

During 2 consecutive years, a total of 27 field experiments with butterhead lettuce (*Lactuca sativa* L. var. *capitata* L.) were laid out at eight commercial greenhouses scattered over the province of West-Flanders (Belgium). The greenhouse selection procedure is fully described in Salomez (2004). The greenhouses were a sample sheet of available infrastructure and present know-how and allow extrapolating the results towards the whole production branch. Fertilization and treatment of plant diseases followed normal practice. In all eight greenhouses, five lettuce heads, loss-leaves included, were harvested on a fortnightly basis and fresh weights determined.

In each greenhouse, soil temperature (°C) was recorded on a half-hourly basis at 10 cm depth with a TRACY®-temperature recorder (Anonymous, s.d.a). Though sampling depth for soil temperature is highly debatable, literature data on both root growth and temperature variations with depth (Kutchera, 1960; Bierhuizen and Feddes, 1973; Burns, 1980; Wurr et al., 1981; Greenwood et al, 1982; Jackson and Stivers, 1993; Jackson, 1995; Thorup-Kristensen, 2001) combined with personal measurements of root growth (data not shown), revealed an optimum depth for measurements near 10 cm. These data were used for soil degree day computations (Wurr et al., 1981; Sharratt, 1996; Bergh et al., 1998):

$$\mathrm{SDD} = \sum_{i=1}^{n} (\mathrm{T}_{a,i} - \mathrm{T}_{b}) \tag{1}$$

whereby

SDD = soil degree day (°C);
n = number of days from planting on;
$T_{a,i}$ = average daily soil temperature on day i (°C);
T_b = base temperature (0°C).

Irradiance (300–3000 nm; = short-wave radiation) was measured with a DeltaT® tube solarimeter (Nicholl, 1993) 25 cm above ground level and data recorded with a MV2 Microvolt Integrator (Anonymous, s.d.b). To minimize the errors due to directional sensitivity, the tubes were oriented north to south. Though only the photosynthetically active radiation (PAR-wavebands, i.e. 400–700 nm) drives the photochemical reactions, PAR is mostly taken as a fraction of total irradiance being 45–50% (De Pinheiro Henriques and Marcelis, 2000; Escobar-Gutiérrez and Burns, 2002); therefore, the relationship will only differ by a factor of ±2.

Model Selection

Though mechanistic dynamic models undoubtedly have higher scientific, forecasting, and instructive value (Penning de Vries and van Laar, 1982), simple empirical models can provide useful information if based on biologically meaningful parameters. Empirical models for plant growth exist manifold, though the autocatalytic function and the closely related Richards and Gompertz functions are the most frequently used (Tei et al., 1996a). Heinen (1999) having compared five growth functions, i.e. the exponential, the monomolecular, the autocatalytic, the Gompertz, and the Richards function, states that all these functions belong to one family of equations; whereby the answer towards best fit will depend on the researcher and his ideas about the growth of the crop.

It was chosen to use the Gompertz asymptotic growth function for modelling purposes. Hunt (1982) states that the growth factors of the Gompertz function are non-limiting and the majority of applications of the Gompertz function have been connected with the modelling of the growth of leafy organs. Wurr et al. (1992) mentioned that the Gompertz model could accurately describe the date of maturity of iceberg lettuce from transplanting on. Tei et al. (1996a) stated that for crisphead lettuce growth the best fit was obtained by the Gompertz equation. The general format of the Gompertz function is given by:

$$WT = a \times \exp^{-b \times \exp^{-c \times t}} \tag{2}$$

whereby:

WT = total weight;
t = chronological time;
a,b,c = constants.

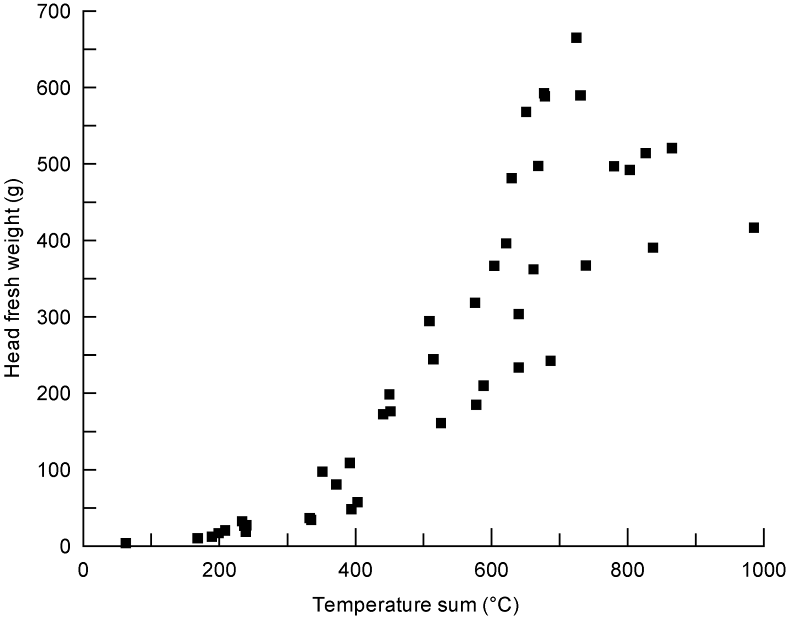

Figure 1. Head fresh weight as a function of accumulated soil temperature.

Furthermore, Gompertz functions, because of their S-shaped form, show three distinct phases: a rather slow initial growth phase, an exponential growth phase, and a maturing phase. The first phase corresponds with the transplant till head initiation stage (Sugiyama and Oozono, 1999), the second phase with the head formation and head-filling phase, and the third phase with the formation of a flower stalk, i.e. bolting. The latter phase, however, is undesirable and therefore crops are harvested just before this stage. The pre-transplant phase is not considered here, as sowing and germination of lettuce seeds take place in specialized plant factories.

RESULTS

The relationship between head fresh weight and SDD is given in Figure 1, whereas the relationship between head fresh weight and accumulated short wave radiation is given in Figure 2. Fitting equation (2) to the measurements of SDD yielded

$$\text{Simgrow} = 503 \times \exp^{\left[-37.22\times \exp^{(-7.59.10^{-3}\times \text{SDD})}\right]} \quad R^2 = 0.71 \tag{3}$$

whereby:

Simgrow = simulated head fresh weight (g);
SDD = accumulated soil temperature (°C),

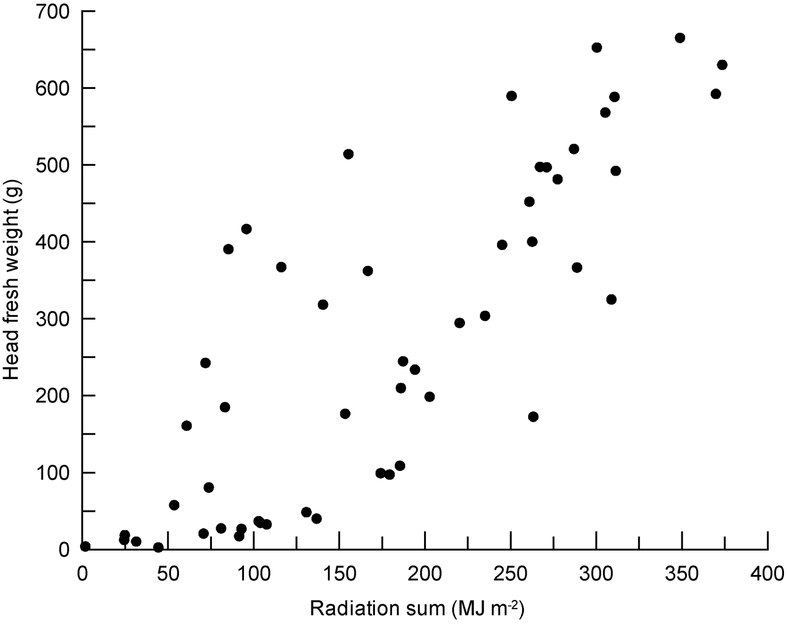

Figure 2. Head fresh weight as a function of accumulated short-wave radiation.

whereas fitting equation (2) to the measurements of accumulated short-wave radiation (radsum) yielded:

$$\text{Simgrow} = 1313 \times \exp^{\left[-3.61\times\exp^{(-4.81.10^{-3}\times\text{radsum})}\right]} \quad R^2 = 0.79 \qquad (4)$$

whereby:

Simgrow = simulated head fresh weight (g);
radsum = accumulated short-wave radiation (MJ m^{-2}).

Taking into account both environmental parameters (Figure 3), the following equation could be derived:

$$\begin{aligned}\text{Simgrow} = {} & 123 \times \exp^{\left[-23.28\times\exp^{(-5.72.10^{-3}\times\text{SDD})}\right]} \\ & + 949 \times \exp^{\left[-5.43\times\exp^{(5.05.10^{-3}\times\text{radsum})}\right]} \quad R^2 = 0.96 \qquad (5)\end{aligned}$$

The plot of measured fresh head weight versus the simulated fresh head weight (Figure 4) shows an almost perfect fit ($R^2 = 0.91$) of the growth model derived (equation 5).

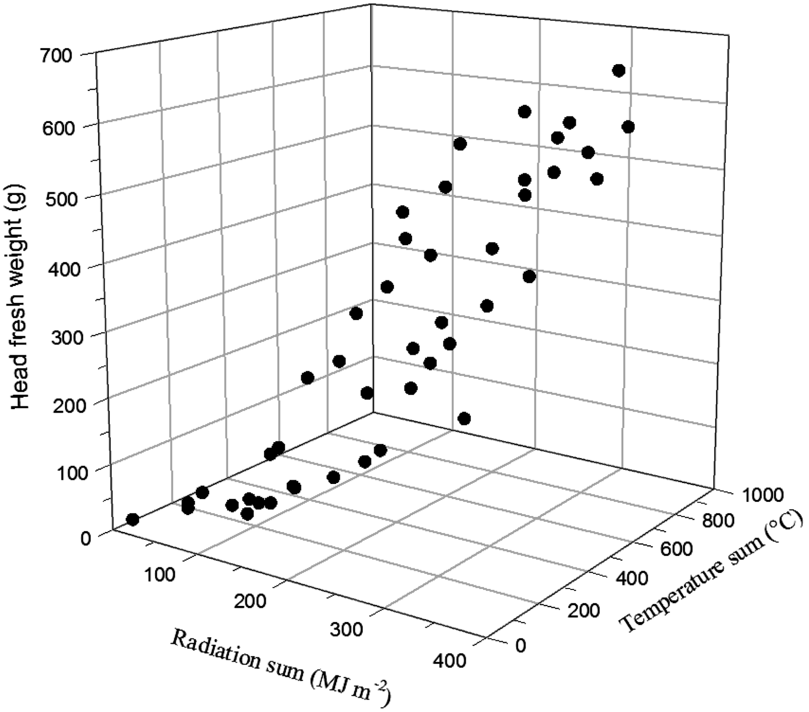

Figure 3. Head fresh weight as a function of accumulated soil temperature and short-wave radiation.

DISCUSSION

The aim of this study was to develop a lettuce growth model for butterhead lettuce cultivated under glass. Although in literature several relationships have been proposed for relating lettuce growth to temperature and radiation, no specific model has been developed for heads with high on-average crop weights of at least 400 g head^{-1}. By combining soil temperature and short-wave radiation with biweekly measurements of head fresh weights, a lettuce growth model could be developed, accurate within the relatively narrow ranges of environmental conditions provided by modern greenhouses (Figure 4). This model provides lettuce growers a tool for a quantitative estimation of crop weight in relation to soil temperature and short-wave radiation.

The modelling of growth, based on both parameters mentioned, neatly follows farmers' practice. At the start of the growing period, a somewhat higher air temperature is induced to reach 100% soil cover as soon as possible, and thereafter lower temperature. Crop growth, however, especially during colder periods, (i.e. November until March), is not checked against air temperature, but

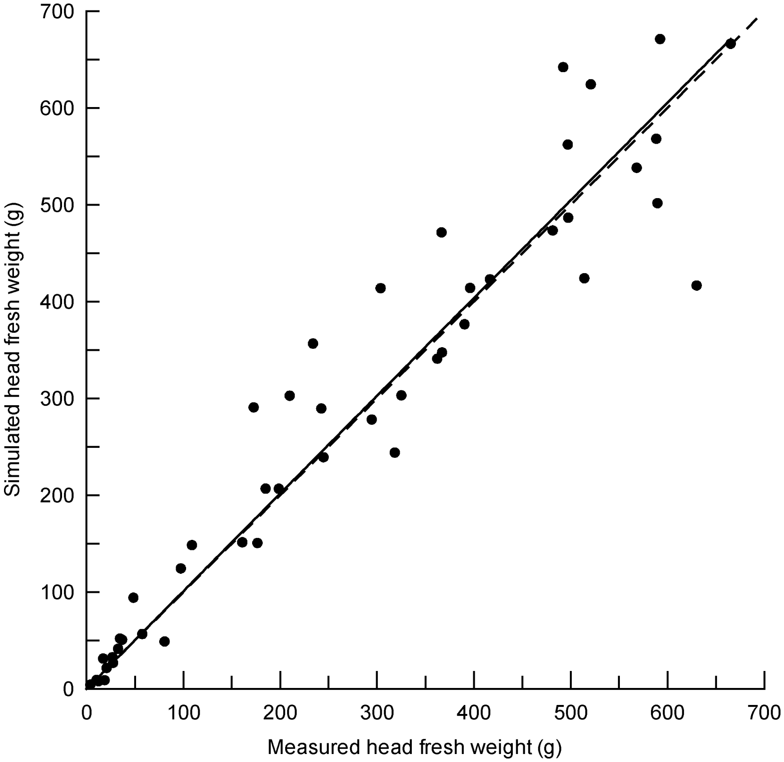

Figure 4. Relationship between measured and simulated head fresh weight. The full curve is Y = 1.006.X, the dotted curve gives the perfect fit.

by taking measurements of soil temperature at regular time intervals. At the start of the growing period a minimum soil temperature of ± 8°C is required whereas later on ± 6°C is satisfactory. Further observations also revealed that during cold and dark winter months, the best quality lettuce originated from greenhouses with the most intense incidence of light. In old and dark greenhouses, the occurrence of loose leaves was much higher and inversely correlated with head formation.

A factor not considered, but also influencing plant growth (Figure 5), was the concentration of carbon dioxide (CO_2) in the greenhouse atmosphere. However, the CO_2 in the greenhouse atmosphere is, except when CO_2-burners are used as heating source, relatively constant during the plant life cycle (Marshall and Porter, 1991). Furthermore, according to Bleyaert (personal communication) a minimum of 800–1000 ppm CO_2 is required to see any significant impact on growth. This concentration, however, is not reached under normal circumstances and not considered in this specific growth model.

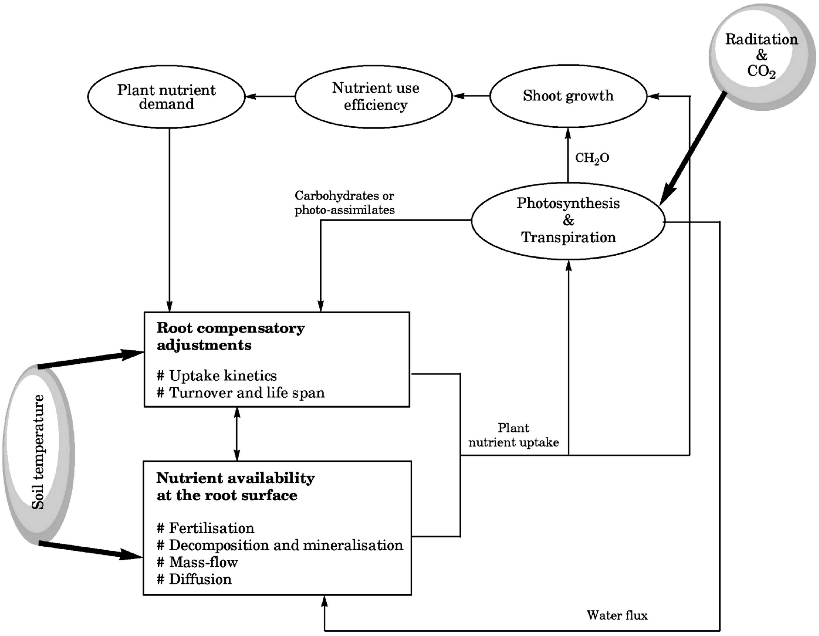

Figure 5. A conceptual diagram depicting the way in which CO_2, radiation and soil temperature, together with various other factors, can influence plant growth (after BassiriRad, 2000).

CONCLUSIONS

A two year sampling campaign in eight commercial greenhouses, which resulted in 27 experiments utilizing lettuce, was at the origin of the development of a lettuce growth model. Every two weeks, results of head weight determination and both soil temperature and radiation were collected. Soil temperature/radiation sum Gompertzian progressions did allow for a unique growth relationship, which can be used for modelling purposes on an individual greenhouse basis. It will be of interest to see how this model will be used and can be an aid to better manage lettuce cultivation in practice.

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