A mathematical approach for understanding intra-plant communication

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$$
\begin{aligned}
\frac{da}{dt} &= \gamma p_h - \tau_{as} \\
\frac{ds}{dt} &= (1-\gamma)p_h + \tau_{as} - r_m^u - r_m^t - r_m s - \eta r_g \\
\frac{d\gamma}{dt} &= L(-\gamma\lambda_{sdr}\frac{s^{min}}{s^{min}+s} + (1-\gamma)\lambda_{sdi}\frac{s}{s+s^{max}}) + (1-L)(1-\gamma)\lambda_{sni}\frac{s^{min}}{s^{min}+s} \\
\frac{dn}{dt} &= u_n - (r_m(s+a)+\eta r_g)c_{sn}\frac{min(b_l^{max}, b_l)}{B} - \frac{p_h}{p_h^{max}} n_{ph}\lambda_f \\
\frac{dp}{dt} &= u_p - (r_m(s+a)+\eta r_g)c_{sp}\frac{min(b_l^{max}, b_l)}{B} - \frac{p_h}{p_h^{max}} p_{ph}\lambda_f \\
\frac{da_n}{dt} &= (1-a_n)((1-\frac{u_n}{u_n+C_n})\frac{n^{max}}{n^{max}+n} + \frac{p_h}{p_h^{max}} - a_n\lambda_k\frac{n-10p}{n+10p}) - \\
&\quad -a_n(\frac{n}{n+n^{min}} + \frac{n_c u_n}{n_c u_n + p_h(1-\gamma) + \tau_{as}}) \\
\frac{da_p}{dt} &= (1-a_p)((1-\frac{u_p}{u_p+C_p})\frac{p^{max}}{p^{max}+p} + \frac{p_h}{p_h^{max}} + a_p\lambda_k\frac{n-10p}{n+10p}) - \\
&\quad -a_p(\frac{p}{p+p^{min}} + \frac{p_c u_p}{p_c u_p + p_h(1-\gamma) + \tau_{as}}) \\
\frac{df_r}{dt} &= (1-f_r)(a_n f_n + (1-f_n)a_p) - f_r(\frac{n f_n}{n+n^{min}} + \frac{p(1-f_n)}{p+p^{min}} + \frac{s^{min}}{s+s^{min}}) \\
\frac{db_l}{dt} &= \lambda_{sb}(1-f_r)\eta r_g b_l min(\frac{b_l^{max}}{b_l}, 1) \\
\frac{db_{r1}}{dt} &= \lambda_{sb} e_1 f_r \eta r_g b_l min(\frac{b_l^{max}}{b_l}, 1) \\
\frac{db_{r2}}{dt} &= \lambda_{sb}(1-e_1) f_r \eta r_g b_l min(\frac{b_l^{max}}{b_l}, 1)
\end{aligned}
$$

The model is composed by 11 non-linear equations: Credit: Tedone et al.

A team of researchers at the Gran Sasso Science Institute (GSSI) and Istituto Italiano di Technologia (IIT) have devised a mathematical approach for understanding intra-plant communication. In their paper, pre-published on bioRxiv, they propose a fully coupled system of non-linear, non-autonomous discontinuous and ordinary differential equations that can accurately describe the adapting behavior and growth of a single plant, by analyzing the main stimuli affecting plant behavior.

Recent studies have found that rather than being passive organisms, plants can actually exhibit complex behaviors in response to environmental stimuli, for instance, adapting their resource allocation, foraging strategies, and growth rates according to their surrounding environment. How plants process and manage this network of stimuli, however, is a complex biological question that remains unanswered.

Researchers have proposed several mathematical models to achieve a better understanding of plant behavior. Nonetheless, none of these models can effectively and clearly portray the complexity of the stimulus-signal-behavior chain in the context of a plant's internal communication network.

The team of researchers at GSSI and IIT who carried out the recent study had previously investigated the mechanisms behind intra-plant communication, with the aim to identify and exploit basic biological principles for the analysis of plant root behavior. Their previous work analyzed robotic roots in a simulated environment, translating a set of biological rules into algorithmic solutions.

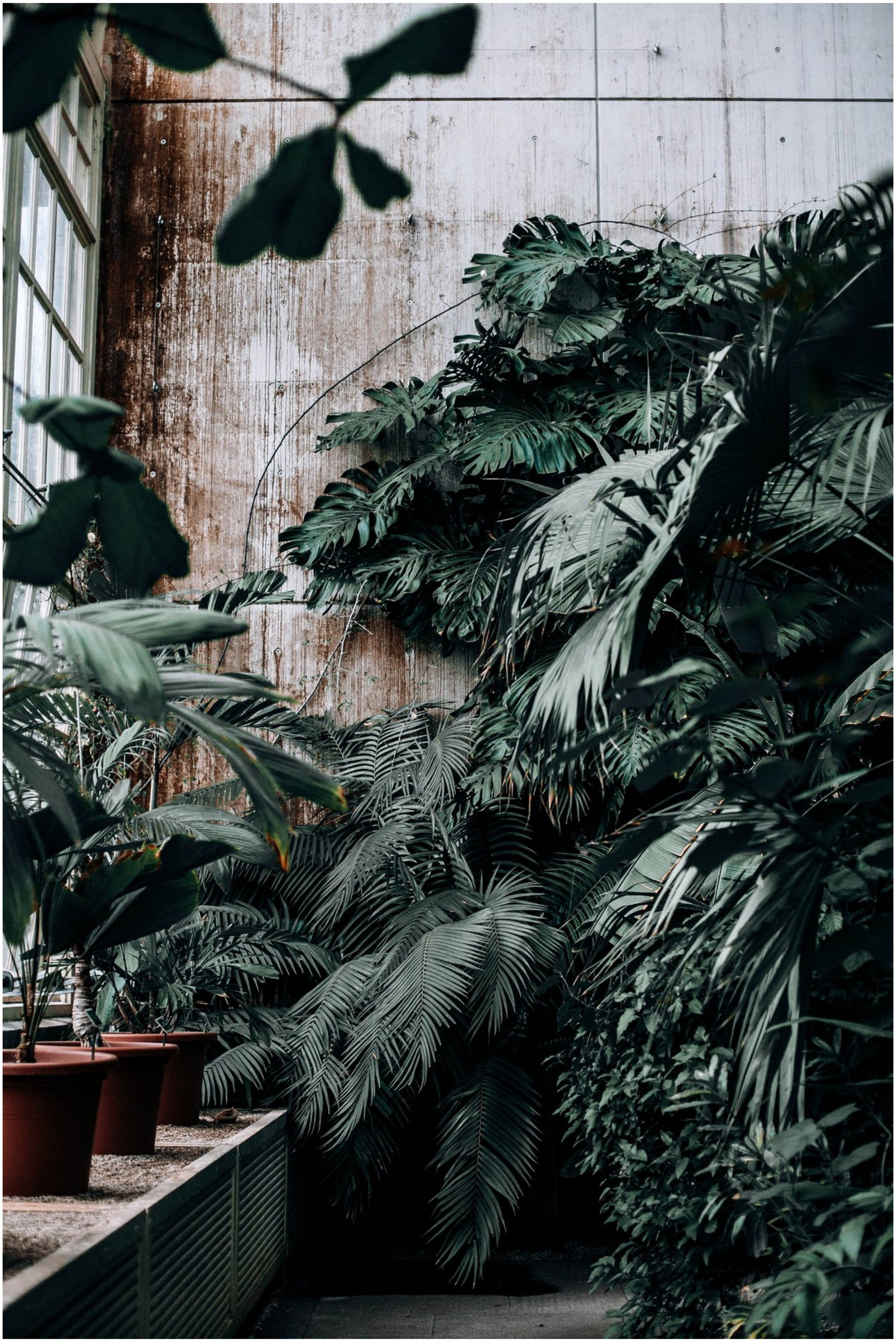

Photo by Alex Loup on Unsplash.com.

Even though each root acted independently from the others, the researchers observed the emergence of some self-organizing behavior, aimed at optimizing the internal equilibrium of nutrients at the whole-plant level. While this past study yielded interesting results, it merely considered a small part of the complexity of intra-plant communication, completely disregarding the analysis of above-ground organs, as well as photosynthesis-related processes.

"In this paper, we do not aspire to gain a complete description of the plant complexity, yet we want to identify the main cues influencing the growth of a plant with the aim of investigating the processes playing a role in the intra-communication for plant growth decisions," the researchers wrote in their recent paper. "We propose and explain here a system of ordinary differential equations (ODEs) that, differently from state of the art models, take into account the entire sequence of processes from nutrients uptake, photosynthesis and energy consumption and redistribution."

In the new study, therefore, the researchers set out to develop a mathematical model that describes the dynamics of intra-plant communication and analyses the possible cues that activate adaptive growth responses in a single plant. This model is based on formulations about biological evidence collected in laboratory experiments using state-of-the-art techniques.

Compared to existing models, their model covers a wider range of elements, including photosynthesis, starch degradation, multiple nutrients uptake and management, biomass allocation, and maintenance. These elements are analyzed in depth, considering their interactions and their effects on a plant's growth.

To validate their model and test its robustness, the researchers compared experimental observations of plant behavior with results obtained when applying their model in simulations, where they reproduced conditions of growth similar to those naturally occurring in plants. Their model attained high accuracy and minor errors, suggesting that it can effectively summarize the complex dynamics of intra-plant communication.

"The model is ultimately able to highlight the stimulus signal of the intra-communication in plants, and it can be expanded and adopted as a useful tool at the crossroads of disciplines such as mathematics, robotics and biology, for instance, for validation of biological hypotheses, translation of biological principles into control strategies or resolution of combinatorial problems," the researchers said in their paper.

More information: Fabio Tedone et al. Plant behavior: A mathematical approach for understanding intra-plant communication. DOI: 10.1101/493999. www.biorxiv.org/content/early/2018/12/11/493999