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Spatial Leaf Density-based Modelling of Teleonomic Crown Dynamics of Crops and Trees

Functional-structural plant growth models (FSPMs) have emerged as the synthesis of mechanistic process-based models, and geometry-focussed architectural models. In terms of spatial scale, these models can essentially be divided into small-scale models featuring a topological architecture -- often facing data-demanding parametrisations, parameter sensitivity, as well as computational heaviness, which imposes problematic limits to the age and size of individuals than can be simulated -- and large-scale models based on a description of crown shape in terms of rigid structures such as empirical crown envelopes -- commonly struggling to allow for spatial variability and plasticity in crown structure and shape in response to local biotic or abiotic growth conditions.

In response to these limitations, and motivated not least by the success-story of spatial density approaches in theoretical populations ecology, the spatial distribution of foliage in plants in this thesis is characterised in terms of spatial leaf density, which allows for a completely local description that is a priori unrestricted in terms of plasticity, while being robust and computationally efficient. The thesis presents dynamic growth models specific ally developed for crops and trees, exploring different mathematical frameworks in continuous and discrete time, while critically discussing their conceptual suitability and exploring analytical simplifications and solutions to accelerate simulations.

The law of Beer-Lambert on the passing of light though an absorbing medium allows to infer the local light conditions based on which local biomass production can be computed via a radiation use efficiency. A key unifying mechanism of the different models is the local expansion of leaf density in the direction of the light gradient, which coincides with the direction most promising with regard to future biomass productivity. This aspect falls into the line of teleonomic and optimization-oriented plant growth models, and allows to set aside the otherwise complex modelling of branching processes. The principle induces an expansive horizontal and upward-directed motion of foliage. Moreover, it mechanistically accounts for a slow-down of the horizontal expansion as soon as a neighbouring competitor's crown is reached, since the appropriate region is already shaded, implying a corresponding adaptation of the light gradient. This automatically results in narrower crowns in scenarios of in creased competition, ultimately decreasing biomass production and future growth due to lesser amount of intercepted light. In an extension, the impact of water availability is incorporated into the previously light-only dependency of biomass production by means of a novel hydraulic model describing the mechanistic balancing of leaf water potential and transpiration in the context of stomatal control. The allocation of produced biomass to other plant compartments such as roots and above-ground wood, e.g. by means of the pipe model theory, is readily coupled to leaf density dynamics.

Simulation results are compared against a variety of empirical observations, ranging from long-term forest inventory data to laser-recorded spatial data, covering multiple abiotic environmental conditions and growth resources as well as stand densities and thus degrees of competition. The models generate a series of complex emergent properties including the realistic prediction of biometric growth parameters, the spontaneous adaptability and plasticity of crown morphologies in different competitive scenarios, the empirically documented insensitivity of height to stand density, the accurate deceleration of height growth, as well as popular allometric relationships -- altogether

demonstrating the potential of leaf density based approaches for efficient and robust plant growth modelling.