EVALUATION OF TOMATO CULTIVATION STRATEGIES: UNCERTAINTY ANALYSIS USING SIMULATION

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Abstract: Tomato cultivation strategies with respect to plant density and increased shoot density during the season were evaluated by means of physiological and economic simulation. For various climate scenarios and market conditions effects on annual tomato yield, labour requirements, profitability and cost price were analyzed. Retaining side shoots early in the season (week 8) combined with a somewhat lower plant density at the start of the cultivation seems a promising alternative for traditional tomato cultivation practices with a fixed 2.5 shoots m\(^2\) throughout the season. Furthermore, the applied modelling approach contributes to the analysis of cultivation management principles.

Keywords: simulation, tomato, cultivation management, side shoots.

1 INTRODUCTION

In Western Europe, the tomato is one of the major greenhouse crops. In the Netherlands, it covers circa 1400 ha, which is about one third of the Dutch greenhouse vegetable production area. Recently, Dutch greenhouse tomato production is come up against reduced price levels, increased environmental legislation and higher quality demands (Challa et al., 1993). Thus, tomato growers search for new strategies in cultivation to ensure continuation of their enterprises in these uncertain times.

In Western Europe, tomato is grown in greenhouses which are heated by a distribution system of heating pipes just above ground level fed by a central boiler. CO\(_2\) enrichment is common practice and
heating, ventilation and CO₂ supply are computer controlled. Cultivation is almost exclusively in artificial substrates, mainly rockwool with trickle irrigation for water and nutrient supply. Thus, tomato growers have a rather high degree of control over the production system.

With increasing 'threats' on the one side and numerous opportunities for cultivation control on the other side, improvement of production management may be a key factor in responding to changing market and social conditions. In this respect, (physiological) production system models may support greenhouse growers in their search for new options in greenhouse production system management (Leutscher et al., 1995). Simulation modelling of the tomato production system can be applied to evaluate cultivation strategies under uncertainty and with respect to multiple objectives. Cultivation strategies relate to aspects like, for example, plant density, CO₂ level and temperature in the greenhouse, and length of the production season. A cultivation strategy may consist of a set of planned actions or a set of rules which trigger such actions during the cultivation.

The aim of the present paper is to analyze consequences of plant and shoot density related tomato cultivation strategies by means of simulation. An increase of shoot density (not plant density) by retaining side shoots during the season is currently an important topic in Dutch greenhouse tomato production (Verbruggen, 1996). Traditionally, all side shoots of a tomato plant are removed during the cultivation. By retaining one or more side shoots during the cultivation the shoot density can be increased, whereas the plant density remains unchanged. Decisions on plant and shoot density, however, are complex, as they influence a lot of factors, e.g. light interception and thus crop growth (De Koning, 1994), fruit set (De Koning, 1994), fruit size (Heuvelink, 1995b), yield (Heuvelink, 1995b), but also costs of plant material and labour.

2 MODELLING APPROACH

2.1 The model

The model used in the present study simulates crop physiological processes as well as organizational and economic consequences of tomato production. A modified version of the TOMSIM simulation model of tomato crop growth (Heuvelink, 1995a; Heuvelink, 1996) was used to simulate tomato yield based on the level of global radiation outside the greenhouse and a pre-declared cultivation strategy. From the photosynthetic characteristics of single leaves the daily total amount of CO₂ assimilation of the crop is calculated (Heuvelink, 1995a). Subsequently, dry matter partitioning is simulated based on a relative sink strength approach. The sink elements described in the model are the individual fruit trusses and the vegetative units, i.e. three leaves and stem internodes between two trusses (Heuvelink, 1996). The vegetative sink increases with the number of side shoots.

Fig. 1. Specific leaf area (cm² g⁻¹) simulated for: 2.5 plants m⁻² (L:L), 4.2 plants m⁻² (H:H) and 2.5 plants m⁻² with 4.2 shoots m⁻² from week 8 (L:H).
In the present study, the calculation of specific leaf area (SLA) and the calculation of the harvested fruit weight were modified in TOMSIM. The SLA is calculated as the leaf area divided by the leaf dry weight averaged over the whole crop and affects the light interception by the crop. The original seasonal function of SLA was extended with an effect of (plant and) shoot density on the minimum SLA value around the middle of the season. Thus, from identical initial conditions a specific SLA function is determined for every plant and shoot density (fig. 1). The daily amount of picked fruit weight in the present study is calculated by smoothing the originally simulated weight of every harvested truss over a period from three days before to three days after the harvest of the complete truss from the plant as simulated by TOMSIM.

The simulation of organizational and economic consequences concerns labour requirements, profit and cost price. Labour requirements are simulated based on standard times (Hendrix, 1993) per kg of harvested tomatoes and per plant or shoot for specific operations, like planting and crop treatment. Profit is calculated as the difference between the financial returns of tomatoes minus the sum of all variable and fixed costs at the 1992 price level, whereas the overall cost price is calculated as the sum of all annual variable and fixed costs divided by the annual tomato yield. Thus, the model, as a whole, simulates production of tomatoes over the period of one season (i.e. one year) and given a pre-declared cultivation-strategy.

2.2 Design and analysis of the simulation experiment

Five cultivation strategies were formulated (table 1). Here, densities of 2.5, 3.1, 4.2 and 5.0 plants m⁻² or shoots m⁻² correspond with plant or shoot distances of 50, 40, 30 and 25 cm in the row respectively. Thus, starting from the traditional plant density of 2.5 plants m⁻² side shoots were kept on every fourth plant to establish a shoot density of 3.1 shoots m⁻², on every third plant to establish a shoot density of 4.2 shoots m⁻², and on every second plant to establish a shoot density of 5.0 shoots m⁻². Furthermore, production was assumed to take place in a modern Venlo-type glasshouse with a transmissivity of about 70%, a fixed temperature of 20 °C, and a fixed CO₂ concentration of 400 ppm. With respect to the crop, no water shortages or nutrient deficiencies, and no pests and diseases were assumed.

All cultivation strategies were replicated for ten annual scenarios in order to evaluate average results as well as variances. Thus, uncertainty with respect to the consequences of various cultivation strategies could be addressed. The ten annual scenarios were based on climatic and tomato price data over the period 1982-1992 (with exception of 1987 because of missing values in the climatic data). Tomato price data were corrected for inflation and traditionally early season high prices, and expressed at the 1992 price level.

Criteria for evaluating cultivation strategies were yield, labour requirements, profitability, and cost price. Due to the replication of cultivation strategies with the same set of annual scenarios simulation results were autocorrelated. Therefore, ordinary analysis of variance could not be

Table 1. Definition of the applied cultivation strategies: plant density and shoot density after week 8.

<table>
<thead>
<tr>
<th>Cultivation Strategy</th>
<th>Plant density</th>
<th>Shoot density after retaining side shoots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(plants m⁻²)</td>
<td>(shoots m⁻²)</td>
</tr>
<tr>
<td>S₁</td>
<td>2.5</td>
<td>2.5*</td>
</tr>
<tr>
<td>S₂</td>
<td>3.1</td>
<td>3.1*</td>
</tr>
<tr>
<td>S₃</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>S₄</td>
<td>2.5</td>
<td>4.2</td>
</tr>
<tr>
<td>S₅</td>
<td>2.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

* No side shoots retained.
applied. Instead, for each criterion a pairwise comparison for the difference between cultivation strategies over all ten simulated years, as suggested by Kleijn and Groenendael, (1992) was executed by means of a Student t-test ($P<0.05$).

3 SIMULATION RESULTS

3.1 Effects of plant and shoot density on annual results

In case all side shoots are removed during the season ($S_1$ and $S_2$), annual tomato yield increases significantly with plant density due to increased light interception (table 2). However, over a larger interval of plant densities, fruit yield will show an optimum response to plant density. This optimum response results from increased leaf area and thus light interception (saturating response) combined with a decreased assimilate partitioning to the fruits at higher plant density (De Koning, 1994). Labour requirements also increase significantly with plant density. Besides more labour for crop treatment, this involves also extra harvest labour. Apparently, the additional tomato yield more than compensates extra costs (among which extra labour costs), since annual profit increases significantly with plant density. With respect to the overall cost price, the higher plant density leads to a small, however significant, reduction.

Cultivation strategy $S_1$ with an increase in shoot density during the season, results in a significantly higher annual yield than the corresponding cultivation strategy without side shoots ($S_1$). Moreover, the differences in yield as well as in required labour between cultivation strategies $S_1$ and $S_2$, though significant, are relatively small. By increasing shoot density instead of starting at a higher plant density, however, profit is increased and the overall cost price is reduced.

Table 2 also shows an optimum shoot density with respect to annual profit. Although significantly higher annual tomato yields can be obtained with more side shoots, the overall cost price is lower.

Table 2. Effects of cultivation strategies with respect to plant density and possible shoot density increase during cultivation on annual tomato yield (kg m$^{-2}$), annual labour requirement (h m$^{-2}$), annual profit (Dfl. m$^{-2}$) and overall cost price (Dfl. kg$^{-1}$) (with standard errors of mean) over ten annual scenarios (Dfl. is the Dutch currency: 1 Dfl. $\approx 0.63$ US$).

<table>
<thead>
<tr>
<th>Cultivation strategy</th>
<th>Annual tomato yield (kg m$^{-2}$)</th>
<th>Annual labour requirement (h m$^{-2}$)</th>
<th>Annual profit (Dfl. m$^{-2}$)</th>
<th>Overall cost price (Dfl. kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$: 2.5</td>
<td>40.98a (1.1)</td>
<td>0.79a (&lt;0.1)</td>
<td>3.86a (2.5)</td>
<td>1.75d (&lt;0.1)</td>
</tr>
<tr>
<td>$S_2$: 3.1</td>
<td>43.41c (1.1)</td>
<td>0.89c (&lt;0.1)</td>
<td>4.59b (2.7)</td>
<td>1.74c (&lt;0.1)</td>
</tr>
<tr>
<td>$S_3$: 2.5</td>
<td>43.19b (1.1)</td>
<td>0.87b (&lt;0.1)</td>
<td>5.10c (2.6)</td>
<td>1.71b (&lt;0.1)</td>
</tr>
<tr>
<td>(week 8): 3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_4$: 2.5</td>
<td>45.90d (1.0)</td>
<td>1.00d (&lt;0.1)</td>
<td>5.79d (2.8)</td>
<td>1.69a (&lt;0.1)</td>
</tr>
<tr>
<td>(week 8): 4.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_5$: 2.5</td>
<td>47.46c (1.0)</td>
<td>1.10e (&lt;0.1)</td>
<td>5.51cd (2.9)</td>
<td>1.69a (&lt;0.1)</td>
</tr>
<tr>
<td>(week 8): 5.0</td>
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</table>
shocks, cultivation strategy $S_4$ in terms of annual profit and overall cost price seems preferable.

3.2 Effects of retaining side shoots on the dynamic yield pattern

The dynamic patterns of weekly tomato yield in the first part of the 1992 production season for cultivation strategies $S_1$, $S_2$ and $S_3$ are shown in fig. 2. Comparing the two strategies without side shoots, the higher plant density ($S_2$) continuously has higher yields than $S_1$. Furthermore, cultivation strategy $S_3$, at first is equal to $S_1$, since it starts at the same plant density, but later leads to lower weekly yields, because of the increased vegetative sink shortly after retaining side shoots. By week 17 the side shoots start producing and for some weeks $S_3$ produces even more than $S_2$ (which has an identical shoot density at that time) because of lower maintenance respiration due to a smaller crop weight. Later in the season, as the crop grows, the difference in crop weight between $S_2$ and $S_3$ disappears and both strategies follow the same yield pattern. So, retaining side shoots clearly affects the dynamic tomato yield pattern.

4 DISCUSSION

Simulation results in this study confirm recent changes in Dutch tomato cultivation practices, as described by Verbruggen (1996). Retaining side shoots early in the production season combined with a somewhat lower starting plant density is a profitable alternative for the traditional cultivation strategy with a starting plant density of 2.5 plants m$^{-2}$ and no side shoots. Despite higher labour requirements, annual profit can be improved with about 1.9 Dfl. m$^{-2}$, which is considerable and corresponds with approximately 30,000 Dfl. per nursery. Simulated annual profit, however, is rather high in the present study compared to the current economic situation in Dutch greenhouse tomato production. Adding annual profit per kg tomato yield to the overall cost price indicates average simulated tomato prices of approximately 1.8 Dfl. kg$^{-1}$, while 1995 statistics (Ekkes et al., 1995) estimate an average tomato price of about 1.4 Dfl. kg$^{-1}$. Higher tomato prices in the simulation experiment were due to the application of annual scenarios from 1982 to 1992, when tomato prices were in general on a higher level. Moreover, the applied price patterns resulted from traditional supply patterns, whereas large scale implementation of proposed alternative cultivation strategies may lead to different supply patterns. Apart from the need of good price forecasts, the applied simulation model seems rather valid. In fact, the simulated tomato yield under the given greenhouse climate and the simulated labour requirement given the simulated tomato yield correspond rather well with 1995 statistics (Ekkes et al., 1995).
Despite trustworthy simulation results, it remains impossible to determine the exact optimum of plant density, shoot density and the moment at which side shoots are retained. Because every grower may weigh the analyzed criteria differently and may respond differently to risk, this optimum has to be determined implicitly or explicitly by the grower himself. To support him, however, further study will focus on the application of regression metamodels (Kleijnen & Groenendaal, 1992) to develop response surface diagrams and multi attribute methods to weigh different criteria. In this respect, not only annual results should be taken into account, but also the dynamic patterns over the season. Growers, for example, should keep in mind that structural changes in the seasonal price pattern may have different effects on various cultivation strategies, because of different dynamic yield patterns. Furthermore, although the timing of side shoots affects annual labour requirements only to a limited extent, growers should consider the incidental peak labour requirements due to retaining side shoots. In fact, in the present study the availability of labour was not considered, whereas this generally is a major concern on the individual nursery.

In conclusion, the present study shows a modelling approach contributes to the study of cultivation management principles in greenhouse production. Thus, also other related issues may be studied. The possibility to market tomatoes on the truss, for example, is expected to have significant impact on production features. Moreover, environmental objectives, as for example the reduction of energy consumption by the greenhouse and the efficient supply of CO₂, are interesting topics which we hope to study by means of this modelling approach in the future. From a methodological perspective further research should concentrate on the use of simulation results to actually make decisions both in practice and in theory.

REFERENCES


