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Patchiness, Collective Dynamics, and Emergent Computation in Stomata

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Background

- Patchiness is one of the most ubiquitous phenomena in all of nature. Thermal “patchiness” in stomata (see Figure 3) in particular is pervasive in all plant species, and therefore it may confer an important biological advantage [1]. The goal of our research is to understand and model what causes patchiness and what its possible advantages are.

- Stomata are tiny pores on the surface of plant leaves formed by two cells called guard cells (Figure 1), allowing for exchange of water and CO2 between the mesophyll and the environment. They respond to changing air humidity, temperature, light intensity, and CO2 concentration in such a way as to maximize photosynthesis (CO2 uptake) and minimize water loss (by evaporation through the pore) [2].

- In addition, many guard and epidermal cells acting collectively through exchanging pressures may lead to emergent behavior that solves gas exchange problems. This phenomena may explain the patchiness of leaves.

Objectives

- Construct and test a dynamic model of stomata incorporating reactions to light, CO2, humidity, and temperature
- Create, solve, and simulate differential equations describing the stomata behavior
- Connect many stomatal units into an array and allow the system to evolve under nearest neighbor interactions, with certain initial conditions.

Setup

Experimental setup (Figure 2) includes a leaf chamber that measures and controls water vapor, CO2, and oxygen concentrations, along with a FLIR high-resolution thermal imaging camera, one of the few being used exclusively for stomata research.

Experiments

- Experiments include humidity, air temperature, and light intensity changes.
- Stomatal conductance (openness of the pore) for individual, homogenous temperature patches is calculated from equation (1) below, and matched against model predictions. Θ is the leaf temperature, as measured by the thermal camera (Figure 3, 4).

\[ g_s = \frac{R(K\Theta + T)}{L\Delta w} \]  

Model

- Figure 5 shows the schematic setup of the vapor-phase model for a stomatal unit [3]. Changes in guard cell pressure are regulated by equilibrating water potentials within the mesophyll, epidermal, and guard cells. These changing pressures are modeled by equations (2) and (3).
- Light induces photosynthesis, a by-product of which is a signal (possibly an ion [4]) that causes changes in stomatal conductance. A way to measure this ion is through the use of Tradescantia pallida (Purple Trad), whose maroon epidermal cells change color in response to pH changes (Figure 6).

\[ \frac{dp_a}{dt} = \lambda_c (\Delta w) \left( \Theta + m_x R_x \Delta w \right) (P_a - P_c) + \pi_a \]  

\[ \frac{dp_e}{dt} = \lambda_e (\Delta w) \left( \Theta \right) (P_e - P_c) + \pi_e \]  

Results

- In humidity experiments, stomata exhibit oscillatory behavior and "wrong-way" response captured by the pressure equations (Figure 7, 8).
- Stomata tend to return to previous average conductance after changes in light intensity.
- Stomata respond to ions.
- Further research is needed to fully model the effect of CO2 and the signal upon the stomata and hence leaf patchiness. Changes in the pH of Purple Trad due to external electric fields will be measured, and information concerning the signal then inferred.
- Once a more comprehensive model of stomata is constructed, multiple stomatal units will be placed together and allowed to interact to reproduce patchiness and a full, dynamic model of the leaf.

Conclusions


- Is the signal from the mesophyll to the guard cells a vapor-phase ion? Plant, Cell & Environment, 37(5), 1184-1191. doi:10.1111/j.1365-3040.2013.02329.x

References