

Unravelling the CO₂ Diffusion Pathway in C₃ Plants

H. N. C. Berghuijs¹, X. Yin¹, B. M. Nicolai², P. C. Struik¹

¹Wageningen University and Research Centre, Wageningen, The Netherlands

²Katholieke Universiteit Leuven, Leuven, Belgium

Abstract

Introduction:

Photosynthesis can be defined as the conversion of solar energy into chemical energy. In green plants, this applies to the conversion of CO₂ into organic compounds. The energy stored in these compounds can later be used to supply energy to run physical and chemical processes in plant cells. Since photosynthesis allows crops to maintain themselves and to grow, it is of great importance for agriculture to understand this process. The efficiency of CO₂ transport from the atmosphere to the sites where CO₂ is fixed depends on various CO₂ sources (normal respiration, photorespiration), CO₂ sinks (RuBP carboxylation), and physical intercellular (figure 1, left) and intracellular barriers (figure 1, right) for CO₂ diffusion along the diffusion pathway in mesophyll cells to the sites of fixation. Commonly, these constraints are lumped in a single, apparent parameter, called mesophyll conductance. However, this approach does not provide a mechanistic explanation on how various structures and processes affect CO₂ transport in the mesophyll. Therefore, we moved beyond these resistance models. In this study, we investigated how the location of photorespiration and normal respiration affects the leaf photosynthetic efficiency in C₃ plants.

Computational Methods:

Figure 2 shows the computational domain. The geometry consists of a gas phase (intercellular air) and a liquid phase (mesophyll cell) compartment. The liquid phase compartment is further subdivided into loose chloroplasts, surrounded by a cytosol layer. This cytosol layer is further subdivided into outer cytosol (facing gas phase), cytosol gap (between two chloroplasts), and inner cytosol. We used the COMSOL physics interface "Transport of Diluted Species" to solve a reaction-diffusion model over this geometry. Sources for CO₂ consisted of normal respiration and photorespiration in either the inner cytosol, the outer cytosol or both of these compartments. The CO₂ sinks consisted of RuBP carboxylation in the chloroplasts.

Results:

We solved the model for three scenarios (release of (photo)respired CO₂ in either the inner cytosol, the outer cytosol or both, figure 3). We up-scaled the local rates of CO₂ production and consumption to calculate net CO₂ assimilation rate of the whole leaf. The simulated net CO₂ assimilation rates described measured rates reasonably well (figure 4). We suspected that differences between the scenarios can be explained by the re-assimilation of (photo)respired CO₂.

Conclusions:

We developed a model to simulate CO₂ transport and assimilation in leaves by reaction-diffusion equations, rather than resistance models. Reaction-diffusion models are more flexible, which gives us additional opportunities to study the relationship between leaf anatomy and photosynthesis. As a case study, we used the model to show that the localization of (photo)respiration does affect the net CO₂ assimilation rate. In future research, we will use our model to quantify the fraction of (photo)respired CO₂ that is re-assimilated to see to what extent re-assimilation affects the photosynthetic efficiency of a leaf. We surmise that our model contributes to a better understanding of C₃ photosynthesis and, ultimately, to more efficient crop production.

Figures used in the abstract

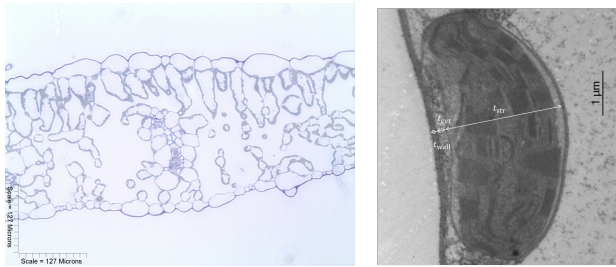


Figure 1: CO₂ can only enter the mesophyll cells at the exposed mesophyll surface (left). Once inside the mesophyll cell, CO₂ has to cross a number of barriers in mesophyll cells to reach the sites of fixation (right).

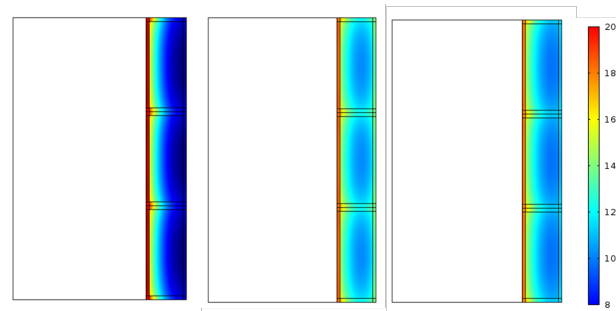


Figure 2: CO₂ partial pressure within mesophyll cells at ambient CO₂ levels and saturating light. The color bar displays partial pressures (Pa). Photorespired CO₂ is produced in either the inner cytosol (left, the outer cytosol (right) or both compartments (middle).

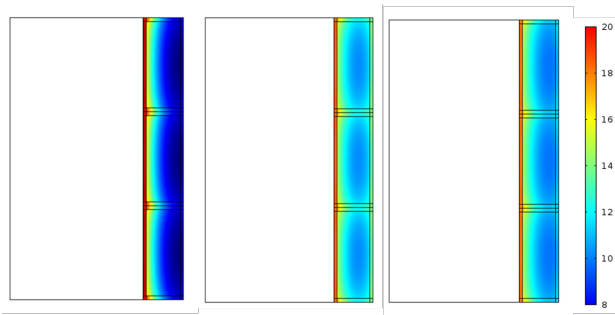


Figure 3: Geometrical model for mesophyll cell tissue

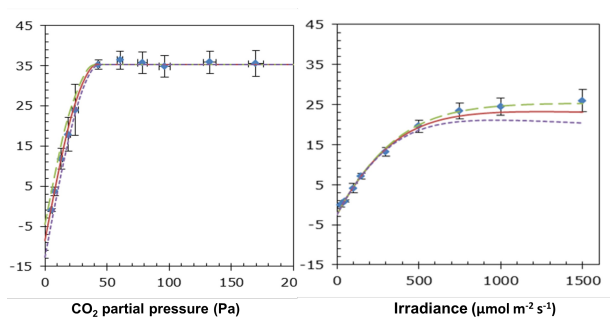


Figure 4: CO₂ response curve (left) and light response curve (right). (Photo)respiration takes either place in the inner cytosol (green dashed line), the outer cytosol (purple dotted line) or both these compartments (solid red line).