Quantifying Green Life: Grand Challenges in Plant Biophysics and Modeling

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Quantifying green life: grand challenges in plant biophysics and modeling

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Biophysics is best defined as a mindset than as a specific subject matter (Nobel, 1974; Phillips et al., 2008). The biophysicist strives to quantify biological processes and to analyze them in terms of universal physico-chemical principles such as mass conservation, force balance, and thermodynamic equilibrium. Biophysics has played an important role in the growth of biology, especially in elucidating how the folded structure of proteins determines their function (Anfinsen, 1973; Dobson, 2003), but also in providing a solid foundation for electro-physiology, photosynthesis, respiration, and many other basic biological functions. The lasting contributions of physicists-turned-biologists such as Max Delbrück (Luria and Delbrück, 1943; Delbrück, 1970) and Francis Crick (Watson and Crick, 1953; Crick, 1970) illustrate the power of the physical perspective in biology.

The scope of biophysical investigations in plants is vast. Photosynthesis makes plants both unique in their biology and indispensable for life on Earth. Most of the processes taking place within plants support, directly or indirectly, the central photosynthetic function of the chloroplasts. Plant biophysics can thus be thought of as a rigorous quantification of the processes associated with green life. The 400 million years elapsed since the movement of plants onto land have yielded a tremendous diversity of structures capable of lifting chlorophyll-bearing cells to more than 100 m into the air (Holbrook and Zwieniecki, 2008), of accessing water in arid conditions (Mooney et al., 1980), and even endowing plants with the ability to move with sufficient swiftness to catch insects (Forterre et al., 2005). Many of the problems that had to be solved to accomplish these feats are physical in nature. It is therefore to be expected that plant biophysics has had a long and illustrious history that dates back to the publication of Stephen Hales’ “Vegetable Staticks” in 1727. To these days, the steady publication of monographs on various aspects of plant biophysics is a testimony of the sustained appeal the field has had on quantitatively minded people (Clayton, 1965; Briggs, 1967; Slatyer, 1967; Nobel, 1974, 2005; Preston, 1974).

Several broad areas of research are likely to be the cornerstones of plant biophysics in the coming decade:

The problem of the structure–function relationship of proteins occupies a central place in biophysics. In and of itself, it reflects many of the subtleties involved in understanding how the information encoded in the genes contributes to the functions that support life at the cell level and above. Although the amino acid sequence, hence the primary structure, of a protein is plainly specified by the codon sequence of the gene, the detailed function of many proteins is not clearly seen until the tertiary structure of the polypeptide has been computed. This requires understanding in quantitative terms the electrostatic and steric interactions between different protein subdomains. Therefore, biophysics shows its importance from the very first step of the long causal sequence between the genes and plant functions. Yet, five decades after the formulation of the central dogma of molecular biology outlining the flow of information from the genes to proteins (Crick, 1958), computation of protein structures from first principles remains a daunting problem. The development of tools and new approaches to solve the structure–function relationship of proteins will undoubtedly continue to be an active area of research in coming years. Of particular interest for plants are the structure of photosystems I and II (Liu et al., 2004; Loll et al., 2005), of the various proteins involved in the assembly and modification of the cellulosic cell wall (Hrmova et al., 2002; Burton et al., 2006), and of cellulose itself (Nishiyama et al., 2002).

The use of light energy for the reduction of CO2 and, ultimately, its incorporation into organic molecules, i.e., photosynthesis, is the best recognized biophysical problem in plant biology; and for good reason since the conversion of light into chemical energy is one of the most striking feats achieved by living organisms. In particular, the oxygenic photosynthesis performed by plants has led to the most drastic atmospheric change that the planet has seen (Canfield, 2005; Knauth and Kennedy, 2009) and presents itself again as a central player to counter the warming effect of rising CO2 levels (Cox et al., 2000). Research efforts to understand photosynthesis resulted in several Nobel prices; yet we are just starting to comprehend this process well enough to tackle the fundamental trade-offs that have held photosynthetic efficiency to less than 5% of intercepted light energy for millions of years. Studies of carbon dioxide transport, membrane properties, light focusing, and protein interaction are just a few examples of biophysical research that could provide us with the tools to improve photosynthetic efficiency.

Another active area of biophysical research is the mechanism of plant cell expansion or plant growth in general. Some of the greatest challenges are to explain: (i) the dual role of the cellulosic wall in supporting the internal turgor pressure of the cell while, at the same time, allowing cell expansion (Geitmann and Ortega, 2009; Szymanski and Cosgrove, 2009); (ii) the feedback between growth and the flow of water across tissues to maintain osmotic equilibrium (Boyer and Silk, 2004); and (iii) the control of the direction of expansion in cells and plant organs (Baskin, 2005). Most plant cells grow in a highly anisotropic fashion, i.e., growth favors one direction over all others. The role of cellulose microfibrils in controlling the mechanical anisotropy of the wall was demonstrated many decades ago.
Biomimicking efforts lead to the construction of transport systems that may exceed 10 MPa, dwarfing the range of forces exerted by molecular motors. The role of structure and material properties in the maintenance of the transport capacity under tension remains an active area of biophysical research. Another important axis of research focuses on the exquisite control of the transpiration stream exerted by stomata. Yet, they show a significant degree of functional and structural integration. As plants do not have any designated information distribution network, the two transport systems that pervade the plant body must act in lieu of a nervous system. The biophysical principles behind the use of the vascular network as "information superhighway" and its possible role to coordinate response at the organismal level is still an open and fascinating area of research. Chemical transport, changes in tension and pressure, the sensing of pathogen attacks, and many other plant interactions with the external and internal environments result in systemic responses that use transport systems as the primary signal carrier with speeds often exceeding mass flow rates.

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way in promoting quantitative approaches in biology and quantitative skills among biologists. Schrödinger’s (1962) excitement that the study of life would yield new physical principles not yet explored in physics laboratories lives on within the field of biophysics.

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