A dynamic 3D model of rape (*Brassica napus* L.) computing yield components under variable nitrogen fertilisation regimes

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Introduction

Oilseed rape (*Brassica napus* L.) is a crop which is grown mainly for its high quality oil and protein. Rapeseed provides a versatile oil, being used not only for cooking and frying but also as a fuel and a raw material for the chemical industry. In the face of global climate change, rapeseed could play a much more important role in the future as source of renewable energy. There is thus a considerable interest in an optimisation of seed yields. One factor determining yield of rapeseed in the field is the amount and timing of nitrogen (N) fertilisation. The major downside of this crop management measure is the easy overfertilisation and subsequent infiltration of nitrate into the groundwater. The experimental determination of optimal fertilisation timing and dosage scenarios is notoriously difficult under variable soil and climate conditions and thus justifies the use of a functional-structural rapeseed model.

We will here present such an FSPM of rapeseed, which has been implemented in the modelling language XL (Kniemeyer 2004), an extension of the rule-based L-system formalism. This FSPM constitutes a set of morphogenetic rules describing the dynamics of organ formation and extension, as well as the topology of organs to form the next higher scale, that of the plant individual. The model is coupled with a Java implementation of a leaf photosynthesis model, allowing the computation of CO_2-assimilation for each leaf, based on climatic input parameters. Furthermore, assimilates are transported according to a sink-source model based on credit points, explained below.

Materials and Methods

The FSPM of rapeseed presented here includes, besides detailed morphogenetic rules, a set of rules and functions that describe certain important metabolic processes (mainly concerning carbon (C) and N budget). Associated processes that have an influence on both morphological and physiological aspects of the plant have also been considered in the model, such as: leaf senescence, respiration and interdependencies between N and C metabolism, especially during photosynthesis.

Composition of the rapeseed FSPM: Scope of morphology and phenology: The model has been constructed from published morphological and phenological descriptions (e.g., Sylvester-Bradley and Makepeace, 1984) and parameterised using several data sets captured during field trials conducted at the University of Göttingen over several years. The mature virtual rapeseed individual is made up of the following organ categories: shoot (shoot apical meristem, leaf, stem internode), inflorescence (inflorescence internode, flower petiole, flower (sepal, petal, stamen, carpel → silique)). The time frame considered for the model is March 1 (vernal regrowth of the hibernated leaf rosette) to July 15 (harvest of the mature plant in Germany). The time from sowing (end of

August) to the rosette stage (end of February) is neglected as no yield-relevant processes are taking place during this period and therefore no usable biometrical and developmental information were available about this period. The developmental phases covered in the model are thus: 1) late rosette growth, 2) bolting (i.e. rapid elongation of upper internodes with a terminal inflorescence), 3) flowering, 4) maturity (including formation of siliques and seeds).

C- and N budget: In our model, we only closely consider assimilation of C and N. All other mineral nutrients are regarded as non-limiting, to simplify matters. Sources of C-assimilates in rapeseed are the leaves and the walls of the siliques. C-assimilates are transported from the sources to sinks via internodes. Every part of the plant is a sink, thus C-assimilates are also consumed in source organs. However, flowers, seed forming siliques and meristems, including all young extending organs, are much stronger sinks. Part of the assimilates is also allocated to root growth although roots are not explicitly included in the structural model. C-assimilation depends on a set of environmental (temperature, humidity, radiation) and biometric variables (leaf area). Finally, the onset of senescence decreases the assimilative power of leaves. Further factors that determine consumption of assimilated C are growth respiration and maintenance respiration, which are computed as losses of about 30% of assimilated C, and 2 % per day per g biomass, respectively. A big percentage of assimilates is stored in seeds, and maximisation of this amount is an important breeding target.

To model C assimilation, a Java implementation of the model LEAFC3 (Nikolov et al. 1995) was used and its extension LEAFC3-N (for photosynthesis at different N-regimes in winter wheat, Müller et al. 2005) consulted. Leaf senescence was simulated as a linear function of leaf age.

N-assimilation in rapeseed takes place via the roots only and as nitrate. As roots are not modelled here, N-assimilation is achieved via a set of parameters linked to a virtual root node. The parameter-set is an XML-formatted file containing an array of daily input values for nitrogen. Missing daily values are interpolated. Shortage of nitrogen induces early bolting and flowering, ensuing a short stature and reduced yield. Vice versa, additional doses of N during the right developmental phases can lead to considerable increments in yield, but this easily ensues overfertilisation. Assimilated N is used in the first place in C-assimilating plant organs and seeds. N thus plays an important role for C-assimilation.

Shading of leaves was simply computed as a function of the topological rank of a shaded organ relative to the maximum rank, assuming that lower leaves are more shaded than higher ones. Light distribution within the canopy was therefore not computed in this simplified shading model.

Sink-source method and transport system: Sink strengths were determined according to a system of credit points where each organ category (root, leaves, internodes, petioles, flowers, siliques, and seeds) was allocated a fixed number of basic credit points for C and N (e.g., 1000 for internodes, 500 for seeds, 400 for leaves). These basic points were derived from field observations of dry matter courses of these organ classes during development. The sink strength for C or N of a single organ instance is then computed as the ratio of the basic points for that organ category and the number of instances of that organ currently present on the plant.

The transport system is intrinsically related to the system of sinks and sources in the plant (e.g., cf. GREENLAB, de Reffye et al. 2004). We tested four different approaches to modelling transport: distribution based on requirement analysis, transport based on sink strength, direct transport with fixed rates, and transport based on diffusion. Of these, only the first proved to be practical; the features and disadvantages of the other three solutions will be discussed in the extended paper.

Simulations

Fig. 1 gives some screenshots of simulated oilseed rape individuals at three different developmental stages (bolting, flowering, full maturity). Model development and all simulations were done using our modelling language XL within the GroIMP environment (Kniemeyer 2004). The model is

capable of reproducing the overall dynamic appearance realistically, given an input weather file. Simulated time courses of dry masses of all organs, C-assimilation rates, C and N contents largely corresponded to observations and measurements, with simulated C- and N-assimilation rates typically showing ranges between 0.1 - 0.95, and 0.001- 0.009 g plant^{-1} d^{-1}, respectively, within the simulated time span of 122 days. However, simulated leaf dry mass decreased by only 50%, whereas in reality it drops to 10% of the maximum dry mass. This was due to the fact that the model just included leaf shedding but did not consider enough remobilisation of biomass from dying leaves. A comparative survey of simulated mobile and fixed C and N contents yielded that in the simulated days 30 to 60 there were hardly any mobile N reserves available: This can be explained by the fact that during this time mobile C reserves are built up which are later used to form flowers, siliques and seeds.
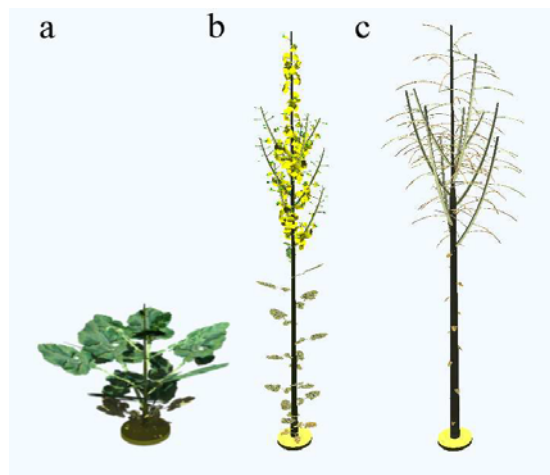

Fig. 1: Developmental stages of the virtual rapeseed: a) bolting, b) flowering, c) harvest maturity

Outlook

Future work will concentrate on the recalibration of parameters with new field data as well as on the application of optimisation algorithms (e.g., Hill Climbing, Threshold Accepting, Simulated Annealing) for the optimisation of seed oil content at reduced nitrogen fertiliser input. Also, the simple light model will be replaced with a raytracer-based radiation model in GroIMP in order to make proper use of the capabilities of the LEAFC3 photosynthesis model.

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