

## CHAPTER 18

# TOWARDS FUNCTIONAL-STRUCTURAL MODELLING OF GREENHOUSE CUCUMBER

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**Abstract.** At present, much effort is put into increasing the efficiency of cultivation systems for greenhouse vegetables. There are many options to manage plant growth factors in a greenhouse. For example, supplemental light can be given, even directed at specific plant parts. Functional-structural modelling is expected to help exploring different cultivation and plant manipulation regimes in order to optimize production over a prolonged period of time or in a period of high market prices. To introduce structural modelling for greenhouse cucumber, an experiment is described that showed differences in yield due to different plant densities and plant distributions. As a first step towards virtual cucumber plants, a static structural model of cucumber was conceptualized to picture differences in the potential of the stands to intercept direct light with an orientation perpendicular to the ground, measured by the projected leaf area per unit ground area, the so-called light interception efficiency ( $\text{m}^2 \text{m}^{-2}$ ). The formalism of parametric L-systems was used to describe a dynamic structural model of cucumber with focus on realistic plant geometry. At present sophisticated functional-structural models of greenhouse cucumber or other vegetables do not exist, but they are highly desirable and under construction.

### INTRODUCTION

There are many options to manage plant growth factors related to plant structure in a greenhouse. For example, supplemental light can be given and even directed at specific plant parts (Hovi et al. 2004; Boonekamp 2005a; Marcelis et al. 2005). At present, much effort is put into increasing the efficiency of cultivation systems for greenhouse vegetables, e.g., researchers and growers are still searching for a better cucumber production system (Boonekamp 2005b). High-wire systems, four times cropping and supplemental light are some means of optimizing production over a prolonged period of time or in a period of expected high market prices.

Functional-structural (FS) modelling is expected to help exploring different cultivation and plant manipulation regimes. In functional models, like TOMSIM for tomato (Heuvelink 1996; Heuvelink and Dorais 2005) and KOSI for cucumber (Marcelis and Gijzen 1998) it is assumed that the amount of intercepted light

209

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depends mainly on leaf area. Plant density is taken into account, but the plant distributions as well as effects of plant manipulation like leaf pruning are neglected. For fruit vegetables in general, a 1% reduction of solar radiation leads to an average yield reduction in a range of 0.8 to 1% (Marcelis et al. 2005). Moreover, light intensity influences canopy architecture and this, in turn, the light interception. On the other hand, supplemental light of varying quality may be provided. This would influence the ratio of red to far red within the canopy and again the plant's morphology.

Dong et al. (2003) presented an FS model of tomato growth addressing interactions between its physiological functions and morphological structure. A finite automaton, which is a model of behaviour composed of states, transitions and actions, was applied to build the topology and 3D structure of tomato, whereas organ size was simulated using a hydraulic model that was based on plant transpiration. However, light distribution and light interception were not included in this model. Higashide et al. (2000) presented a stochastic Lindenmayer system (Prusinkiewicz and Lindenmayer 1990) of cucumber. They investigated flower and branching patterns and the influence of topping on branching patterns of different cultivars, but a realistic visualization of the whole-plant architecture was beyond the scope of their work.

At present, sophisticated FS models of greenhouse cucumber or other vegetables do not exist. As a first step towards a functional-structural plant model (FSPM) of greenhouse cucumber, the objective of this chapter is to present a static and a dynamic structural model of cucumber. The description of a greenhouse experiment is introducing the topic of architecture, light and yield in case of cucumber.

#### INFLUENCE OF CANOPY STRUCTURE ON YIELD

In a greenhouse experiment conducted in spring 2002 in Hannover, Germany, plant density and plant distribution were varied with plant densities of 1 and 2 m<sup>-2</sup> and plant distributions in rows and in isometric stands. An isometric stand was characterized by equal distances between a plant and all its neighbouring plants. The plant distances in row distributions were 186 cm between rows and 54 cm and 27 cm within the rows for population densities of 1 and 2 plants m<sup>-2</sup>, respectively. Plants were vertically trained and twisted around a cord. Main stems were topped at 220 cm. Just one fruit per axil was allowed at nodes above node rank 6 counted from the bottom of the plant. All remaining fruits and lateral branches were removed. Plants were cultivated under ample supply of water and nutrients and under prevailing climatic conditions. In all treatments fruits were harvested over an interval of two weeks, when fruit abortion did not occur. Fruit yields differed among treatments. In isometric stands yields were at least 15% higher than in row cultivations (Table 1).

**Table 1.** Cumulated fresh weight of fruits harvested during the first two weeks of harvest

Plant density (plants m <sup>-2</sup> )	Yield in an isometric stand (g m <sup>-2</sup> )	Yield in row cultivation (g m <sup>-2</sup> )
1	4484a	3774b
2	6148c	5332d

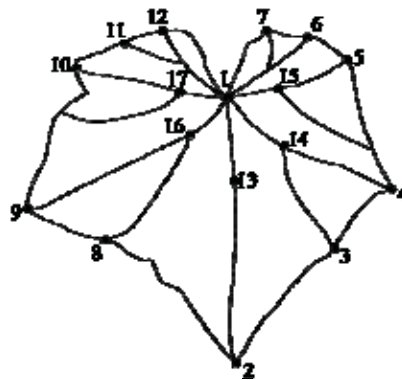
Means within one column or row followed by different letters are significantly different ( $P = 0.05$ )

One aspect of the explanation of this result is that different canopy architectures result in different distributions of light within the canopies. Light distribution is a function of sun angle and canopy architecture, whereby the latter is a product of plant architecture and plant distribution. Plant architecture itself is a result of plant management regimes among other factors.

Virtual reconstructions of the canopy architecture may help to identify different light distributions and differences in the distribution of intercepted direct light within the canopy. For this purpose, static structural models can be used. Dynamic structural models may help to identify the time course of light distributions within the cultivation period.

#### STATIC STRUCTURAL MODEL OF CUCUMBER

Three-dimensional architectural data of cucumber were collected using a 3D digitizer (Fastrak, Polhemus, Colchester, VT, USA). Three plants per treatment of the above mentioned experiment were digitized once per week. Plant parts were digitized in standardized sequences (Kaitaniemi et al. 1999; Rakocevic et al. 2000). For each node one point placed opposite the petiole insertion was digitized. An

**Figure 1.** Standardized sequence of positions of 17 digitized points of a cucumber lamina

internode was defined by two consecutive nodes, a petiole by the corresponding node and the insertion point of the lamina. Seventeen points were digitized from a lamina (Figure 1). For each fruit four points were digitized: the top and bottom tips and two opposite, circumferential points at half length.

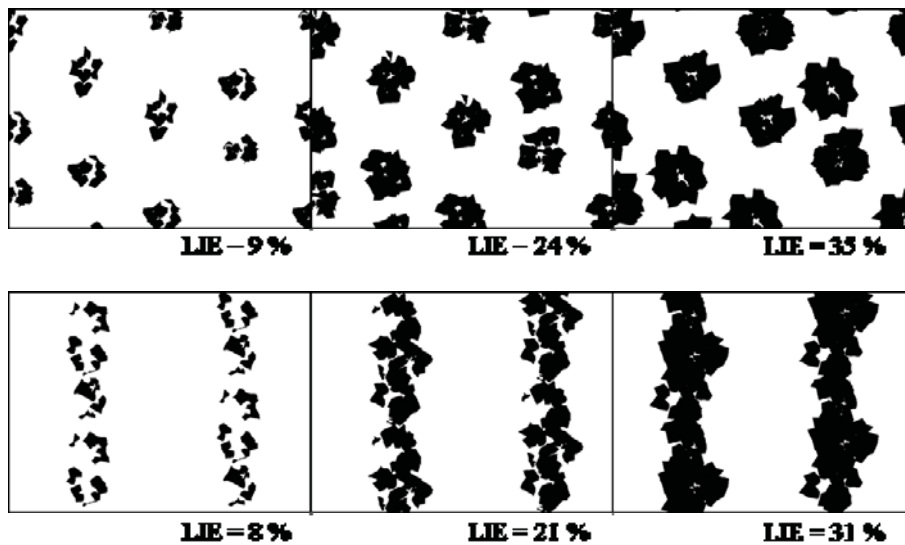
Morphological parameters were derived from digitized data such as leaf area, leaf elevation angle or leaf azimuth. Realistic visualizations of digitized plants were produced by including the digitized data into ray-tracing codes of the *POV-Ray* freeware. Such a code essentially consisted of a view position, the light source and the digitized data of the plant. Figure 2 shows a picture of a real plant and a picture of a virtual plant reconstructed from the digitized data of the real plant. Visual comparison of these pictures allows hypothesizing that the chosen standardized sequences provided accurate architectural data.



**Figure 2.** Picture of a real plant and picture of a virtual plant reconstructed from digitized data using ray-tracing software

Pictures of top views of the reconstructed plants can be used to identify differences in the interception of direct light with an orientation perpendicular to the ground, which result from different plant densities and plant distributions in the greenhouse. Projected leaf areas allow estimating intercepted direct light with an orientation perpendicular to the plane of projection, and pictures of top views of reconstructed plants allow calculating projected leaf area per square meter ground. Thus, light interception efficiency of a canopy with respect to light with an orientation perpendicular to the ground, LIE, can be defined as projected leaf area per square meter ground ( $\text{m}^2 \text{m}^{-2}$ ) (Díaz-Ambrona et al. 1998). In case of the above-

mentioned experiment, virtual stands of  $10 \text{ m}^2$  were reconstructed for one replication of treatments of plant density  $1 \text{ m}^{-2}$ . Each virtual stand consisted of the three digitized plants and was filled up by copies of these plants. The projected leaf area was determined by pixel counting using the freeware *ImageJ*. In Figure 3 the resulting top views are shown of stands digitized one, two and three weeks after transplanting. LIE increased with time, but the isometric stand obtained a 13% greater increase within week one to week three after transplanting than the row stand.



**Figure 3.** Top views of reconstructed cucumber stands. The digitized data resulted from three measurements dates: one, two and three weeks after transplanting. The upper panels show an isometric stand and the bottom panels represent a row stand, both at  $1 \text{ plant m}^{-2}$

The current simple concept of light interception efficiency should be extended. A first extension should picture the influence of changing sun azimuth angles and sun elevation angles in their course over the day on the amount of intercepted direct light. For each sun position, the projection plane has to be placed perpendicular to the incoming direct light. Thanisawanyangkura et al. (1997) used a similar approach for single cotton plants. They used an individual elliptic reference area of projection to calculate direct light interception for each plant. However, in case of greenhouse vegetables, LIE should pertain to light intercepted by the canopy per unit ground surface, accounting for mutual shading of neighbouring plants. The next step of extension of the LIE concept should take account of leaf properties such as light transmission and light reflection (Thornley and Johnson 2000). And, moreover, diffuse light should be incorporated, e.g., as shown by Sinoquet et al. (1998).

## DYNAMIC STRUCTURAL MODEL OF CUCUMBER

The formalism of parametric L-systems was used to construct a dynamic structural model of cucumber (Kahlen 2006). Due to the lack of published geometric data of the cucumber architecture, data of plants grown in isometric stands of density  $1 \text{ m}^{-2}$  were chosen to parameterize the model. Morphological parameters were derived from digitized data such as leaf area and leaf elevation angle. Growth functions for single organs were derived from repeated measurements.

The model is based on thermal time assuming a base temperature of  $10 \text{ }^\circ\text{C}$  for cucumber (Marcelis 1994). Each time step thermal time is increased by  $1 \text{ }^\circ\text{Cd}$ . The initial structure, called axiom, consists of an apex  $A$  with two parameters, age  $t$  and phytomer rank  $nn$ . The apex ages with thermal time as long as its temperature sum is less than  $16.7 \text{ }^\circ\text{Cd}$ . When this threshold is reached, the apex produces a phytomer consisting of internode, petiole, lamina and a new apex. This is expressed by the following production rule:

$$A(t,nn): t \geq 16.7 \ \& \ nn < 7 \ \rightarrow I[PL]A(0,nn+1) \quad (1)$$

Generative growth starts with node rank 7 due to the chosen plant manipulation regime. For this purpose, production rule (1) is extended by a module  $C$  for a fruit. Newly produced modules have an initial individual temperature sum of  $0 \text{ }^\circ\text{Cd}$  and they all age with thermal time. Moreover, organ growth is logistic with thermal time:

$$Y = a*b/(b+(a-b)\exp(-\mu*X)) \quad (2)$$

where:  $Y$  = length of the organ (cm)  
 $a$  = maximal length of the organ (cm)  
 $b$  = minimum length of the organ (cm)  
 $\mu$  = the specific growth rate of the organ ( $\text{d}^{-1}$ )  
 $X$  = thermal time ( $^\circ\text{Cd}$ ).

Table 2 shows the individual parameter values as derived from the experiment.

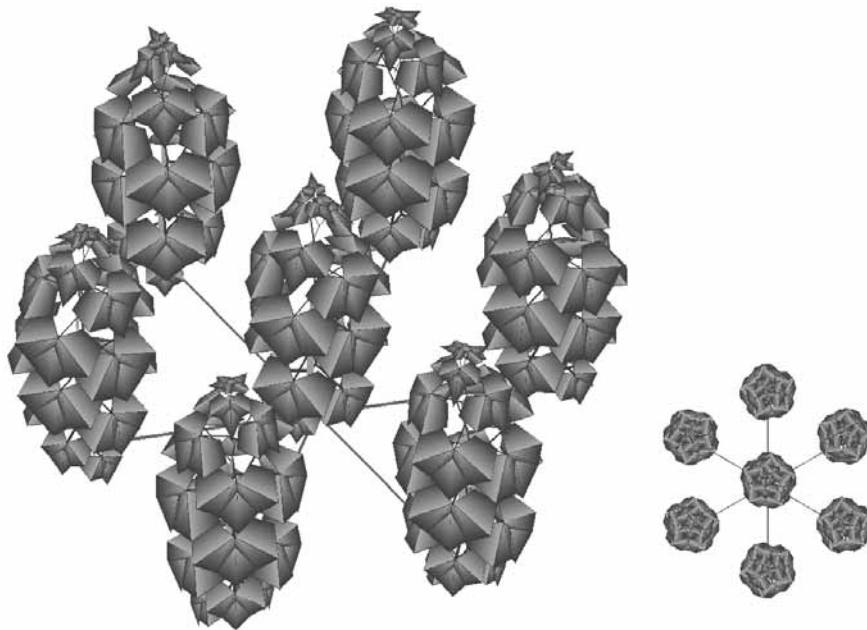
**Table 2.** Parameters used for the logistic organ growth functions

	Maximum organ size ( $\text{cm}^2$ for lamina or else cm)	Minimum organ size ( $\text{cm}^2$ for lamina or else cm)	Specific growth rate ( $\text{d}^{-1}$ )
Lamina	$117.4+210.7nn-14.9nn^2+0.3nn^3$	50	0.0524
Petiole	$10.973+1.874nn-0.0722nn^2$	1	0.0312
Internode	9	1	0.1040
Fruit	30	1	0.0362

$nn$  = phytomer rank

Cucumbers are generally characterized by a  $2/5$  phyllotaxis; thus a constant phyllotaxis angle of  $2/5 \cdot 360^\circ = 144^\circ$  is used in the model, even though measured data showed slight deviations from this constant value (data not shown). Initially, each leaf was more or less vertically oriented, which is expressed in a leaf elevation angle of  $0^\circ$  within the L-system. Maximum leaf elevation angle of  $162^\circ$  was reached at  $100^\circ \text{Cd}$ . Thus, leaf elevation angles are assumed to change with thermal time. Measured initial petiole angles were ca.  $20^\circ$  and maximum angles varied between  $100^\circ$  for the phytomer ranks below 7 and  $70^\circ$  above rank 7. In the model, petiole elevation angles are assumed to change with thermal time, too.

In the geometrical output of the L-system, petioles, internodes and fruits are represented by cylinders. A lamina is defined by a set of triangles resulting in a 3D leaf shape. This shape is based on derived relationships between lengths of individual leaf ribs and angles between them. An example of such an angle is the one between the line defined by the digitized points 1 and 13 and the line between the points 1 and 14 as shown in Figure 1. Internodes showed slight deviation from being perfectly vertically arranged. To picture this, orientation angles of  $20^\circ$  for each internode are included in the production rules. Fruits are forced to grow vertically downwards due to gravity.



**Figure 4.** Visualization of the parametric L-system for cucumber. This output represents a model simulation after  $390^\circ \text{Cd}$  of an isometric stand consisting of seven plants with plant density of  $1 \text{ m}^{-2}$ . The small picture on the right shows a top view of the stand

This dynamic structural model can be used to construct cucumber stands. In Figure 4 an isometric stand with plant density of  $1 \text{ m}^{-2}$  is simulated. The L-system production rules were interpreted by the plant and fractal generator program *CPFG* implemented in the software *L-studio* 3.1.03 (Měch 2005; Prusinkiewicz et al. 2000).

Obviously, big limitations of the presented dynamic structural model of greenhouse cucumber are that it does not take into account the interactions between neighbouring plants in a crop stand and that organ growth is forced due to the chosen growth functions. To overcome this, growth rates should be used, which have to be determined from dry-matter production and dry-matter allocation depending on actual environmental conditions. For this purpose, existing process-based models (Marcelis 1994; Marcelis and Gijzen 1998) should be coupled or integrated with the structural model.

The presented dynamic structural model can be regarded as a first approach to model plant manipulation regimes of cucumber with focus on plant architecture.

## CONCLUSIONS

Static structural models can help to identify differences in light distribution and light interception of cucumber canopies as dependent on plant density and arrangement. The concept of LIE can be incorporated in the dynamic structural model, because at each time step it produces a static structural model of the cucumber plant. Finally, to explore the effects of different cultivation and plant manipulation regimes on plant canopy and resulting light interception, it is necessary to couple the dynamic structural model with a functional model.

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