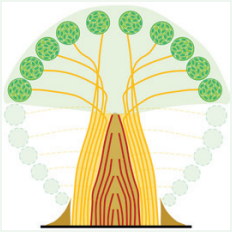
Advancing plant science through functional-structural plant (FSP) modelling

Annals of Botany 121: 767–772, 2018
doi: 10.1093/aob/mcy050

The need to integrate the expanding body of knowledge in the plant sciences has led to the development of sophisticated modelling approaches, such as functional-structural plant (FSP) modelling, which are the result of cross-fertilization between the domains of plant science, computer science and mathematics. FSP models simulate growth and morphology of individual plants and interactions with the environment, from which complex plant community properties emerge. **Evers *et al.,*** in the preface to this 2018 Annals of Botany Special Issue, present the latest developments in FSP modelling, including simulation of novel plant ecophysiological concepts and new model applications. FSP modelling is now an established approach that has matured over the years, offering opportunities for computational botany to address questions in complex plant systems that cannot be fully explained by empirical approaches alone.

Authors: Jochem B. Evers, Veronique Letort, Michael Renton, and Mengzhen Kang



The Pipe Model Theory half a century on (Review)

Annals of Botany 121: 773–795, 2018
doi: 10.1093/aob/mcx194

Lehnebach *et al.* review the diverse and multi-disciplinary uses of the Pipe Model Theory (PMT) and associated properties, and scrutinize their validity in the light of current anatomical and physiological knowledge. They discuss applications and modifications of the PMT theory in the context of biomass allocation and hydraulic models, with a particular focus on its extensive use in functional-structural plant modelling. Lehnebach *et al*. conclude that the PMT is not valid as a universal rule: in particular, the suggested ratio between sapwood and leaf area is generally not constant, varying not only between species, but also with ontogeny and environmental conditions. Nevertheless they argue that it continues to be useful as a first approximation for relevant functional-structural processes at appropriate scales.

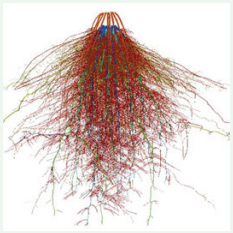
Authors: Romain Lehnebach, Robert Beyer, Véronique Letort, and Patrick Heuret

High light aggravates functional limitations of photosynthesis

Annals of Botany 121: 797–807, 2018
doi: 10.1093/aob/mcx100

Experimental results of salinity effects on cucumber (*Cucumis sativus*, Cucurbitaceae) can be interpreted with the help of a functional-structural plant (FSP) model. **Chen *et al.*** use this novel approach to quantify different salinity effects on canopy photosynthesis and discover interactions between plant architecture, stomatal regulation and light conditions. Salinity effects on plant architecture and photosynthetic functions of leaves reduce canopy photosynthesis significantly but the magnitudes of these effects depend on instantaneous light condition. High light enhances functional limitation of canopy photosynthesis through the ionic effects on stomatal regulation.

Authors: Tsu-Wei Chen, Hartmut Stützel, and Katrin Kahlen



Optimizing soil-coring strategies using 3D root architecture models

Annals of Botany 121: 809–819, 2018
doi: 10.1093/aob/mcx117

Virtual assessment based on root system architecture (RSA) modelling has great value in the optimisation of core-sampling strategies. Based on the measurement dataset of two maize cultivars having contrasting axile root angles, **Wu *et al.*** construct contrasting three-dimensional RSA models of individual maize plants in which the different lateral rooting angles are represented. The accuracies of various core-sampling strategies for estimating root length density (RLD), including a new two-core sampling strategy based on an area-weighting algorithm, are assessed using these models. The new two-core sampling strategy shows considerable promise as a cost-efficient way of obtaining good-quality RLD estimates for maize.

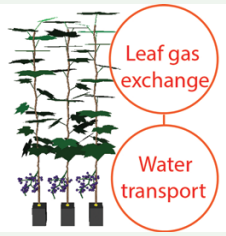
Authors: Qian Wu, Jie Wu, Bangyou Zheng, and Yan Guo

Modelling temporal variation of parameters used in photosynthesis models

Annals of Botany 121: 821–832, 2018
doi: 10.1093/aob/mcx139

Several studies have found seasonal and temporal variability in leaf photosynthesis parameters in different crops. **Poirier-Pocovi *et al*.** use six-year-old fruit-bearing branches of ten-year-old apple trees to study and model the seasonal variation of photosynthetic parameters in leaves of vegetative shoots, as a function of global fruit load (at the branch level), with and without girdling, during the growing season of 2015. The originality of the experiments is they were carried out in the orchard. A comparison was made that predicted variation in photosynthesis rates using several models.

Authors: Magalie Poirier-Pocovi, Jérémy Lothier, and Gerhard Buck-Sorlin

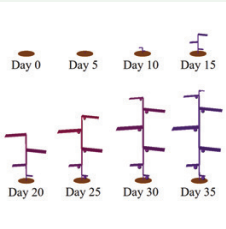


GrapevineXL: a model coupling plant water transport and leaf gas exchange

Annals of Botany 121: 833–848, 2018
doi: 10.1093/aob/mcx141

Quantifying the response of plant water status to environmental conditions and its effect on carbon acquisition are essential for simulating plant growth and fruit composition, especially in the context of climate change. **Zhu *et al.*** present GrapevineXL, a functional-structural grapevine model that couples the dynamics of water transport from soil to leaf with gas exchange at individual leaf level. The robust performance of this model makes it ideal for modelling climate effects on crops with complex, non-homogenous canopies and for studying plant water use behaviours. It also provides the basis for future modelling efforts elucidating the physiology and growth of individual organs in relation to water status.

Authors: Junqi Zhu, Zhanwu Dai, Philippe Vivin, Gregory A Gambetta, Michael Henke, Anthony Peccoux, Nathalie Ollat, and Serge Delrot



Towards turgor-driven growth in FSPs

Annals of Botany 121: 849–861, 2018
doi: 10.1093/aob/mcx144

In many scenarios, water availability plays a determinant role in plant growth. Current functional-structural plant models (FSPs) mainly focus on plant-carbon relations and largely disregard the importance of plant-water relations. **Coussement *et al.*** adapted an existing water-flow and a storage model was made was for integration into FSPs. It applies explanatory concepts of water flow, water potential and turgor on the scale of individual plant organs with a direct link to plant growth in 3D. The model is applicable to any plant architecture and allows visual exploration of the dynamics in plant organ water content and growth.

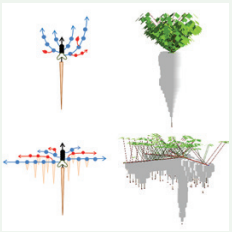
Authors: Jonas R. Coussement, Tom De Swaef, Peter Lootens, Isabel Roldán-Ruiz, Kathy Steppe

Subtle variation in shade avoidance responses has profound consequences for plant competitiveness

Annals of Botany 121: 863–873, 2018
doi: 10.1093/aob/mcx151

There is limited knowledge on how variation in plastic responses plays a role in determining plant competitiveness. To address this issue, **Bongers *et al.*** combine experimentations and simulation modelling to test competitiveness for light in *Arabidopsis thaliana* growing in dense stands. Plant plasticity was represented by changes in leaf angle and petiole elongation in response to R:FR signals, which are typical shade avoidance responses. Results showed that differences in competitiveness may arise between genotypes with only marginally different plastic responses, suggesting that there could have been strong selection for fine-tuning the sensitive shade avoidance responses found in plants.

Authors: Franca J. Bongers, Ronald Pierik, Niels P.R. Anten, and Jochem B. Evers

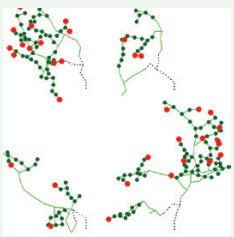


A generic individual-based model (IBM) tool to disentangle plant interactions in forage legumes

Annals of Botany 121: 875–896, 2018
doi: 10.1093/aob/mcx154

Louarn and Faverjon develop a generic model to account for the growth and development of herbaceous legume species with contrasting above- and below-ground architectures. The individual-based model (IBM) integrates plant responses to light, water and nitrogen and solves competition for multiple resources in a spatially explicit environment. The IBM's behaviour was assessed on a range of monospecific stands grown along three resource gradients. In addition to predicting the main density-dependent responses known about even-age plant populations, the IBM correctly anticipated plastic changes in the partitioning of dry matter, the N nutrition of legumes and the architecture of shoots and roots.

Authors: Gaëtan Louarn and Lucas Faverjon



Simulating ephemeral seagrass growth

Annals of Botany 121: 897–908, 2018
doi: 10.1093/aob/mcx156

Ephemeral seagrasses provide important marine habitats, but are under threat due to human activity. **Whitehead *et al.*** develop a new functional-structural environmentally dependant model, in order to integrate existing knowledge of ephemeral seagrass growth dynamics and to assess potential management options, such as transplantation. The model is parameterised for a population of *Halophila stipulacea* (Hydrocharitaceae) in the Persian Gulf, and is able to successfully simulate its dynamic structural growth patterns. The model is freely available and easily adapted for new species and locations, although validation for more species and environments is required.

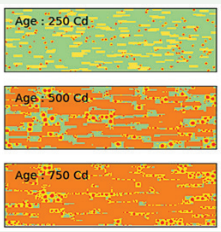
Author: S. Whitehead, M. L. Cambridge, and M. Renton

Designing oil palm architectural ideotypes for optimized light interception

Annals *of Botany* 121: 909–926, 2018
doi: 10.1093/aob/mcx161

Enhancement of light harvesting in annual crops has successfully led to yield increase and has been achieved by selecting plants with optimal canopy architecture for specific agronomic practices. In this simulation study, **Perez *et al.*** investigate potential improvements in light interception and carbon assimilation in oil palm (*Elaeis guineensis*) under conventional agronomic conditions. A sensitivity analysis is performed on three-dimensional virtual plants to assess the impact of architectural traits on light interception efficiency and potential carbon acquisition. Results highlight the significant contribution of erect leaves, short leaves and high density of leaflets on leaves to efficient light capture. Four architectural ideotypes are proposed based on their capacity to limit mutual shading and optimize light distribution within plant crown. This study opens the way to further investigate ideotypes carrying optimal trade-off between carbon assimilation, plant transpiration and biomass partitioning.

Authors: Raphaël P. A. Perez, Jean Dauzat, Benoît Pallas, Julien Lamour, Philippe Verley, Jean-Pierre Caliman, Evelyne Costes, and Robert Faivre

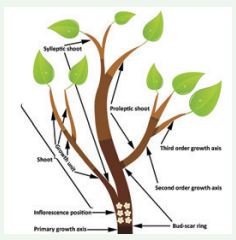


Modelling interaction dynamics between two foliar pathogens in wheat: a multi-scale approach

Annals of Botany 121: 927–940, 2018
doi: 10.1093/aob/mcx186

This study presents a new model combining two wheat fungal diseases, caused by *Zymoseptoria tritici* (septoria) and *Puccinia triticina* (brown rust), with a functional-structural plant (FSP) model of wheat. Most epidemiological models focus on a single type of pathogen, ignoring the interactions between different fungal parasites competing on the same host and how properties of the canopy impact them. **Garin *et al.*** simulated these processes from the leaf scale to the 3D canopy scale to explore the complex dynamic interactions between these pathogens and the plant in diverse conditions. Using FSP modelling helps to understand how canopy properties influence the development of competing pathogens.

Authors: Guillaume Garin, Christophe Pradal, Christian Fournier, David Claessen, Vianney Houlès, and Corinne Robert

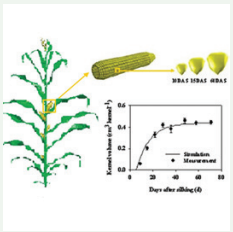


A novel approach to verification and validation of functional–structural plant models

Annals of Botany 121: 941–959, 2018
doi: 10.1093/aob/mcx187

Functional-structural plant modelling is an established approach to realistically represent plant growth, but testing and documenting realism beyond visual comparisons is challenging. We used elements of pattern-oriented modelling to test the realism of a new model of the annual growth module (AGM) of avocado (*Persea americana*, cv. Hass. Lauraceae). **Wang *et al.*** use seven patterns characterising AGMs to calibrate the model, which then successfully predicted nine further patterns that were not used during calibration. Their model can thus be claimed to be structurally realistic, which implies that it will be able to predict the response of an AGM to changing environmental conditions.

Authors: Ming Wang, Neil White, Volker Grimm, Helen Hofman, David Doley, Grant Thorp, Bronwen Cribb, Ella Wherritt, Liqi Han, John Wilkie, and Jim Hanan



Modelling individual kernel filling-processes with source–sink interactions

Annals of Botany 121: 961–973, 2018
doi: 10.1093/aob/mcx189

Failure to account for the variation of kernel growth may cause serious deviations in the simulation of crop yield. **Ma *et al.*** built a GREENLAB-Maize-Kernel model to incorporate source-sink limited allocation approach to simulate individual kernel filling process. Three basic traits characterizing individual kernel: (i) final kernel size, (ii) kernel growth rate, and (iii) kernel filling duration are compared on simulated and measured data. Source-sink dynamic and remobilization for kernels growth are quantified to show that remobilization processes accompanied source-sink dynamics during the kernel filling process. The model can be used to explore options for optimizing plant kernel yield by matching maize management to the environment, taking into account responses at the level of individual kernels.

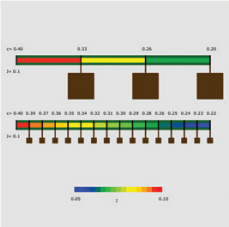
Authors: Yuntao Ma, Youjia Chen, Jinyu Zhu, Lei Meng, Yan Guo, Gerrit Hoogenboom, and Baoguo Li

The race between wheat and *Zymoseptoria tritici* epidemics

Annals of Botany 121: 975–989, 2018
doi: 10.1093/aob/mcx192

Robert *et al.* explore how canopy growth, spatial organization, and leaf senescence impact epidemics of wheat Septoria tritici blotch (STB) caused by *Zymoseptoria tritici*. Strikingly, the timing of leaf senescence is one of the most influential traits. When the green lifespan duration of leaves is reduced epidemics are strongly reduced. They introduce the notion of a race between the growing canopy and the developing epidemics. This race is twofold: (i) an upward race at the canopy scale where *Z. tritici* must keep up with the emerging leaves, (ii) a local race at the leaf scale where *Z. tritici* must use the resources before leaf apical senescence sets in. The results shed new light on the importance of dynamic interactions between host and pathogen.

Authors: Corinne Robert, Guillaume Garin, Mariem Abichou, Vianney Houlès, Christophe Pradal, and Christian Fournier

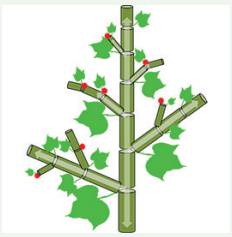


A coupled phloem/xylem transport model

Annals of Botany 121: 991–1003, 2018
doi: 10.1093/aob/mcx204

Transport of carbohydrates and water are essential aspects of plant functioning. This paper presents a novel approach for modelling these processes combining mathematical and computational methods. **Seleznyova and Hanan** have produced the first mechanistic transport model that is capable of simulating continuous distributions of the system variables in a complex developing structure. The model simulations emphasize sensitivity of the phloem and xylem fluxes to the presence of distributed sinks and sources. The methods will be useful for modelling carbohydrate transport and distribution at different scales of plant organization.

Authors: Alla N. Seleznyova and Jim Hanan



A network of phytomers in cotton

Annals of Botany 121: 1005–1017, 2018
doi: 10.1093/aob/mcx210

Within-plant spatial variability in the production and demand for assimilates may have major implications for the formation of fruits. **Gu *et al.*** propose an FSP model for cotton (*Gossypium hirsutum*) based on local pools to quantify the variability of local carbohydrate availability within a plant. This model is plausible and simulates cotton performance effectively in terms of leaf area dynamics, dry mass allocation and transport of carbohydrate. Spatial variability of local carbohydrate availability has is captured as an emergent property in the model. CottonXL is a tool to explore the underlying mechanism of fruit abortion and branching pattern in cotton.

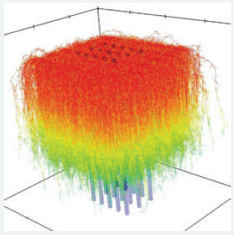
Authors: Shenghao Gu, Lizhen Zhang, Zhenzhen Yan, Wopke van der Werf, and Jochem B. Evers

Modelling the interaction between light competition and herbivore feeding patterns

Annals of Botany 121: 1019–1031, 2018
doi: 10.1093/aob/mcx212

de Vries *et al.* use a 3D functional-structural plant (FSP) model for *Brassica nigra* that mechanistically simulates light competition and herbivory to investigate the interaction between competition and herbivore feeding location on plant performance. The model predicts that plants can tolerate herbivory under low competition pressure but face higher costs of herbivore feeding on young compared to old leaves under strong competition pressure.

Authors: Jorad de Vries, Erik H. Poelman, Niels Anten, and Jochem B. Evers



CRootBox: A functional-structural root model

Annals of Botany 121: 1033–1053, 2018
doi: 10.1093/aob/mcx221

Functional-structural plant (FSP) root models are increasingly used to investigate root-soil interactions. **Schnepf *et al.*** present CRootBox, a C++ based modelling framework for root architectures that combines usability, availability and high computing speed. It can simulate multiple root systems of dicotyledons and monocotyledons. Its Python library facilitates modelling root-soil interactions using external dynamic soil models. A web-application enables anyone to create, modify and export a root system from one of the 22 available input parameter sets. The model can be used to analyse strategies to maximise resource acquisition from soil. In the future, this approach can be extended to the whole plant level.

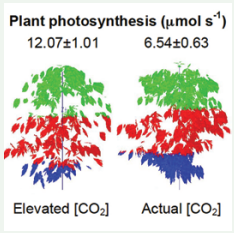
Authors: Andrea Schnepf, Daniel Leitner, Magdalena Landl, Guillaume Lobet, Trung Hieu Mai, Shehan Morandage, Cheng Sheng, Mirjam Zörner, Jan Vanderborght, and Harry Vereecken

Biomass allocation between lamina and petioles in a game of light competition in a dense annual plant stand

Annals of Botany 121: 1055–1064, 2018
doi: 10.1093/aob/mcy001

Plant architecture is important for light capture. In the field, plants compete with neighbours for light. In a competing system, game theory is needed to consider advantageous strategy (evolutionarily stable strategy; ESS). **Yoshinaka *et al.*** focus on a trade-off between lamina area and petiole length and analyse an evolutionarily stable petiole length in stands of *Xanthium canadense* (Asteraceae) using a simulation model YPLANT. They find that there are multiple evolutionarily stable petiole lengths even in one stand, suggesting that plants with different architectures can coexist across plant communities. The mean of evolutionarily stable petiole length was similar to the real one. Yoshinaka *et al*. conclude that actual plants realize evolutionarily stable architecture in dense stands.

Authors: Kenta Yoshinaka, Hisae Nagashima, Yusuke Yanagita, and Kouki Hikosaka



Structural and functional responses of coffee trees to elevated [CO_2]

Annals of Botany 121: 1065–1078, 2018
doi: 10.1093/aob/mcy011

Air [CO_2] tends to increase due to climate changes, affecting plant growth. Field-grown *Coffea arabica* trees were grown under actual and elevated [CO_2] for four years. **Rakocevic *et al.*** find that elevated [CO_2] stimulated stomatal conductance and whole-plant photosynthesis, increasing water-use efficiency during the fourth dry period. Elevated [CO_2] reduced leaf area and carbon investment in 2nd order branches, but also changed plant carbon partitioning by elevated [CO_2], with plants showing structure rejuvenation. Data also suggest carbon allocation to root system under elevated [CO_2]. After long-term exposure to elevated [CO_2], structural and functional responses balanced each other and must be considered when studying impacts of elevated [CO_2] in perennial species.

Authors: Miroslava Rakocevic, Rafael Vasconcelos Ribeiro, Paulo Eduardo Ribeiro Marchiori, Heloisa Ferreira Filizola, and Eunice Reis Batista

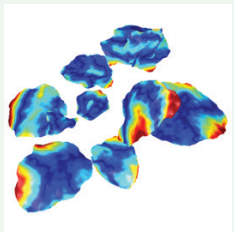
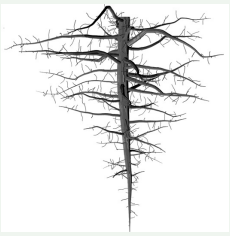


Image-based dynamic quantification and 3D evaluation for canopy structure

Annals of Botany 121: 1079–1088, 2018
doi: 10.1093/aob/mcy016

Phenotypic analysis with high-throughput, high-accuracy and low-cost technologies has become widely accessible. **Hui *et al.*** reconstruct and evaluate 3D canopy of plant population for cucumber (*Cucumis sativus*), pepper (*Capsicum annuum*) and eggplant (*Solanum melongena*) based on the multi-view stereo approach. A high level of overlap was found between surfaces of image-based reconstruction and laser scanning. High-accuracy 3D evaluation of reconstructed quality indicates that dynamic capture of canopy structure of plant population based on the multi-view stereo approach can potentially be used in 3D phenotyping for applications in breeding, model simulation and field management.

Authors: Fang Hui, Jinyu Zhu, Pengcheng Hu, Lei Meng, Yan Guo, Baoguo Li, and Yuntao Ma



DigR: a generic model and simulator of 3D root-system architecture

Annals of Botany 121: 1089–1104, 2018
doi: 10.1093/aob/mcy018

Several models of root system architecture exist in the literature but few of them are targeted at the organ level in response to environmental factors and none of them have modelled both annual plant and perennial tree root systems. **Barczi *et al.*** propose a generic, open-source, user friendly, 3D model (DigR) which simulates the architecture and dynamics of a wide range of root systems based on root-system architectural analysis and typology. External plugins enhance virtual simulations of plastic responses of roots to environmental constraints. DigR can output contrasting root system structures such as tap-root, fasciculate, tuberous, nodulated and clustered root systems.

Authors: Jean-François Barczi, Hervé Rey, Sébastien Griffon, and Christophe Jourdan