Systems Biology Research of Photosynthesis for Greater Crop Yields

Max Planck-CAS Research Group on Plant Systems Biology

Shanghai-Golm, 2008.8.8 – 2015.8.7

The Max Planck-CAS Research Group of Plant Systems Biology at the CAS-MPG Partner Institute for Computational Biology in March of 2014. First row from left to right: WANG Sisi, CAO Chensi, LV Mingzhu, WANG Shuyue, WANG Yu, WANG Yaling, CHEN Dairui; Second row from left to right: SONG Qingfeng, ZHENG Guangyong, Jeema Essemine, Saber Hamdani, XU Jiajia, LI Ming, ZHU Xinguang; The last row from left to right: XIN Changpeng, TAO Yimin, Johannes Hofberger, XIAO Yi.

Photos/Images: By courtesy of Prof. ZHU Xinguang.

Officially set up in 2008 by Dr. ZHU Xinguang at the Partner Institute for Computational Biology, the Plant Systems Biology Group focuses on systems biology research of photosynthesis with the goal of improving photosynthetic efficiency for greater crop yields. The group at MPG in cooperation with this team is the Systems Regulation Department led by Prof. Mark Stitt at the Max Planck Institute of Molecular Plant Physiology.

Reported by Group Leader ZHU Xinguang

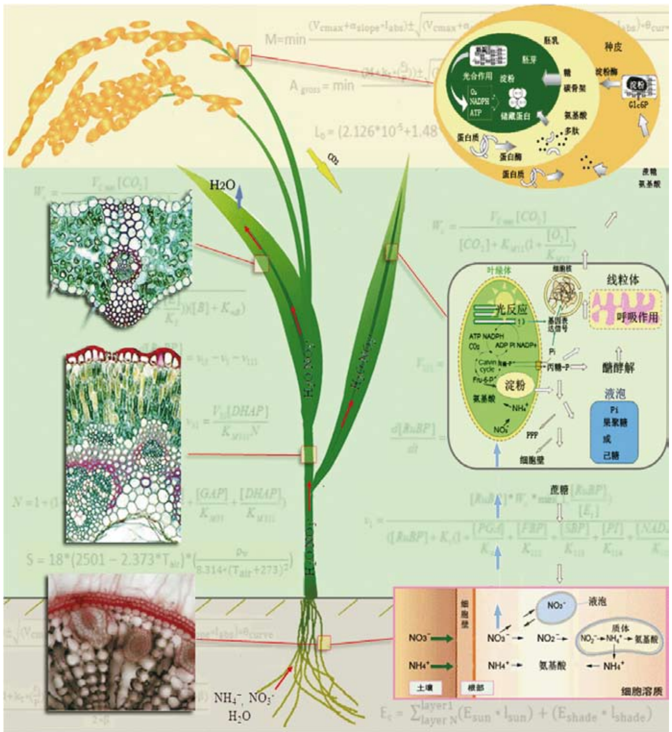

Figure 1: The ePlant model schematic. The overall ePlant model will include not only the plant primary metabolism (photosynthesis, respiration, nitrogen assimilation and H_2O uptake and transport processes), but also the major regulatory processes and the transport of materials among different organs. The ePlant model will play a key role in guiding the engineering of both food and energy crops to increase productivity.

Photosynthesis is the process by which plants utilize solar energy to convert CO_2 and H_2O into carbohydrates and release O_2. Via this process, plants serve as the ultimate source of all our food and fossil fuels, and have the potential to play a critical role in producing renewable energy and hence in mitigating global warming. Dr. ZHU Xinguang's group is focusing on developing next-generation computational models and algorithms to identify new approaches to improving photosynthesis, aiming to meet societal needs and to improve photosynthesis beyond the accomplishments of evolution. Specifically, Dr. Zhu's lab is working on two projects, representing two different approaches with the shared goal of engineering higher photosynthetic energy conversion efficiency, *i.e.*, optimizing existing C_3 photosynthetic systems (the ePlant project) and engineering C_4 photosynthetic pathway into C_3 crops (the C_4 rice project).

The overall goal of the ePlant project is to develop mechanistic models of C_3 plant primary metabolism (photosynthesis, respiration, nitrogen uptake and assimilation, nitrogen metabolism, and water movements through the plants from the soil to root, stem and leaf until its release into the atmosphere) and its regulation, and integrate these individual models into a functioning ePlant systems model (Figure 1). Once built, the e-Plant model will be used as a research platform to study systems properties of plant metabolic and regulatory processes, to study molecular mechanisms underlining the adaptation and evolution of plant traits (genetic, metabolic and structural properties related to productivity) under different environments, to identify new ways to engineer higher plant productivity. So far, Dr. ZHU's group has developed systems models at metabolism, leaf, and canopy scales for C_3 photosynthesis and revealed that decreasing leaf chlorophyll content can increase crop potential yields.

The goal of the C_4 Rice Project is to engineer the C_4 photosynthetic metabolism, which is more efficient than the C_3 photosynthetic metabolism, into rice, which performs C_3 photosynthesis. If successful, this engineering will simultaneously improve the nitrogen, water

"What I have experienced are the philosophy of Max Planck Society 'Knowledge must precede applications' and the long-term trust of MPG in their scientists. These two factors have contributed substantially to what I have achieved in the past few years."
— Prof. ZHU Xinguang

and light use efficiencies of modern rice cultivars. The major difference between C_3 and C_4 photosynthesis is that the C_4 photosynthesis has a CO_2 concentrating mechanism, which increases the CO_2 concentration around Rubisco and correspondingly suppressing photorespiration (*i.e.*, oxygenation) and increasing the net CO_2 fixation rate (*A*). The CO_2 concentrating mechanism depends on the cooperation between two specialized cell types, *i.e.*, the bundle sheath (BS) and mesophyll (M) cells. There are substantial amount of biochemical and anatomical differentiations between these two cell types. One major challenge in the C_4 Rice project is to identify what

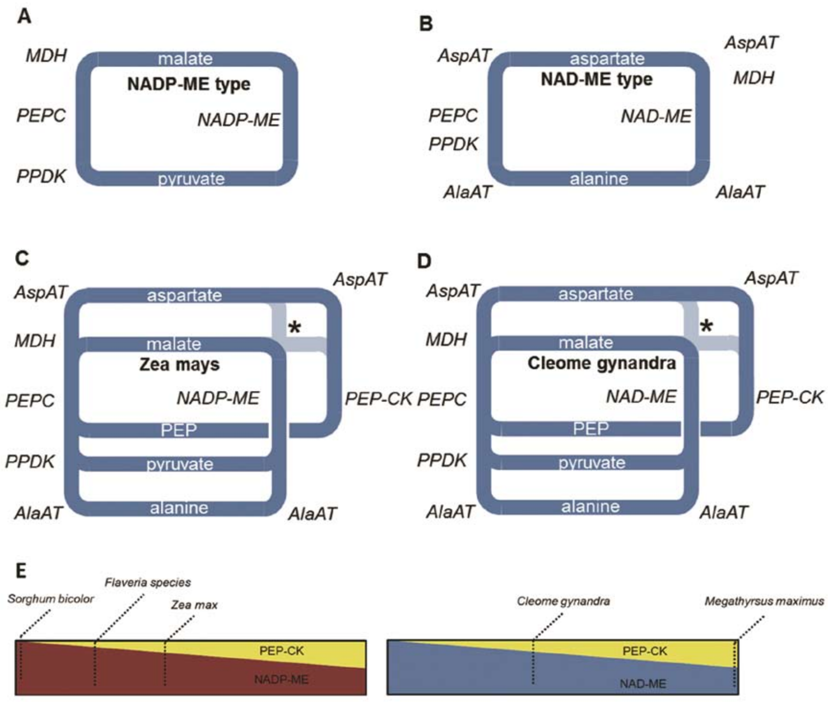

Figure 2: The textbook images (A and B) in comparison with the situation in the plant (C and D) for NADP-ME type, and NAD-ME sub-type C_4 photosynthesis, respectively. The proportions of different transfer acids probably vary with changing environmental conditions, for example light for malate reduction or nitrogen availability for amino acids as transfer acids. E) Contribution of PEPCK to malic enzyme activity in five different C_4 species. Figure cited from Wang *et al* (2014), *Journal of Experimental Botany* with author's permission.

biochemical and anatomical features are required to gain the high photosynthetic efficiency in C_4 plants; furthermore, what are the genetic controls over these different biochemical and anatomical features in C_4 leaves. Dr. ZHU's lab focuses on answering the first question. In the past few years, substantial progress was made in developing metabolic and reaction diffusion models of both C_3 and C_4 photosynthesis. Especially, the C_4 metabolism model developed by Dr. WANG Yu at ZHU's lab has been used to define the require biochemical features to run a C_4 photosynthesis. Dr. WANG's work further showed that triose phosphate transport is required to maintain a C_4 photosynthesis. His team's work, which was recently published in the *Plant Physiology*, led to a blueprint of the steps required to engineer C_4 rice.

Another major discovery from Dr. ZHU's lab on C_4 photosynthesis is that the traditional classification of C_4 photosynthesis is inappropriate. Traditionally, C_4 photosynthesis was classified into three sub-types, *i.e*. NADP-ME type, NAD-ME type and PEPCK type, dependent on the decarboxylation enzymes and also transfer acids used between bundle sheath and mesophyll cells. Together with Prof. Andreas Weber's group at the Heinrich Heine University of Düsseldorf, Dr. ZHU's lab found that C_4 photosynthesis should be classified into either NADP-ME or NAD-ME subtypes, given that the original PEPCK sub-types always accompany with either NADP-ME subtype or NAD-ME subtype, and cannot exist alone in nature (Figure 3). This work was recently published in the *Journal of Experimental Botany*. Joining hands with Prof. Mark Stitt, Dr. ZHU's group demonstrated that the C_4 photosynthesis, being a system which can cope with fluctuating light environments with a range of molecular mechanisms, is an ideal system to study the coordination of multicellular system. The work has been published in the *Plant Cell and Environment*.

In China, Dr. ZHU actively works with Chinese C_4 rice research communities to map out the Chinese National Programs of C_4 engineering as well as programs on developing systems models to support research aimed at rice yield improvements.

Dr. ZHU's group is recognized by colleagues around the world as a major hub on photosynthesis systems biology research. This is demonstrated by Dr. ZHU's leading role in a number of international research programs aimed at improving photosynthesis, including two prominent photosynthesis engineering projects funded by the Bill and Melinda Gates Foundation, *i.e*. both the C_4 rice project and also the RIPE project. Dr. ZHU also plays a leading role in developing systems biology models for crop yield improvements in Chinese national programs funded by the Minstry of Science and Technology of China and the Chinese Academy of Sciences. In recognition of Dr. ZHU's research achievements, he was awarded a number of national and international awards, in particular the 2013 "Melvin Calvin–Andrew Benson" Award by the International Society of Photosynthesis Research, which was granted once every three years to one scientist under age 40, on Jan 1st of the year of award to recognize outstanding investigations into the metabolic and cellular aspects of photosynthetic process. ◀