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Mathematical and Experimental Investigation of Water Migration in Plant Xylem

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Abstract

Plant can take water from soil up to several metres high. However, the mechanism of how water rises against gravity is still controversially discussed despite a few mechanisms have been proposed. Also, there still lacks of a critical transportation model because of the diversity and complex xylem structure of plants.

This paper mainly focuses on the water transport process within xylem and a mathematical model is presented. With a simplified micro channel from xylem structure and the calculation using the model of water migration in xylem, this paper identified the relationship between various forces and water migration velocity. The velocity of water migration within the plant stem is considered as detail as possible using all major forces involved, and a full mathmetical model is proposed to calculate and predict the velocity of water migration in plants.

Using details of a specific plant, the velocity of water migration in the plant can be calculated, and then compared to the experimental result from Magnetic Resonance Imaging (MRI). The two results match perfectly to each other, indicating the accuracy of the mathematical model, thus the mathematical model should have brighter future in further applications.

Keywords: plant water migration, mathematical model, MRI, bionic

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1 Introduction

Scientists have been interested in the water migration within plants for over a century, and various theories were proposed to explain the mechanism. However, researchers start to focus on this interesting phenomenon again recently because of the development of bionic engineering[1–3]. As we know today, water transports in plants through the vascular system, xylem and phloem, from root to leaf. Xylem and phloem are formed by a brunch of dead-cell rings, in vast number of shapes, through evolution. Xylem is believed to be the conduit that moves water upward from root to leaf, while phloem is the one that moves nutrients, and the study of the relationship between plant and water is called Hydraulic Architecture (HA).

The idea of HA is believed to be firstly proposed by Zimmerman in 1978[4]. However, tree hydraulics is not a familiar research field for decades because it contains very complex mechanism with many influential parameters from its microscale inner structure. To analyse the water migration in detail, various forces need to be considered, such as gravity, resistance, Cohesion & Tension (C-T) theory, capillary effect, transpiration effect, root pressure and so on. In this paper, we simplify the xylem as a cylinder vessel without any water passing through conduit walls. Despite most researches so far that would simplify the conduit as smooth surface[5], we put drag force due to surface friction into consideration, and prove that friction force is not negligible. Then all forces are put into one water migration mathematic equation, with basic parameters that could be measured, so that the water transport velocity can be calculated, and compared with experimental measurements. All the

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analysis is based on woody plants after comparison, and a special type of woody plant, Salix Integra Flamingo, is chosen as an example in the calculation of mathematical model and experimental measurements.

As with experimental bionic study methods, most recent techniques studying plant functions are destructive, and could cause inaccuracy when cutting and making into samples. While MRI provides a unique method in measurement in situ without all the labours required in making samples, and could see real situations in live plants; and this become a great advantage of MRI over other techniques, and make MRI a key method in plant analysis[6–13], including metabolomics, structural analysis, *etc*. There has been some researches on water distribution in plants as well with MRI[14–18]. Structural researches are carried out using MRI in botany[19], such as the imaging of water distribution in vegetables[20,21], water distribution in seeds or roots[14,22], and water flow in plant stem[23,24]. While on the other hand, metabolomics researches with MRI focus on various functions inside plants, including growth condition, stress, infection, storage, water balance and so on.

MRI can also measure flow velocity besides water distribution. It is proved that linear flow can be measured when flowing in a magnetic field of MRI technique[25]. As when flowing, the nuclei inside experience a shift in magnetic field strength, and therefore causes change in Larmor equation as in Eq. (5)[26,27], and that could be told from the signals received by the machine. This method has been used in botany studies for several decades[24]. In this paper, we use MRI to measure the flow rate of water migration in xylem conduits.

2 Driving forces involved in water migration

2.1 Cohesion tension theory

Currently, it is mainly believed that the sap rising in plants should be explained by the C-T theory. It doesn't illustrate a novel force that drives the sap or water in plants upward, but instead explains how forces from different part of the plant can work together, as in the negative pressure and tension within water takes water up, while the cohesion force keeps water continuous.

The C-T theory is first proposed by Dixon and Joly in 1895[28], and then developed into modern forms[29]. According to it, there are a few previous assumptions for researches afterward. The liquid water in plant xylem system is considered as a continuous single phase flow, while the narrow conduit wall could enable evaporation from transpiration, but resist the entry of air at the same time, and water is closely contacted to the conduit wall because of the cohesion of water molecules and tension with the wall. Above all, the C-T theory allows forces to provide energy for water to move within xylem, using capillary effect, root pressure (osmosis effect), transpiration effect and friction.

2.2 Root pressure

Root pressure is also known as osmosis effect in plant researches. As water moves in the direction of a decreasing water potential, this effect generates a force along the decreasing water potential from pure water, soil, root, xylem, leaf to atmosphere. Mineral ions in soil can be absorbed by the root cells, which would cause the accumulation of ions on the other side of root cell membranes in the cells, with higher concentration comparing with soil environment outside. This would drive the water to flow into the root cells as well. While due to its limitation, it only accounts for the major water migration when transpiration effect is low, such as during the night. Root pressure is a main reason for guttation, as well as the absorption of minerals by root cells[30]. It would also contribute to the water refill in xylem, as some plants' xylem conduits are empty during winter, even though not always the case[31,32]. However, it is now considered as a positive but relatively unimportant force in water migration in xylem, instead of a major one. Therefore, it is not discussed and analysed in detail in this paper.

2.3 Capillary effect and gravity

Capillary effect and gravity are the two most frequently discussed forces in xylem studies. Most researches would consider a xylem conduit as one capillary tube, and analyse the two forces only. Capillary force generates from the inter-molecule forces between liquid and solid walls, which would be more significant when the size of tube is small enough, while on the other hand, gravity has no need to specify. We are putting the two forces together because they are already well studied and easy to present in mathematical model. Normally, the xylem system of plant is around 10 μm to 100 μm, even at the smallest size, the xylem structure can only lift the water up to 3 m using capillary effect only. It is a big contributing force in water migration, but not the most