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A model of growth and sugar accumulation of sugar beet for potential production conditions: SUBEMOpo II. Model performance

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Abstract

A model SUBEMOpo, to simulate sugar beet growth and sugar accumulation for potential production conditions has been evaluated. Given initial conditions, the growth, development and sugar accumulation of the model are driven by observed weather (i.e. maximum and minimum temperatures, rainfall, wind speed, relative humidity and solar radiation). Soil water and nutrients are considered as non limiting in the model. To evaluate the model, results of historical field trials as well as of field trials especially conducted for this evaluation study were used. These data concern growth, yield and sugar content of sugar beets grown on sandy, loess and clay profiles in Belgium and the Netherlands during several growing seasons. The agreement between measurements and simulation results is so far acceptable. The weakest section of SUBEMOpo is the partitioning of dry matter between structural and non structural dry matter of the tap root.

Keywords: Simulation model; Potential production; Sugar beet

1. Introduction

The primary aim of this modelling research is to increase insight in the processes of growth and sugar accumulation of sugar beet. Therefore, aspects of present knowledge about beet growth have been quantitatively integrated into a dynamic mechanistic simulation model SUBEMOpo. In this paper the model has been evaluated to investigate the effects of weather on growth, yield and sugar content. The simulation results were compared with data from historical field trials (Stumpel,

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1967) and field trials especially conducted for this study. In the period 1982–88 10 field trials with sugar beets, in Belgium and the Netherlands, were intensively monitored for this purpose (Vandendriessche, 1995).

2. Materials and methods

2.1. The sugar beet model

SUBEMOpo has simulated a pool of carbohydrates in the beet resulting from photosynthesis and retrieval of dry matter from ageing and dying leaves. The pool of carbohydrates was depleted to sustain respiration, growth and sugar accumulation. When the plant was faced with a given environment, dry matter was allocated to the different plant organs, including sugar accumulation, in such a way that the plant has attained an optimal specific growth rate in that given environment. Given initial conditions, the growth, development and sugar accumulation of the model were driven by observed weather (i.e. maximum and minimum temperatures, rainfall, wind speed, relative humidity and solar radiation). Soil water and nitrogen were considered as non limiting in the model. A detailed description of the model was given by Vandendriessche, in this series.

2.2. Field trials

From 1982 to 1988 10 field trials with sugar beet, in Belgium and the Netherlands, were intensively monitored to produce a dataset for the development, parameter characterization and validation of a sugar beet growth model. The experimental design at all the sites was standardized: a single-factor block experiment with four replicates and with the rate of N-fertilizer as treatment. On nine of the trials there were at least four N-fertilizer treatments. There was no irrigation. All crops were harvested by hand, exept those at Westmaas, 1987 and Lelystad, 1986. The data collected at the field trials could be arranged in one of the following data groups: (1) initial soil and crop management data; (2) climate data; and (3) soil and crop data at various intervals during the growing season (Vandendriessche, 1995).

Results of the older field trials at Rilland in the south of the Netherlands were collected during 1960, 1961 and 1962 the sugar beets were weekly harvested on the field trials. Fresh weight of leaves (including crowns) and roots (excluding crowns), sugar content and sugar yield are measured on 12 replicates and two varieties at weekly intervals. The results, published by Stumpel (1967), were presented as moving averages over 3 weeks of the mean of the replicates of the two varieties. The results of the individual replicates are not available.

2.3. Hardware and software

The computer code is written in FORTRAN 77 and runs on IBM-compatible microcomputers. Hourly and daily simulation results are written to ASCI files. Post processing of simulation results can be done by a broad range of software. The data of the field measurements are stored in a database (Access) which is organized according the relational model. Statistical processing (analysis of variance, multiple regression) of observed and simulated results is done with SASpc (Vandendriessche, 1995). Excel worksheets are used for plotting observed and simulated values.

3. Results

Evaluation of a simulation model is a comparison of its behaviour with that of a real system in an analogous situation (Penning de Vries, 1982). SUBEMOpo simulates potential production, so water and nutrients are considered as non limiting in the model and there is no influence of weeds, pests or diseases. A comparison of SUBEMOpo with a real system requires field data of sugar beet which were well supplied with water and nitrogen. At least one of the N-fertiliser treatments in the field trials described above should approximate to these requirements. Except at the Halsteren field in 1986, which was infected with beet cyst nematode *(Heterodera schachtii)*, the incidence of weeds, pests and diseases was neglectable.

3.1. Sugar beet growth patterns during the growing seasons

With the exception of the field at Halsteren 1986, simulated sugar beet growth accords well with field data (Figs. 1 and 2). For example the simulated dry matter accumulation of the total plant on the Hélécine field at final harvest was, respectively, 1828, 1466 and 1958 g m^{-2} for the 1983, 1984 and 1985 growing seasons. These values are within the standard deviation of the measurements of the field trials (Fig. 1). The simulated dry matter accumulation reached 2403, 2045 and 1894 g m^{-2} for the Lelystad experimental fields (clay soil) in 1986, 1987 and 1988.

Observed dry matter accumulation, and especially leaf dry matter, on the Halsteren field in 1986 was obviously less than the modelled value with SUBEMOpo. However, the soil was heavily infected with beet cyst nematode: soil analysis showed 3000 eggs and juveniles per 100 ml soil.

On most of the trial fields full cover of the soil by foliage was reached around June 15 (day 166 in the year). From then onwards photosynthetically active radiation would be completely intercepted by the canopy so that potential production could be realized. A straight line indicating the average potential production of 20 g (dry matter) m^{-2} day^{-1} for a C_3 crop like sugar beet growing in a temperate climate (Ivens et al., 1992) is shown on Fig. 1.

The historical dataset with field trials in Rilland contains no dry matter production data. However, these are data of weekly changes in fresh root yield (Fig. 2). The simulated sugar beet growth follows the measured pattern reasonably well for all three growing seasons. For example, during 1960 growth was rapid until the beginning of August (day 214); then heavy rain seems to stop root growth. From 26 September (day 270) root growth resumes, but more slowly. The simulation results predict this trend but the restart near the end of the growing season is simulated 2

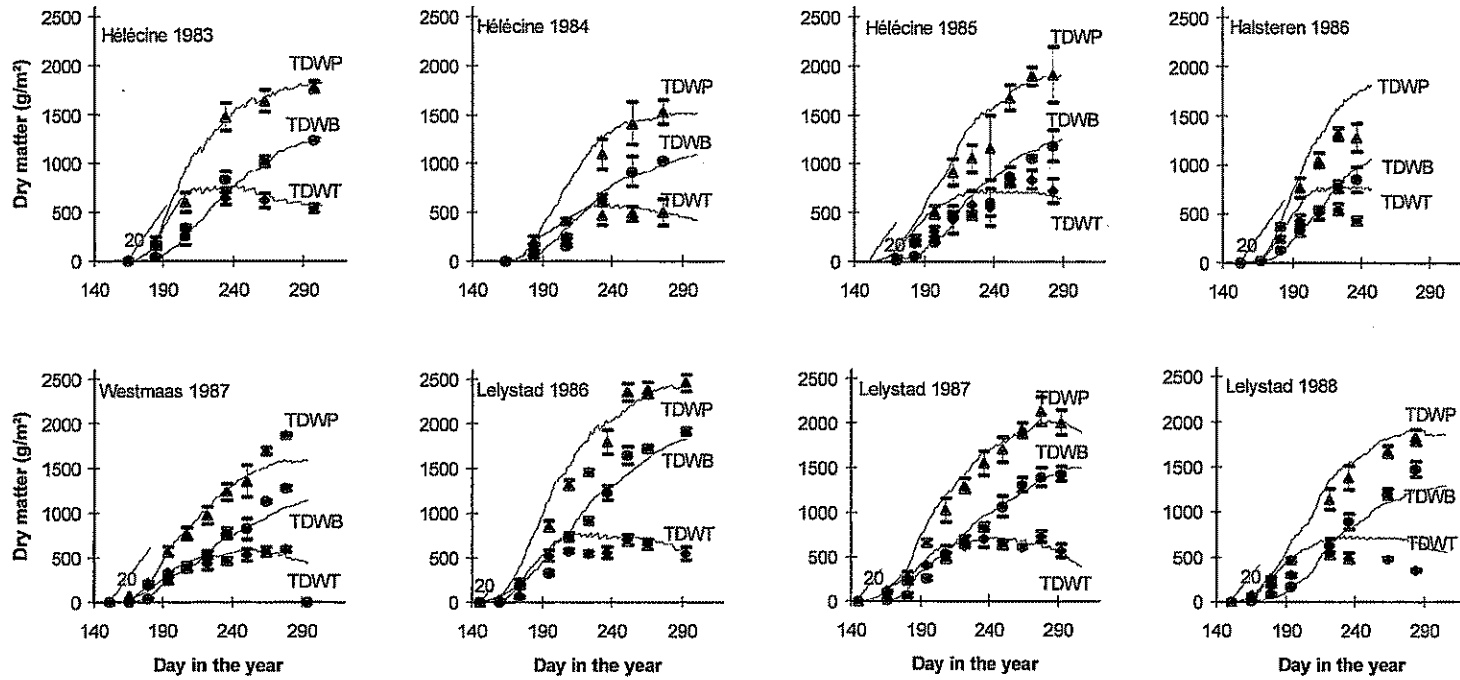

Fig. 1. Observed and simulated growth pattern and dry matter accumulation of sugar beet using the simulation model SUBEMOpo and experimental data of several field trials and experimental years (Vandendriessche, 1995). Continuous lines are the simulation results. Vertical bars represent 2× the standard deviation. TDWB, total dry matter to roots; TDWT, total dry matter to leaves.

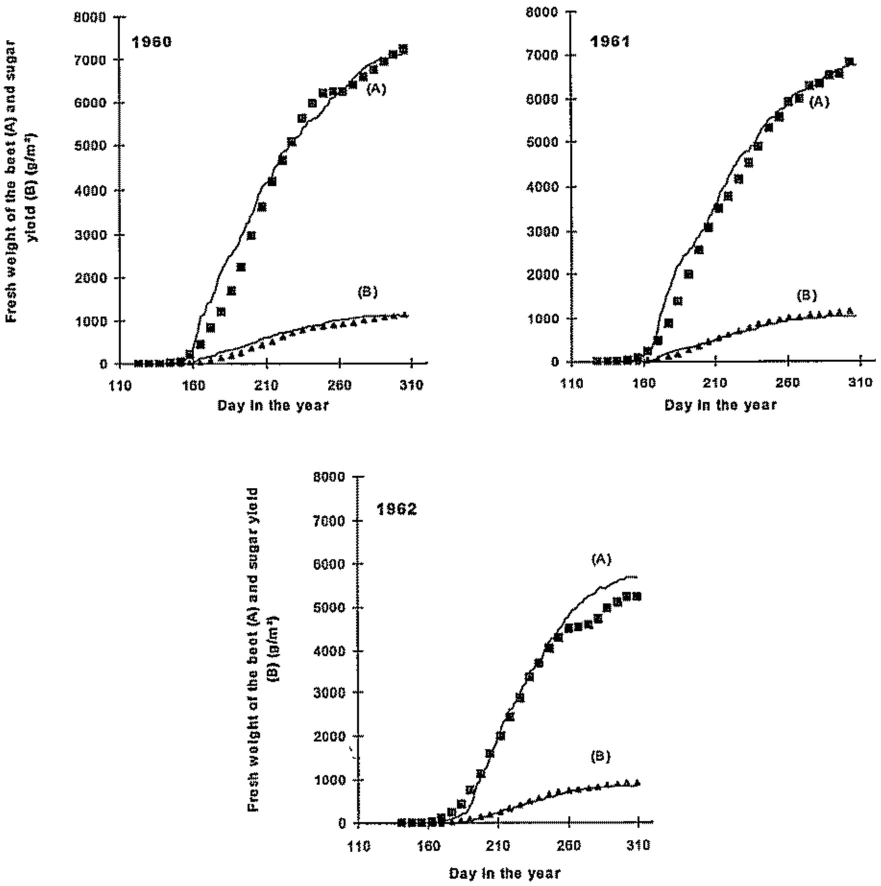

Fig. 2. Observed and simulated root and sugar yield (g m^{-2} on fresh wt. basis) using the simulation model SUBEMOpo and the experimental data of the Rilland 1960–62 experiments (Stumpel, 1967). Continuous lines are the simulation results. Symbols are the moving averages over 3 weeks of the mean of 12 replicates and two varieties.

weeks earlier than observed. It is possible that the calculation of the moving average over 3 weeks of the observed results artificially retards the regrowth.

3.2. Dry matter allocation

The daily gross CO_2 assimilation is allocated to respiration, growth of organs (leaves, tap root, fibrous roots) and to sugar storage. Fig. 3 shows cumulative simulated dry matter allocation for simulation runs of Hélécine 1983 and Lelystad 1987. Sugar storage is part of the dry matter of the tap root. The two component-coupled respiration model simulates that growth respiration is coupled to the rate of biomass increase, and maintenance respiration is related to the amount of biomass. There are no measurements of the respiration on the trial fields available. But builing

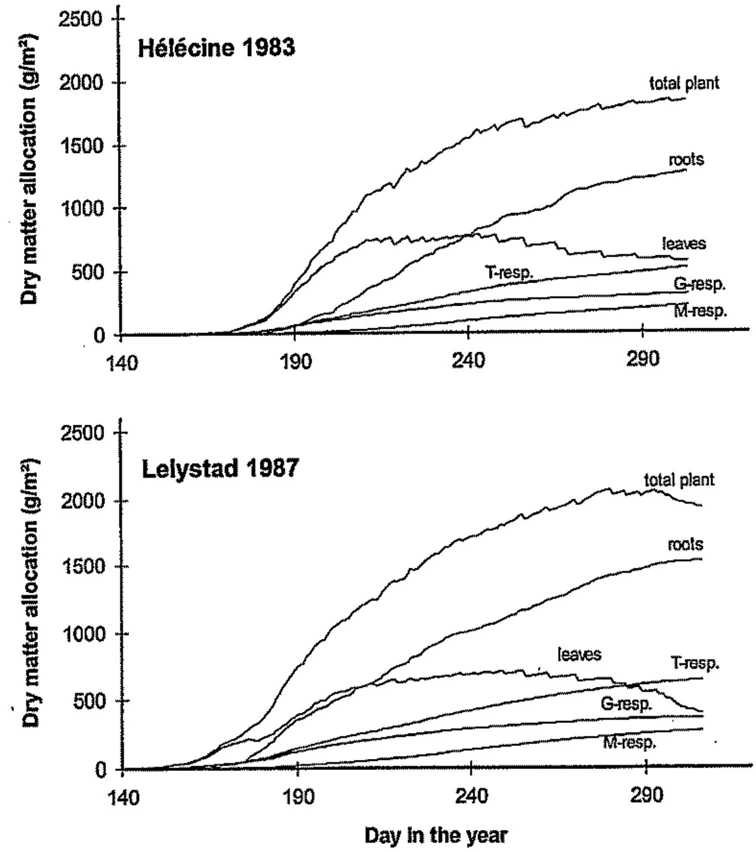

Fig. 3. Cumulative simulated allocation of dry matter in growth (total plant, roots inclusive sugar storage and leaves) and in respiration (total-, growth- and maintenance respiration) for sugar beets. Results obtained using the SUBEMOpo model and the input data from Hélécine 1983 and Lelystad 1987 experimental fields.

on the good simulation results for dry matter accumulation as shown in Figs. 1 and 2, it can be concluded that the simulation of respiration is well done.

The supply–demand model simulation is illustrated in Fig. 4 for simulations of crops at Hélécine in 1985 and Lelystad in 1988. The supply of carbohydrates, mainly as a result of CO_2 assimilation, is followed by demand of carbohydrates by respiration and growth processes (sinks). A carbohydrate pool balancing around zero represents an equilibrium between carbohydrate supply and demand.

The SUBEMOpo model simulated total dry matter accumulation and sugar beet growth and these simulations agreed closely with the field data. In the early days of the simulations with SUBEMOpo however, top dry matter was always overestimated and root weight underestimated, as shown in Fig. 5(A) for two fields. In the model SUBEMOpo, petioles and blades are grouped together as leaves (tops), while the crown is considered to be part of the root. This procedure is taken over from the models SUBGRO I and II (Fick, 1971; Fick et al., 1973) and SUBGOL

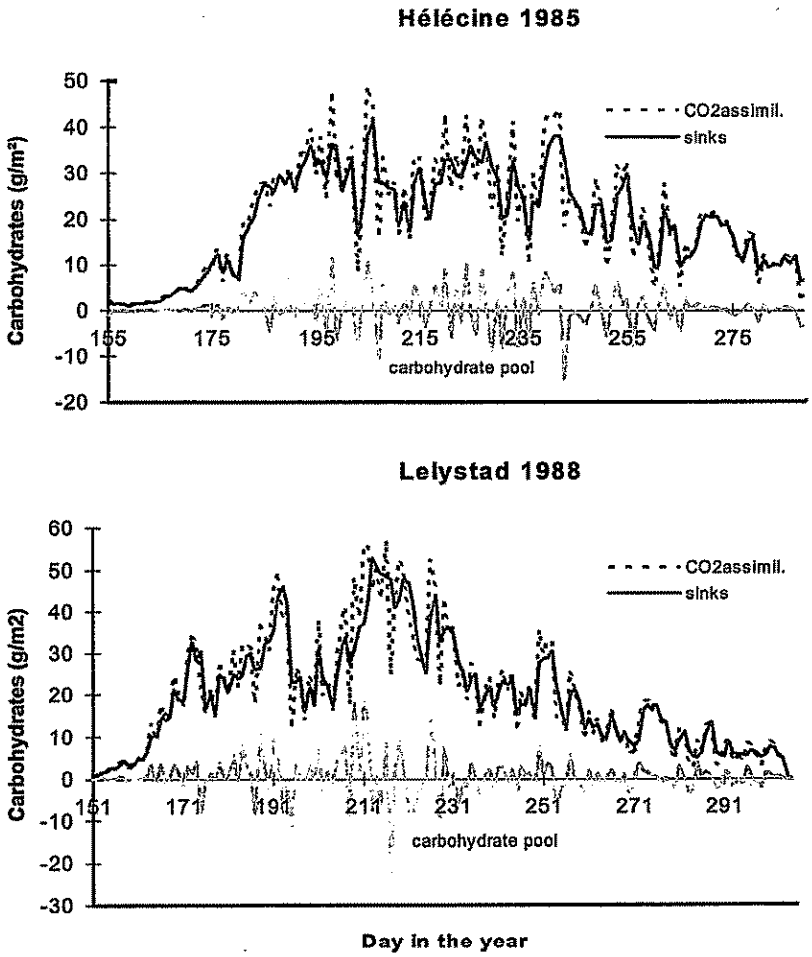

Fig. 4. Simulated amounts of carbohydrates as demanded by the sinks (respiration, growth and sugar storage), as supplied by CO_2 assimilation and as present in the carbohydrate pool.

(Hunt, 1974). Fick (1971) suggests that in future models crown growth should be separate from leaf growth and tap root growth. Using the heuristic way to improve SUBEMOpo, which means experimentation with the model and the system (de Wit, 1978), showed that crown growth should be part of top growth. This resulted in a better agreement between model and observed data for dry matter allocation between tops and roots on all the field trials. A few of these results are selected to show in Fig. 5(B) in comparison with Fig. 5(A). In Fig. 1 observed crown dry matter is already added by leaves dry matter (TDWT). This methodological model improvement is realistic because, morphological, crown growth is depending on leaf initiation (Ulrich, 1954). However no experiments on the explanative level are done within the scope of this work.

As is clear from Figs. 1 and 6 simulated total dry matter allocation to roots (TDWB) accords well with observed data. The weakest section of SUBEMOpo is,

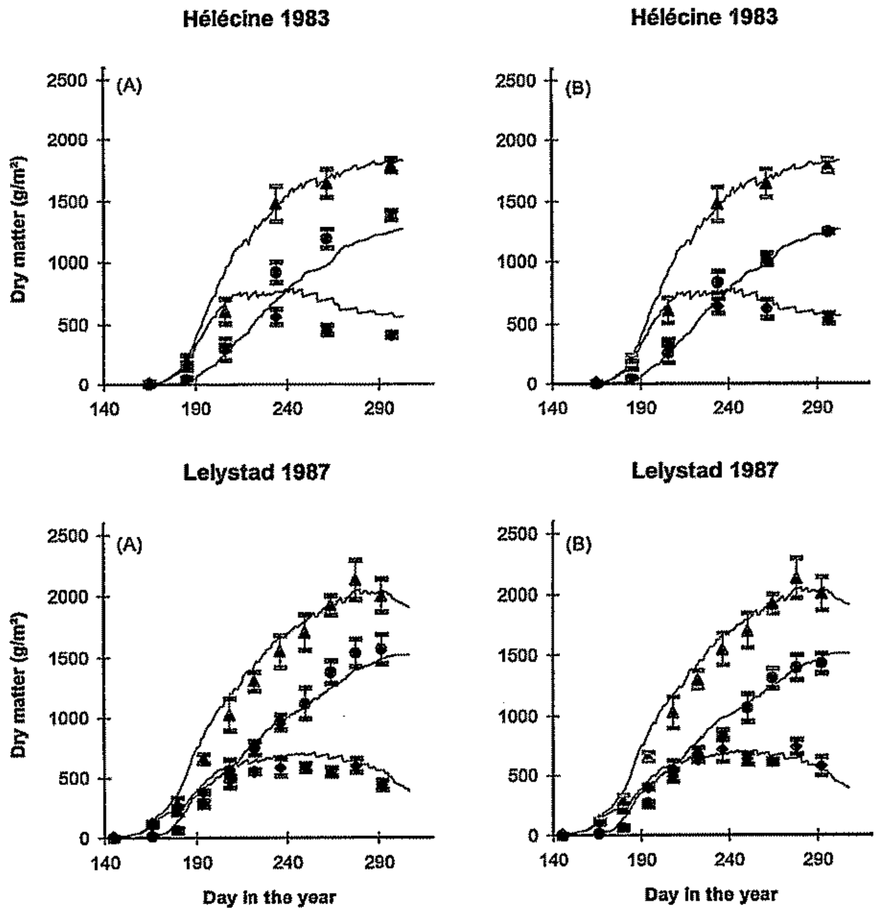

Fig. 5. Observed and simulated dry matter accumulation of sugar beet using the simulation model SUB-EMOpo and experimental data of the field trials of Hélécine 1983 and Lelystad 1987. Continuous lines are simulation results. Vertical bars represent 2× the standard deviation. (A) Observed data of leaves (◆) and of roots inclusive crowns (●). (B) Observed data of leaves inclusive crowns (◆) and of roots (●).

however, the distribution of dry matter within the root to structure (DWB) and sugar (SUGAR).

$$\mathrm{TDWB} = \mathrm{DWB} + \mathrm{SUGAR} \quad (1)$$

In general, structural dry matter was overestimated at the expense of sugar.

3.3. Root and sugar yield

It is usual for the sugar concentration on a fresh weight basis to increase progressively through summer and early autumn, but its maximum value and the time

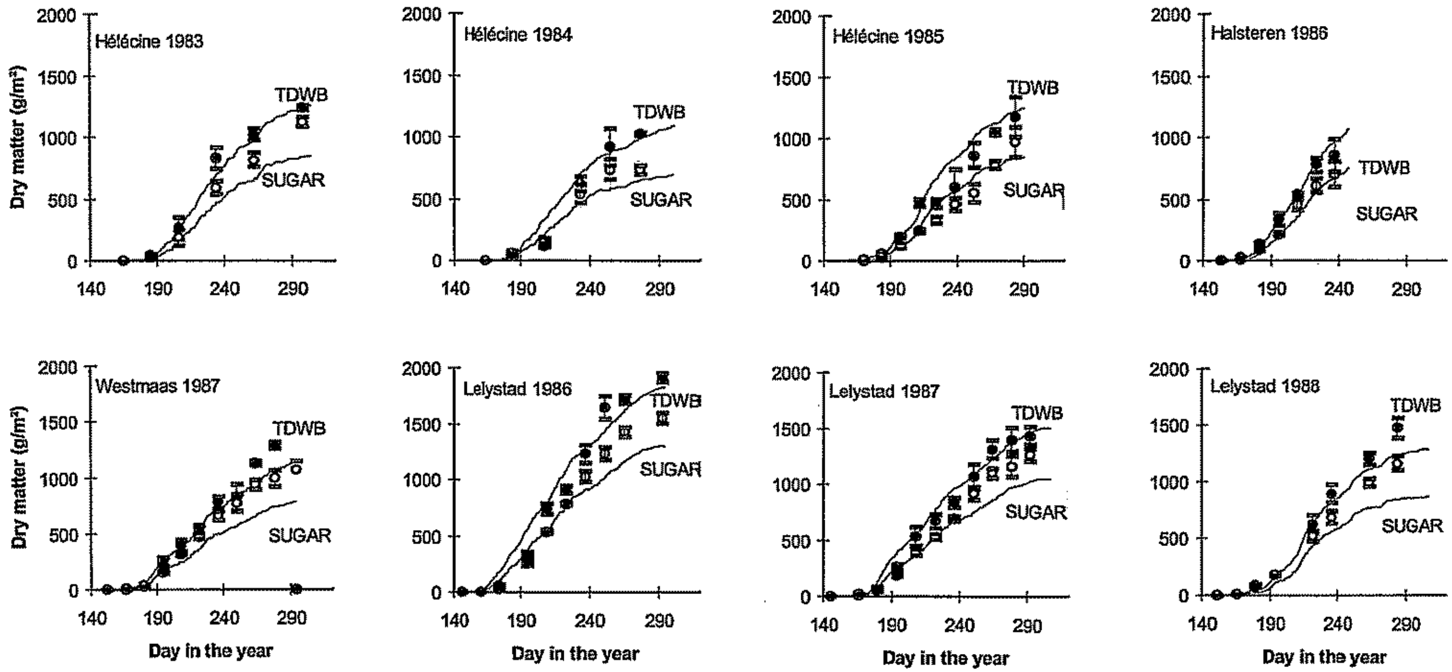

Fig. 6. Observed and simulated cumulative allocation to structural (DWB) and non structural (SUGAR) dry matter in sugar beet roots (TDWB = DWB + SUGAR). Continuous lines are simulation results. Vertical bars represent 2× the standard deviation.

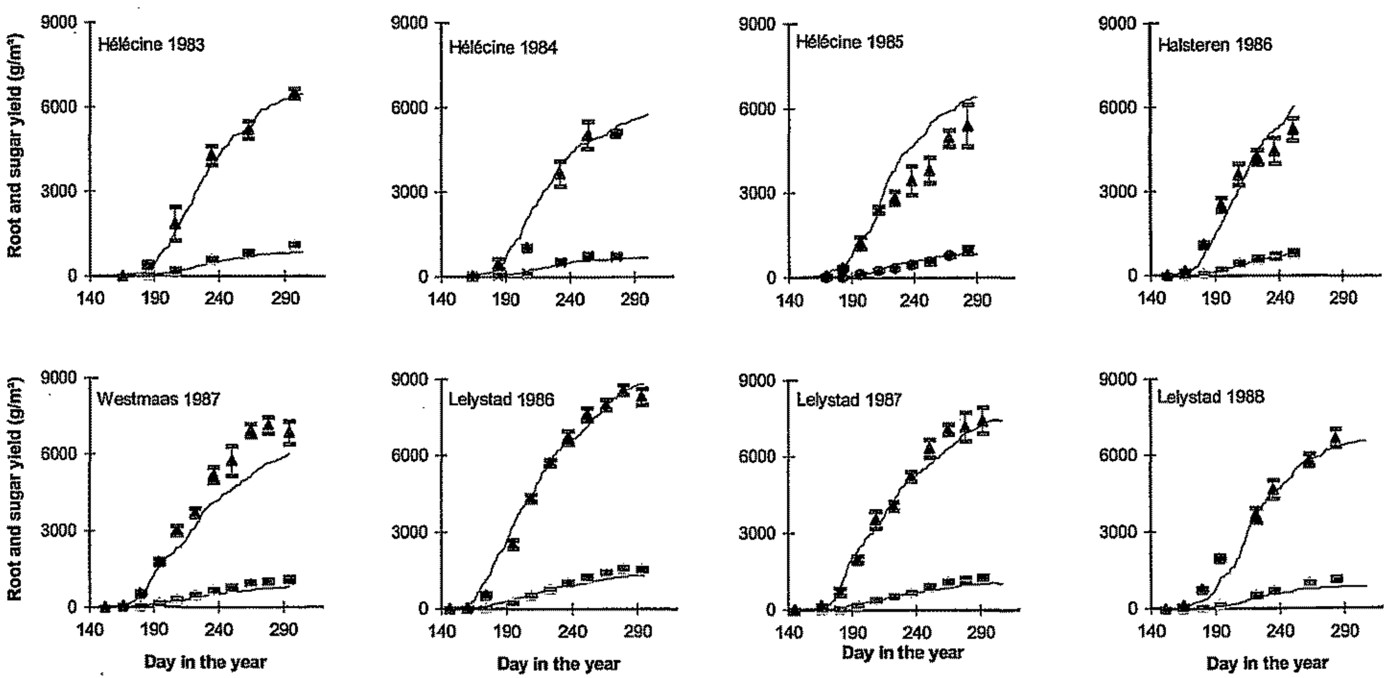

Fig. 7. Observed and simulated cumulative root and sugar yield. Continuous lines are simulation results. Vertical bars represent 2× the standard deviation.

when it is achieved can fluctuate widely from season to season and place to place, mainly in response to change in soil moisture deficit and rainfall (Scott and Jaggard, 1993). Also the dry matter content of the root (DMCB) fluctuates. Because of this, simulation of root and sugar yield on a fresh weight basis is difficult.

At any time step SUBEMOpo simulates total fresh weight of the beet roots (TFWB), the sugar concentration on fresh weight basis (PSUG) and the sugar concentration on dry weight basis (PSUGDW) as follows:

$$\mathrm{TFWB} = \mathrm{TDWB}/\mathrm{DMCB} \tag{2}$$

$$\mathrm{PSUG} = 100 \times \mathrm{SUGAR}/\mathrm{TFWB} \tag{3}$$

$$\mathrm{PSUGDW} = \mathrm{PSUG}/\mathrm{DMCB} \tag{4}$$

Comparison between simulated and observed data (Figs. 2 and 7) are despite the speculative DMCB relation, reasonable. On those fields where the SUBEMOpo underestimated sugar yield, the allocation of dry matter to sugar was also underestimated (Fig. 6), except for the field at Westmaas in 1987, were the allocation in total dry matter of the beet was undersimulated.

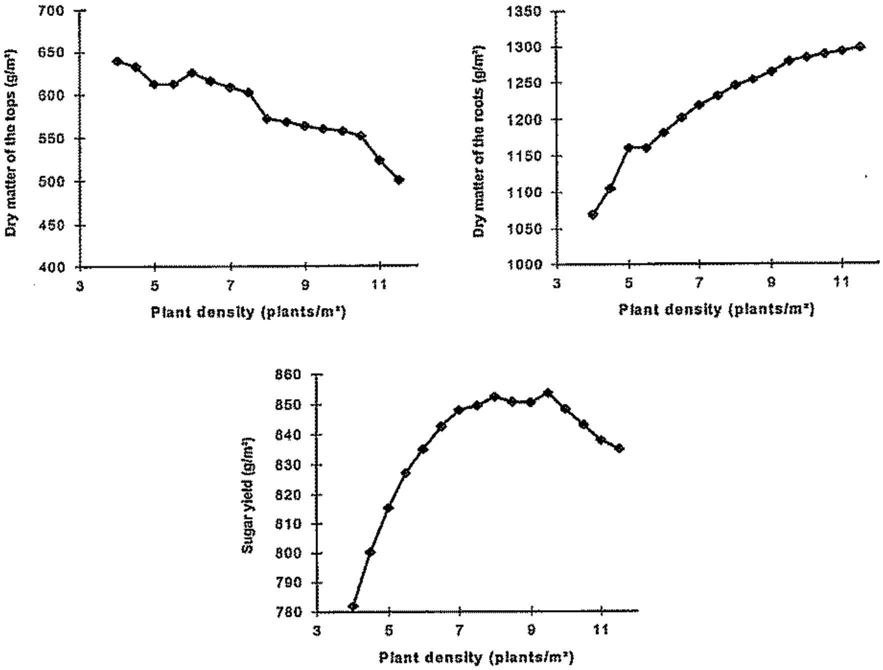

Fig. 8. Simulated tops and roots dry matter and simulated sugar yield per m^{-2} for different planting densities. Results obtained with SUBEMOpo and input data from the Hélécine 1983 experimental field.

3.4. Influence of plant density on components of yield

What does the model tell us about the influence of plant population density on crop growth and on the different components of yield? SUBEMOpo was run several times with the observed weather and the initial conditions of the field at Hélécine in 1983, but for every run the plant population density was changed ranging from 4 to 11.5 plant m^{-2} (Figs. 8 and 9). Increasing plant density increased dry matter accumulation in the roots and a small decrease in dry matter accumulation in the tops for plant densities up to 10.5 plants m^{-2}. SUBEMOpo simulates that sugar yield is at its maximum between 7.5 and 9.5 plants m^{-2}. This supports the observations on many field trials that populations of more than 7.5 plants m^{-2} fail to give extra yield. This is because overlapping leaves from adjacent plants occurs early (when cover is as slight as 10%) and as overlap becomes more extensive individual plants trap less light. In consequence the individual plant produces less dry matter (Fig. 9), its leaves expand more slowly and the benefit to light interception, on a ground area basis, from having additional plants is eroded (Scott and Jaggard, 1993). This effect of increasing plant density on individual plants is obtained with SUBEMOpo and shown in Fig. 9.

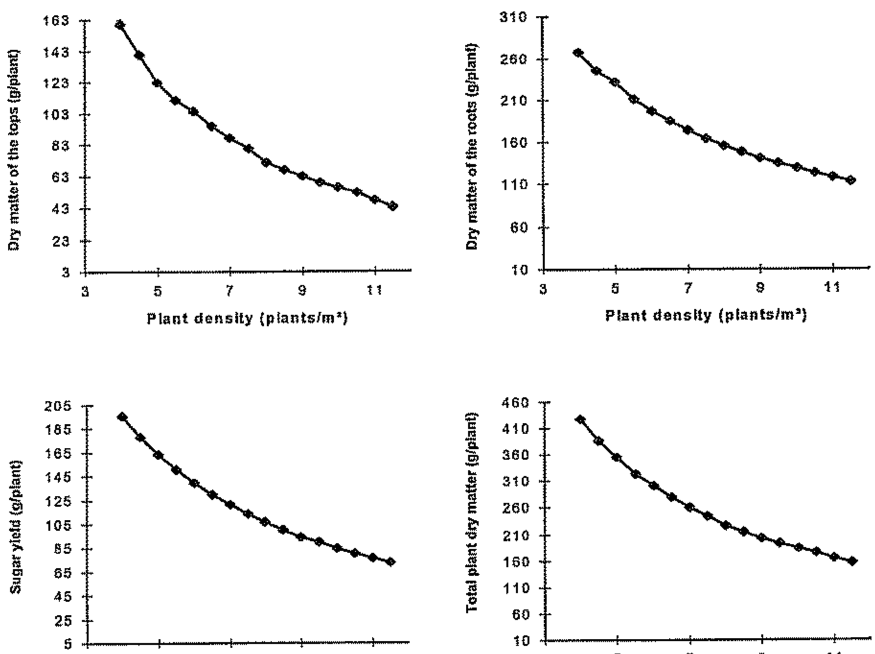

Fig. 9. Simulated tops, roots and total plant dry matter and simulated sugar yield per plant for different planting densities. Results obtained with SUBEMOpo and input data from the Hélécine 1983 experimental field.

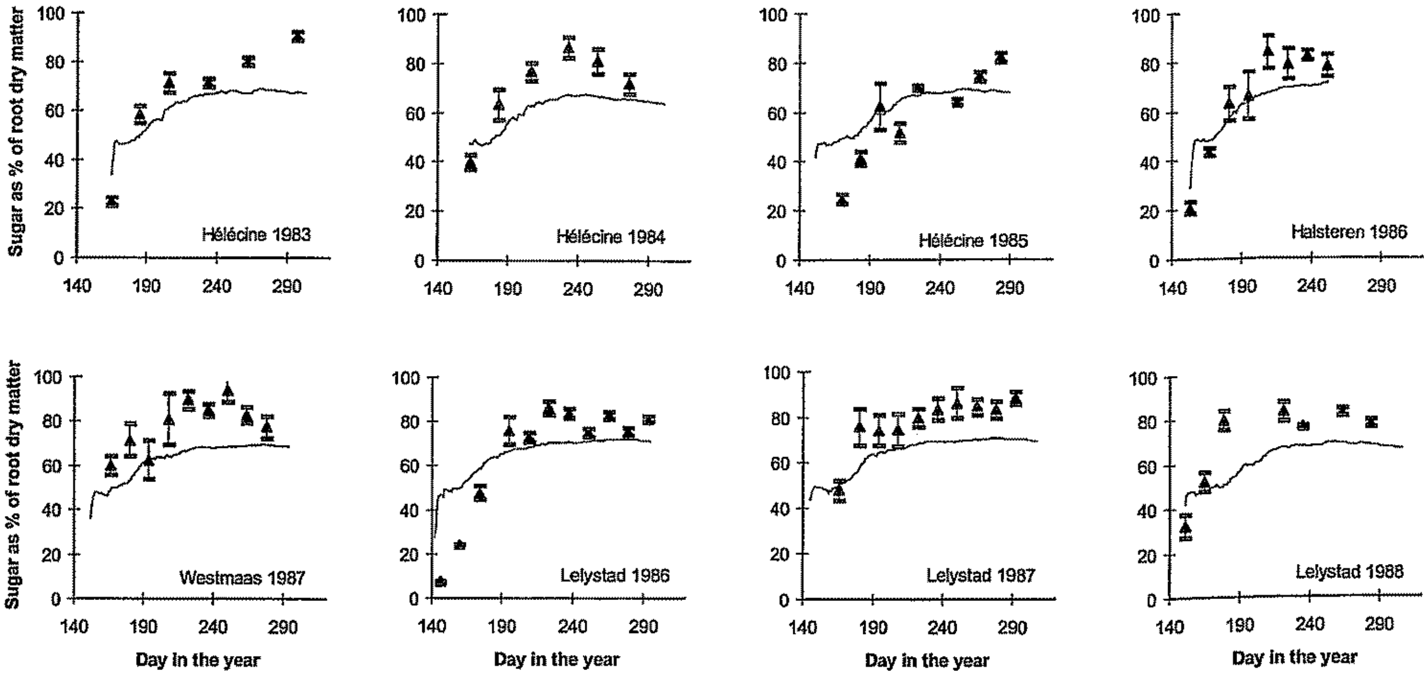

Fig. 10. Observed and simulated sugar as a proportion of root dry matter. Continuous lines are simulation results. Vertical bars represent 2× the standard deviation.

4. Discussion

The model SUBEMOpo simulates growth, yield and sugar accumulation of sugar beets growing with ample supply of water and nitrogen and without negative interactions of weeds, pests or diseases. To evaluate the model, simulation results were compared with observed data from historical field trials and field trials especially conducted for this study. Observed weather and initial conditions have been used to simulate the datasets. In general, simulated sugar beet growth pattern accords well with observed field data. Differences in total dry matter accumulation roots and tops dry matter between seasons and sites are also simulated by SUBEMOpo. The weakest section of SUBEMOpo is, however, the distribution of dry matter between structural and non structural (sugar) dry matter within the tap root. The model allocates too much carbohydrate to structural beet growth at the cost of non structural sugar accumulation.

Concerning the distribution of dry matter to structural material and to sugar several schools of thought exist. Ulrich (1955) supposed that sugar beet undergoes a specific ripening phase known as 'sugaring-up'. In opposite of this, Scott and Jaggard (1993) reported from their observations and those of Milford (1973), that sugar as a proportion of root's dry matter reaches a maximum by early August, and thereafter sugar and non sugar dry matter are accumulated in parallel. The latter is quantified in SUBEMOpo based on experiments of Giaquinta (1979), but as is shown by the results of Fig. 6, the accumulation in parallel is not enough steered to sugar. The measurements of Scott and Jaggard (1993) point out that within the root, the distribution of dry matter to sugar started at a low concentration (25%) and increased to reach a stable value of 75% of the dry matter. This value of 75% was not reached in any of the simulation runs with SUBEMOpo carried out within this study, while the observations on the experimental fields are even larger (Fig. 10).

The allocation of too much carbohydrate to structural beet growth at the cost of non structural sugar accumulation is also reflected in an underestimation of sugar yield on fresh weight basis by the model. Despite the speculative relation between total dry matter of the roots and the dry matter content of the roots, simulated fresh root yield is preponderant within the standard deviation of the observed field data. Also the observed root and sugar yield of historical datasets of Rilland 1960–62 are good approximated by the model.

Of special interest is what the model tell us about the influence of plant density on the components of yield. The model supports the observations in literature that populations above 7.5 plants m^{-2} fail to give extra yield arise.

This exercise of testing SUBEMOpo against historical and for the purpose gathered field data is an evaluation study and does not constitute validation because a model can only be invalidated.

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