In: Weed Control in Vegetable Production.pp. 73-83.
Proceedings of a Meeting of the EC Expert's Group.
Stuttgart 28-31 October, 1986. Balkema, Rotterdam,
Brookfield 1988. R. Cavalloro and A. El Titi (eds.).

Simulation of crop weed competition

M.J.Kropff
Department of Theoretical Production Ecology, Agricultural University, Wageningen, Netherlands

Summary

An explanatory dynamic simulation model for crop weed competition is applied to competition between sugarbeets (Beta vulgaris, L.) and fat hen (Chenopodium album, L.). The model simulates the time course of biomass production very well for monocultures and for a mixture in potential production situations. The simulation results are less in stress situations, because the effect of drought on physiological processes was not taken into account.

Realistic crop-yield weed-density relations at different dates of weed emergence and critical periods for weed control are predicted with the simulation model for potential production situations. A sensitivity analysis with the model shows that further improvement is necessary in the field of morphological and morpho-physiological development of crops and weeds, especially in stress situations. Potentials of the model are discussed in the view of future applications.

1. Introduction

Weeds reduce crop yield by competing for the growth limiting resources light, water and nutrients. Interplant competition has been studied extensively and many quantitative approaches have been developed to describe competition effects. In most approaches simple mathematical equations are used to describe the relation between plant density and yield. The relation between weed density and crop yield can best be described with a hyperbolic equation (9, 14). Although this hyperbolic equation fits very well to experimental data of additive experiments in which only the weed density is varied, it cannot be used to predict effects of weed competition since many other factors determine the competitiveness of weeds (i.e. relative time of weed emergence, row spacing and weather variables influencing morphology and growth of the species (17)).

A very close fit of the hyperbolic model to experimental data on maize yield and barnyardgrass density has been found in two successive years on the same site (6, 14). However, in the first year the maize yield was hardly reduced at high densities of weeds (8% at 300 barnyardgrass plants m^{-2}), whereas in the second year maize yield was strongly influenced even at low densities of weeds (50% yield reduction at 21 barnyardgrass plants per m^{-2}). It has been shown that differences in relative starting position of the weed and severe drought in the second experiment caused these different relationships between crop yield and weed density.

This study indicated that the usefulness of a curve fitted to experimental data of one year is very limited, especially when these relations are used to derive threshold weed densities for weed control advisory systems. The same conclusion holds for experimentally derived so called critical periods (the minimum period of time during which weeds must be suppressed in order to prevent yield losses) (5, 15).

Since so many factors determine the outcome of interplant competition, explanatory simulation models may be useful to gain more insight in the crop weed system and for optimization of management practices. These models are based upon insight in the real processes involved in competition for the growth limiting resources and the use of the captured resources in plant growth processes. Simulation models for crop-weed competition have been developed and evaluated with field-experimental data on maize-barnyardgrass competition (6, 10, 13).

In this study such a model is applied to competition between sugarbeet and fat hen. A short description of the model will be given first, followed by an analysis of model behaviour by comparing the results with two field experiments. The sensitivity of model parameters is tested for this specific situation and finally experiments are performed with the model to predict yield weed-density relations at different times of weed emergence and critical periods at different weed infestations. Implications for future developments and practical use are discussed.

2. Description of the model

Deterministic simulation models for crop-weed competition at different levels of complexity have been developed (10, 11, 13). These models are based upon the existing models for crop growth (8, 16). The time course of competition is simulated by distributing the growth limiting resources over the species. The reached growth rate of the competing species is calculated from the flow rate of acquired resources.

The model applied in this study is derived from the model for maize and barnyard grass (7, 10) and is parameterized for sugarbeet (7) and for fat hen (1, 4). In this paper only a short description of the principles of the simulation model will be given. For a full description of the underlying principles and algorithms we refer to (11).

2.1 Simulation of growth in monoculture

General structure

The model simulates potential dry matter growth and phenological development of a crop as a function of incoming daily radiation, temperature and some crop characteristics (Fig. 1). In this potential production situation it is assumed that water and nutrients are available in non-limiting amounts and the crop is assumed to be free of pests, diseases and weeds. Crop growth in other production situations is simulated by using an empirical site index (10).

Simulation of crop growth

Gross CO_2-assimilation of the canopy is computed by using an analytical approach, which gives satisfactory results when compared with more comprehensive models for CO_2-assimilation of the canopy (11). The starting point for calculation of gross canopy assimilation is the light penetration pro-

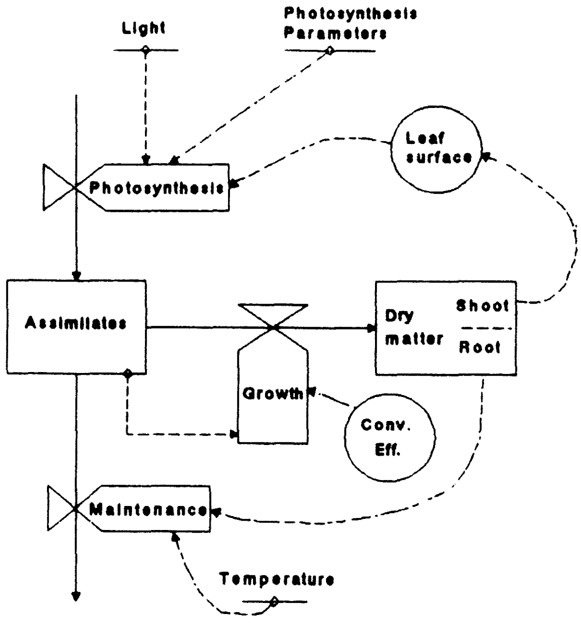

Fig.1. Relational diagram of the carbon balance processes determining crop growth. Rectangles represent state variables; valves: rate variables; Underlined: driving variables; → flow of material; --- flow of information.

file in a crop canopy which can best be described as an exponential function of leaf area:

$$I_h = I_0 \exp(-k \cdot LAI_h) \qquad (1)$$

where I_h is the visible irradiance (J m^{-2} s^{-1}) at a certain height in the canopy; I_0 is the incoming average visible radiation (400-700 nm) corrected for 8% reflection; LAI is the leaf area index (m^{-2} leaf/ m^{-2} ground) calculated from the top of the canopy downwards and k is the light extinction coefficient (-) which is dependent on canopy architecture. The derivative of Eq. 1 gives the absorbed amount of visible irradiation per unit leaf area at a certain height in the canopy:

$$I_{abs,h} = -\frac{dI_h}{dLAI_h} = k \cdot I_0 \cdot \exp(-k \cdot LAI_h) \qquad (2)$$

The CO_2-assimilation light response of individual leaves is described with the rectangular hyperbola:

$$A = \frac{\varepsilon I_{abs}}{(\varepsilon I_{abs}+A_m)} \cdot A_m \qquad (3)$$

where A is the net CO_2 assimilation rate (g CO_2 m^{-2} s^{-1}); ε is the initial light use efficiency (μg CO_2 J^{-1}) and Am is the asymptote (g CO_2 m^{-2} s^{-1}).

Substitution of the absorbed amount of light (eq. 2) into the CO_2 assimilation light response (eq. 3) gives the rate of CO_2 assimilation at a certain canopy depth. Analytical integration over the total leaf area of the canopy gives:

$$A_d = D \frac{A_m}{k} \ln \{\frac{A_m + \varepsilon I_0\ k}{A_m + \varepsilon I_0\ k \exp(-k\ LAI)}\} \qquad (4)$$

in which Ad is the daily CO_2 assimilation of the canopy (g CO_2 m^{-2} d^{-1}) and D is daylength (s).

The computed gross CO_2 assimilation is expressed in carbohydrates which are converted into structural biomass by subtracting losses due to respiration for maintenance and growth processes. Respiration for maintenance of ion gradients across cell walls an protein turnover is assumed to be proportional to the biomass of the standing crop (Q10=2). Respiration for growth is a result of conversion of carbohydrates into structural biomass. The efficiency of conversion is only dependent of the chemical composition of the biomass (8). The dry matter formed is distributed over the plant organs with empirically derived distribution functions in dependence of developmental stage of the crop. Developmental rate is calculated as a function of temperature. Leaf area is assumed to be a function of leaf dry weight with an empirically derived parameter: the specific leaf area (SLA), which is a function of developmental stage.

Because of the positive feedback between leaf area and dry matter growth in simulation of early growth (Fig. 1) the model is very sensitive to the value of the specific leaf area. Large errors may occur in simulation of crop production as a result of overestimated leaf area in early growth (1). When using the SLA-concept it is assumed that leaf area growth is limited by carbohydrate supply. This is a wrong assumption especially in early growth. Therefore leaf area is driven by developmental stage in the early growth period as suggested by (11).

2.2 Simulation of crop weed mixtures

In a mixture of crop and weeds the canopy is divided in a number of horizontal leaf layers equal to the amount of competing species. The leaf layers are bounded by the heights of the species and the leaf area is assumed to be distributed equally over the height of the species (Fig.2). The light absorption of the species in a certain canopy layer is distributed over the species according to their share in leaf area, weighted with their extinction coefficient for light (10).

$$f_{abs,i} = \frac{k_i\ LAI_i}{\Sigma k\ LAI} \qquad (5)$$

where $f_{abs,i}$ is the fraction of light absorbed by species i. Analogue to the derivation of Eq. 3 an analytical expression can be derived for total

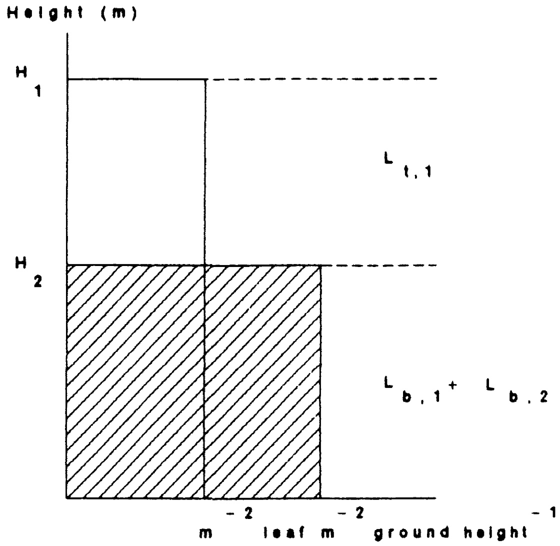

Fig. 2. A schematic representation of the leaf area distribution over the canopy layers of 2 species (1 and 2). The canopy is divided in a top layer (t) and a bottom layer (b).

daily assimilation rate of each of the species per leaf layer. Integration of assimilation rates over the leaf layers gives the daily assimilation rate of the species. Dry matter growth is calculated for each species as in monocultures. Plant height is described with an empirically derived function of developmental stage.

3. Model evaluation

Most parts of the model have been evaluated and validated thouroughly (8, 16). Different versions of the competition model have been tested with 3 field experiments (6, 10, 13). In this study the model was applied to competition between sugarbeets and fat hen (Chenopodium album L.).

In 1984 and 1985 growth of sugarbeet (Beta vulgaris, L. cv. resp. regina and monohil) and fat hen (Chenopodium album, L.) was measured in monocultures and mixtures by frequent harvesting. Both field-experiments were carried out on a sandy soil in Wageningen. Sugarbeets were grown at 30*30 cm and fat hen plants were equally distributed between the sugarbeet plants. In the first experiment fat hen was sown at 5.5 plants m^{-2} in mixture and at 22 plants m^{-2} in monoculture.

Both fat hen and the sugarbeets emerged on day 118. Data were from (4). In the second experiment fat hen was grown at 5.5 plants m^{-2} in mixture and at 11 plants m^{-2} in monoculture.

Sugarbeets emerged at day 129 and fat hen at day 139. Data were from L. Bastiaans, B. Habekotte, H. van Oene and R. Werner (1).

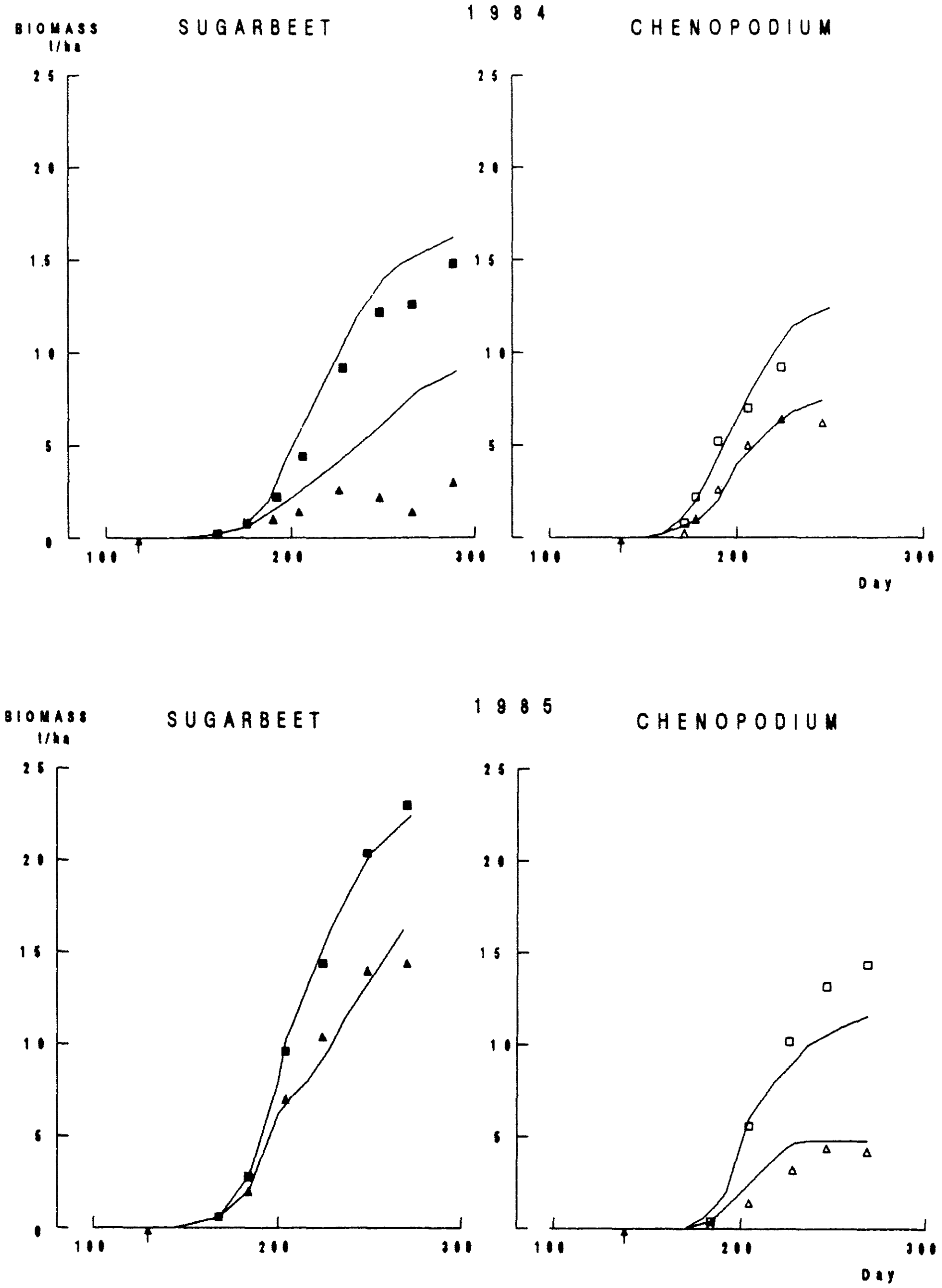

Fig.3. Simulated and observed time course of above-ground biomass in 1984 and 1985 of sugarbeet and Chenopodium album in monocultures (squares) and mixtures (triangles).

Model inputs

Model inputs were the measured weather variables from a nearby station (daily maximum and minimum temperature and daily total global radiation) and dates of crop and weed emergence. Data on species characteristics were derived from literature and from other experiments, and where no data were found for fat hen they were based upon the 1984 experiment.
Input species characteristics in dependence of developmental stage were:

- developmental rate in dependence of temperature
- dry matter distribution functions
- death rate of green leaves
- specific leaf area
- initial leaf area
- light extinction coefficient
- parameters of the CO_2-assimilation light response curve

Model performance

In the first simulation runs the leaf area was input in the model to check simulation of carbon balance processes. Also a site index for monoculture growth was derived for the 1984 situation, because in 1984 severe drought stress occurred in July and August. A very close fit was found for growth of the species in monoculture and mixture. This indicates that apart from leaf area development, processes which determine growth of species in mixture are well understood.

Extrapolation to other situations is only valid when the model correctly simulates dry matter growth without input of measured data on leaf area progression. Because leaf area progression of fat hen in the 1984 experiment was much faster than in other experiments, it was necessary to use measured values for the early growth period in simulation of the 1984 experiment. The simulation results of the model version including simulation of leaf area are presented in Fig. 3. The model simulates dry matter growth of sugarbeets very well for the 1985 situation. Growth of fat hen was underestimated at the end of the season for the monoculture. A slight overestimation was found in mixture. For the 1984 experiment biomass growth of the sugarbeets was slightly overestimated for the monocrop and strongly overestimated for growth of the sugarbeets in the mixture with fat hen. Analysis of the model output showed that this overestimation is caused by the poorly simulated distribution of dry matter. A much too high leaf dry weight was simulated which results in an overestimated leaf area. It is well known that water and nutrient stress influence dry matter distribution patterns (2, 16). Realistic simulation of crop growth under stress conditions is obviously only possible by explicitly simulating the effect of stress factors on physiological processes. These results indicate that care should be taken when using simple techniques such as a site index to take account of stress situations, especially in competition situations.

4. Discussion

Crop and weed characteristics determining competition effects

Spitters (10) showed the relative importance of species characteristics in a simulated mixture of two isogenic maize cultivars. In this study the relative sensitivity of the model to the species characteristics is analysed for a realistic crop weed situation as discussed in this paper.

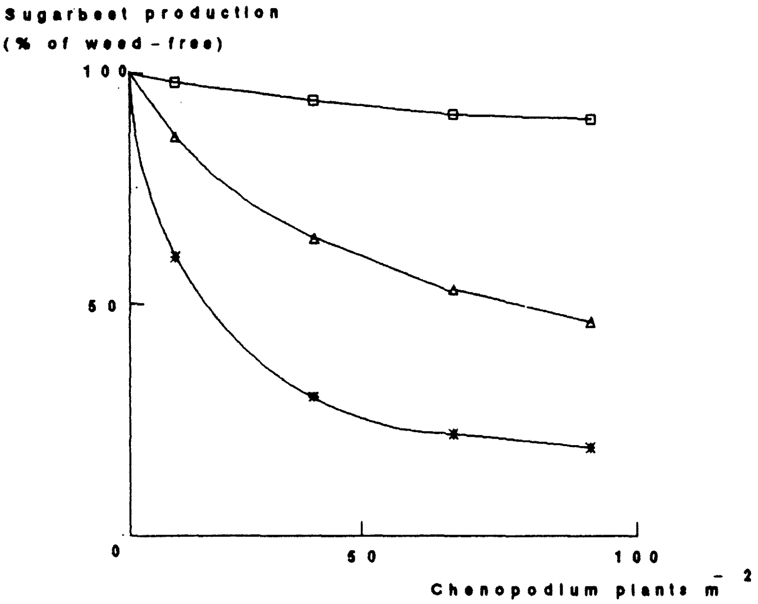

Fig. 4. Simulated relation between sugarbeet yield and weed density at 3 dates of weed emergence (* 10 days after crop emergence; Δ 20 days after crop emergence; □ 30 days after crop emergence.

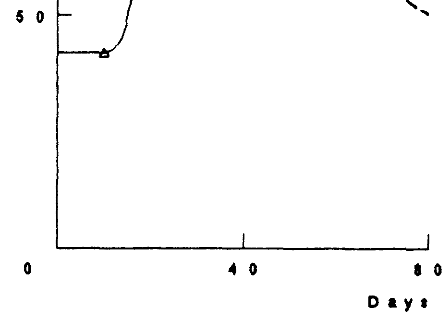

Fig. 5. Simulated relative sugarbeet yield for different durations weed free (———) or weed infested (·····) or 2 weed densities (□ = 5.5 plants m^{-2}; Δ 22 plants m^{-2}).

Sensitivity analysis is only performed for the potential production situation of 1985 because the model is unable to explain the behaviour of the crop weed system under stress conditions as observed in the 1984 experiment.

The relative sensitivity of the model output is expressed as the percentage yield-increase divided by the relative change in the value of the species characteristic. From Table 1 it appears that simulated yield of sugarbeets is much more sensitive to the value of species characteristics in mixture than in monoculture. Spitters (10) found a much higher sensitivity of his model to changes in these parameters for the two isogenic maize cultivars: specific leaf area (4.15), light extinction coefficient (3.5), maximum leaf photosynthesis (2.5) and height (2.6) in mixture. In the model used by Spitters (10) leaf area progression was calculated from leaf dry weight from emergence onwards, whereas in this model leaf area growth in the early growth phase is simulated as a function of developmental stage to avoid the compound interest effect between leaf area and leaf dry weight growth. Although the extreme sensitivity of the model to species characteristics linked up with leaf area development is reduced in this model, it is still necessary to improve simulation procedures for morphological processes because morphological and growth processes may be influenced differently by environmental conditions (3). A better starting point may be to simulate morphological processes like leaf appearance, leaf expansion, stem elongation, branch formation and flowering explicitly in dependence of environmental factors.

Simulation of yield density relationships and critical periods

The validity of the model for potential production situations makes it possible to use the model for prediction of the effect of relative date of weed emergence and weed density in these situations. Crop-yield weed-density relations have been generated for different dates of weed emergence in the 1985 situation (Fig.4). The shape of the simulated yield density relation is very similar to the experimentally derived hyperbolic relations for maize and barnyard grass (6). The strong influence of relative starting position on the yield density relationship is clearly illustrated in Fig. 4.

Table 1. Relative sensitivity of the simulated sugarbeet yield for some species characteristics for a monocrop and a mixture with 5.5 fat hen plants per m^{-2}. The relative effect of a 10% increment of a single sugarbeet-characteristic is expressed as the relative change in yield divided by the relative parameter increase.

variable improved with 10 %	sensitivity monocrop	sensitivity mixture
specific leaf area(m^2/kg)	0.3	1.1
light extinction coefficient(-)	0.1	0.8
maximum leaf photosynthesis(g $CO_2 m^{-2} h^{-1}$)	0.3	0.6
height(m)	0.0	0.6
leaf area in early growth	0.1	0.2

In a second simulation experiment the critical period for weed removal in sugarbeets is simulated at different weed densities.

The results are presented in Fig. 5 and show the typical response curves of relative yield and period weed free as is found in field experiments. The quantitative values are in close agreement with experimentally derived critical periods for sugarbeets (17). An interesting point for further research is the almost independence of the critical period of weed density.

Although care should be taken when interpreting these results quantitatively, these simulation experiments show the merits of the approach for the development of weed control advisory systems.

5. Concluding remarks

One of the advantages of the systems analysis approach is the necessity to formulate precise questions for experimental research, so that the lack in knowledge can be located. From this study it appears that the most important gaps in knowledge are found in the field of morphological development and morpho-physiological development in stress situations. A second advantage of the approach is that imaginary experiments can be performed. Such imaginary experiments can be used for orienting research i.e. the effect of control measures on damage relationships. Labour and cost intensive field experimental work can be directed to test well defined hypotheses.

References

1. Bastiaans, L., B. Habekotte, H. van Oene and R. Werner,1986. Konkurrentie tussen suikerbiet en melganzevoet. Veldproef en Simulatie. Msc thesis. Dept. Theor. Prod. Ecol., Agric. Univ., Wageningen.
2. Brouwer,R. 1962. Nutritive influences on the distribution of dry matter in the plant. Neth. J. Agric. Sci. 10: 399-408.
3. Dobben, W.H.van, 1962. Influence of temperature and light conditions on dry matter distribution, developmental rate and yield in arable crops. Neth. J. Agric. Sci. 10:377-389.
4. Evert, F. van, S. Nonhebel and W. Smeets, 1986. Een systeemanalytische benadering van de konkurrentie tussen suikerbiet en melganzevoet. Msc thesis. Dept. Theor. Prod. Ecol. Agric. Univ., Wageningen.
5. Groot, W. de, et al., 1981. Effect of time of weeding on yields of foodbeans in kenya. Techn. Bull. no. 1. Nat. Hort. Res. Stat., Thika, Kenya.
6. Kropff, M.J., F.J.H. Vossen, C.J.T. Spitters and W. de Groot, 1984. Competition between a maize crop and a natural population of Echinochloa crus-galli(L). Neth. J. Agric. Sci.32: 324-327.
7. Noy, G., 1986. Simulatie van de groei en drogestofverdeling van suikerbieten in afhankelijkheid van stikstofopname. Msc.Thesis Dept. Theor. Prod. Ecol., Agric. Univ., Wageningen.
8. Penning de Vries, F.W.T. and H.H. van Laar (Eds.), 1982. Simulation of plant growth and crop production. Simulation monograph, Pudoc, Wageningen, 308 p.
9. Spitters, C.J.T., 1983. An alternative approach to the analysis of mixed cropping experiments. I. Estimation of competition effects. Neth. J. Agric. Sci. 31: 1-11.
10. Spitters, C.J.T.,1984. A simple simulation model for crop weed competition. 7th Int. Symp. Weed Biology, Ecology and systematics. COLUMA-EWRS, Paris,355-366.
11. Spitters, 1986a. Weeds: population dynamics, germination and competition. In: Simulation and systems management in crop protection (Eds. R.Rabbinge, S.A. Ward and H.H. van Laar). Simulation monograph, Pudoc, Wageningen (Ch. 4.2)

12. Spitters, C.J.T., 1986b. Separating the diffuse and direct component of global radiation and its implications for modelling canopy photosynthesis. Agric. Meteorol.(in press).
13. Spitters, C.J.T. and R. Aerts, 1983. Simulation of competition for light and water in crop weed associations. Asp. Appl. Biol. 4. 467-484.
14. Spitters, C.J.T., M.J. Kropff and W. de Groot, 1987. Use of the hyperbolic yield density relation to describe crop weed competition. Subm. to Ann. Appl. Biol.
15. Weaver, S.E., 1984. Critical period of weed competition in three vegetable crops in relation to management practices. Weed Research, 24: 317-325.
16. Wit, C.T. de et al., 1978. Simulation of assimilation, respiration and transpiration of crops. Simulation monograph, Pudoc, Wageningen.
17. Zimdahl, R.L., 1981. Weed-crop competition. A review. Int. Plant Prot. Centre, Oregon, U.S.A., 195 p.