Extension of a functional-structural model of barley for modelling of carbon and nitrogen partitioning

Katarína Smoleňová[1], Gerhard Buck-Sorlin[2], Reinhard Hemmerling[1]
and Winfried Kurth[1]
[1]Dept. Ecoinformatics, Biometrics and Forest Growth, University of Göttingen, Büsgenweg 4,
37077 Göttingen, Germany
[2]Centre for Crop Systems Analysis, Wageningen UR, Droevendaalsesteeg 1,
6708 PB Wageningen, The Netherlands
ksmolen@gwdg.de

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Introduction

The availability of nitrogen (N) strongly determines crop yield under normal water conditions. The combination of N fertilisation and breeding of cultivars with a strong response to fertilisation has proved to be a powerful tool to increase grain yield in cereals. However, the risk of environmental pollution and the costs of N fertilizer require an optimisation of N fertilisation. Nitrogen Use Efficiency (NUE) of a crop plant can be defined as grain yield per unit N fertilizer applied. A low NUE may indicate the inability of the plant to transport, store, and process N in an efficient way. Crops with high NUE can thus be expected to attain higher yields under conditions of N-limitation. NUE is a complex, genotype-specific trait, in which the interactions with the biotic and abiotic environment play a significant role. The representation of leaf and shoot dynamics as well as of tillering is a central component of a realistic cereal FSPM. There is generally agreement that temperature and day length are the main factors influencing the rate of leaf appearance (RLA: Kirby 1995). Nutrient budget also has an influence on RLA, yet to a lesser extent that the named two environmental factors. Effects of N deficiency on RLA are diverse, depending on the experiment: For instance, it reduced RLA in barley plants grown in nutrient solutions (Dale and Wilson 1978). N deficiency delayed leaf and tiller appearance in barley grown in pots with sand, yet RLA was less sensitive to nutrient deficiency than tillering rate (Prystupa et al. 2003).

Here we present an extension of a winter barley FSPM (*Hordeum vulgare* L.) (Buck-Sorlin et al. 2005, 2008). The original model coupled morphogenesis with the biosynthesis and transduction of a hormonal signal (gibberellic acid). In the extended model, we have further included source (photosynthesis: Nikolov et al. 1995) and sink functions (biomass accumulation according to the relative sink strength concept: Marcelis 1996). We also show how the model is coupled with modules describing C and N partitioning. A similar approach was pursued by Wernecke et al. (2007).

Model description

The present model is organized in different sub-models, or modules, describing morphology (vegetative and generative part), genetics, hormonal control, radiation and shading, C and N partitioning, as well as global model parameters.

The model is implemented in the software GroIMP (Kniemeyer et al. 2010), using the Java-based programming language XL (Kniemeyer 2008).

The environment is simulated using climate data from the weather station of the Institute of Plant Genetics and Crop Plant Research (IPK, Gatersleben, Germany), for the period from October 1, 1998 to July 15, 1999 (288 days).

To simulate photosynthesis, the LEAFC3 model (Nikolov et al. 1995) was used, made sensitive to nitrogen relations and parameterized for barley (Braune et al. 2009). The sub-model covering C/N partitioning between shoots and roots follows a simple compartment-based approach (Thornley and Verberne 1989). A schematic diagram of the sub-model and its connection to the barley model is shown in Fig. 1. A shoot is composed of different organs whose development is described by XL rules.

Sink strengths of individual organs determine the partitioning of C and N assimilates within the shoot and are controlling organ extension. Sink activities are implemented using the concepts of Marcelis (1996) and Yin and van Laar (2005). The control of root and shoot growth by available C and N does not yet interact with the sub-model on hormonal metabolism.

A new important feature used in the present model is the approximate solution of ODEs using a *rate assignment operator* (Hemmerling et al. 2010). This is an extension of XL which allows easy specification and solution of differential equations on graphs. Furthermore, it separates the specification of the problem from its solution (the modeller does not need to implement a solver within the model). The new operator is used, e.g., for the numerical solution of differential equations describing partitioning between shoot and root and within the shoot.

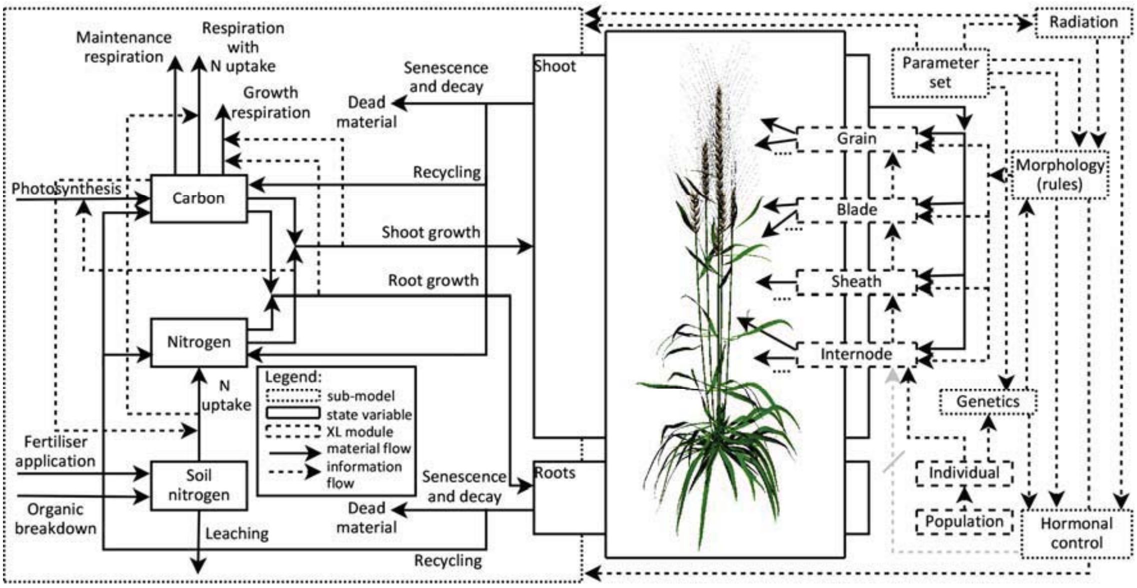

Fig. 1. Schematic diagram showing the sub-models of the winter barley FSPM (not all of the XL structural modules are included) and interactions between them. The new partitioning sub-model is described in more detail. An example of the resulting 3D model is shown.

Results and Discussion

As an example of the numerous possibilities of the extended barley model, Fig. 2 shows the comparison of two different leaf photosynthesis models (Thornley & Verberne 1989, Nikolov et al. 1995) with and without sensitivity of photosynthesis rate to nitrogen. The current model is also well able to simulate the biomass dynamics of plants grown at different N fertilization scenarios (results not shown). Future work will focus on parameterisation of the model and further coupling and extension of the existing but currently unused regulatory network model describing the production, transport and signal transduction of gibberellic acid, a hormone which plays an important role in internode elongation. Internode elongation is also a growth process that requires C and N allocation to the growing organ. It is envisaged to link the two models describing internode elongation (hormonally or using source/sink relations) with each other by introducing a simplified network model of biochemical processes involving key enzymes for C and N metabolism. We will also address the dependence of tiller formation from N status and hormonal signals.

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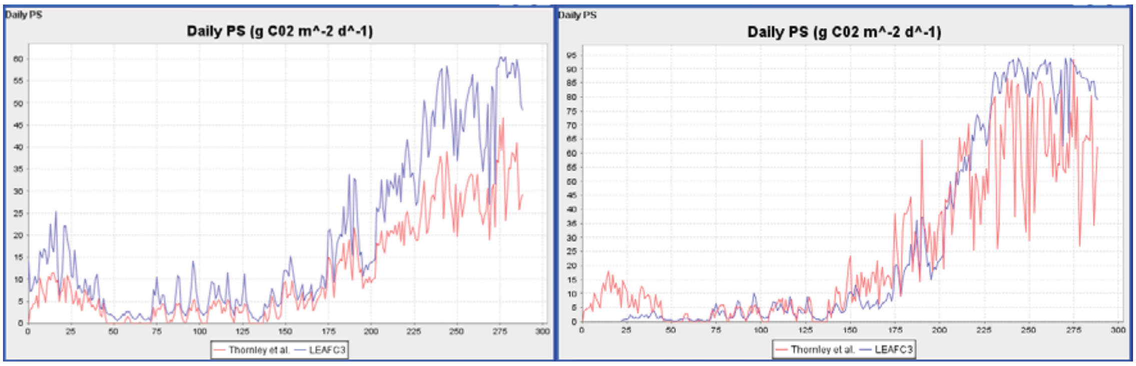

Fig. 2: Comparison of two different leaf photosynthesis rate models. The dynamics of the simulated daily rate of CO_2 assimilation (g CO_2 m^{-2} d^{-1}) is shown for the entire season (1.10.1998 – 15.7.1999). Left: photosynthesis not sensitive to nitrogen, right: with sensitivity to nitrogen. Rates are indicated for a leaf area of 1 m^2; application of 100 kg N ha^{-1} at t = 0 (1.10.1998).

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