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Electricity Derived from Plants

Mohammad Islam[1], Douglas Janssen[2], David Chao[3], Jerry Gu[2], David Eisen[1] and Fow-Sen Choa[1]

1. Department of CSEE, University of Maryland Baltimore County Baltimor 21250, Maryland, USA

2. Greater Grace Christian Academy, 6063 Moravia Park Drive, Baltimore 21206, Maryland, USA

3. Department of Biological Science, National Sun Yat-Sun University, Kao-shiun, Taiwan, ROC

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Abstract: The phenomenon of electrical potential differences along the plant apoplast has been reported for more than a century. Earlier works of harvesting energy from trees reported nW range of power with a few hundred-mV open circuit voltage and near uA range short circuit current. In this work, we show that if we cut a stem into pieces, each segment would maintain nearly the same open circuit voltage and short circuit current regardless of length. Using a pico-ampere meter, we also found that the living cells in the vascular cambial and secondary xylem and phloem tissues are the source of electricity. They provide a relatively constant voltage and current to external environment for reasons still under investigation. We demonstrate that by cascading separated stems we can accumulate up to 2 V of open circuit voltage. We also demonstrate by connecting them in parallel we can increase the short circuit current.

Key words: Plants, cell electricity, electrophysiology, ion gates, parallel circuits.

Nomenclature

VP	Variation potential
SP	System potential

1. Introduction

The phenomenon of electrical potential differences along the plant apoplast has been reported for more than a century [1]. Stimulus-induced extracellular electrical phenomena in plants consist of (a) transient AP (action potential) [2-5] and (b) more gradual or sometimes slow changes VP (variation potential) or some called SP (system potential) [6-10]. AP is usually considered to be "genuine" electrical signals, self-propagated through living cells such as the phloem [11-13]. In our earlier works we have demonstrated using mechanical, electrical, and optical signals to close a *Venus flytrap* [14, 15]. As a well known scheme for plants to catch insects, a flytrap will close its two lobes when its trigger hairs are stimulated twice within 20 seconds. We found that each time a trigger hair is stimulated, an electrical pulse will be generated and it does not matter whether the stimulation is mechanical, electrical, optical [14, 15]. It clearly shows that plants utilize electrical signals to increase the speed of communication and motor cell control. By the same token, SP, as simply an accumulated bio-potential difference between points along the body of a plant, has also been utilized by plant to monitor and communicate information about its own environment and health. It has been reported in a variety of plant species in response to various stimuli, including light [16], gravistimulation [17], wounding [18-24], osmotic stress and irrigation [25, 26], localized increase in xylem pressure [22], and communicating with insects [27].

2. The System Voltage of Plants

To understand the characteristics of SP, we have conducted the following initial studies. Fig. 1a shows a simple wild plant, which can be easily found in a home backyard in many northeast states of North America.

Corresponding author: Mohammad Islam, M.Sc., research field: optics.

(a) (b)

Fig. 1 Picture of the plant used in the experiment. (a): before the wound; (b): after it is wounded.

Fig. 1b shows the wounded plant that experienced burning to one of its leaves twice.

A multi-meter with RS232 communication to a PC is used to record the bio-potential. The negative probe is connected to the silver spot on one of the leaves, where a silver-filled epoxy was applied. The positive probe of the meter is connected to the bottom part of the stem close to the soil with another silver epoxy application. The wounded leaf is located between the two contact points.

Fig. 2 shows the voltage signal measured between the two contact points. The generated bio-potential change is larger than 300 mV. Fig. 2a shows the measured bio-potential with/without external stimulations, which include adding water to the plant, fire burn, and illuminating with UV. As illustrated in the figure, incidents of adding water to the pot and burn of leaves with fire all cause noticeable bio-potential changes.

It should be noted that the effects of UV illumination on voltage are difficult to measure. Present work is focusing on development of a low-cost, high-sensitivity current measurement technique by which we can observe the effect of UV illuminations to the plant. Fig. 2b shows the recorded signal with a second fire burn to the same leaf. Again, a noticeable signal is observed. One shall notice that if the wounded leaf is located outside the path between the two contact points like, e.g. above the top contact point, no electrical signal change can be observed.

We have also measured many other plants and they all showed very similar results but the amplitude of the measured SP and the wound generated electrical potential changes varied for different plants. Fig. 3 shows some measurements done on a trunk of a maple wood. One electrode contacted the soil the other electrode is inserted into the tree branch. Small branches at 3 locations were cut or burn to observe the

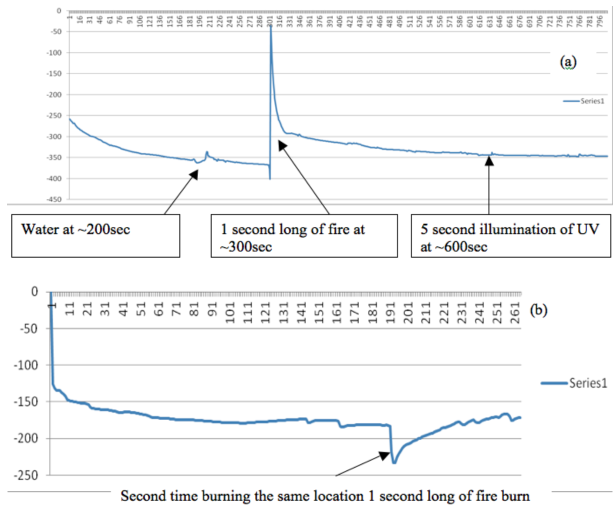


Fig. 2 Recorded results of bio-potential measurement for (a) adding water, first fire burn, and UV illumination; (b) second fire burn at the same location.

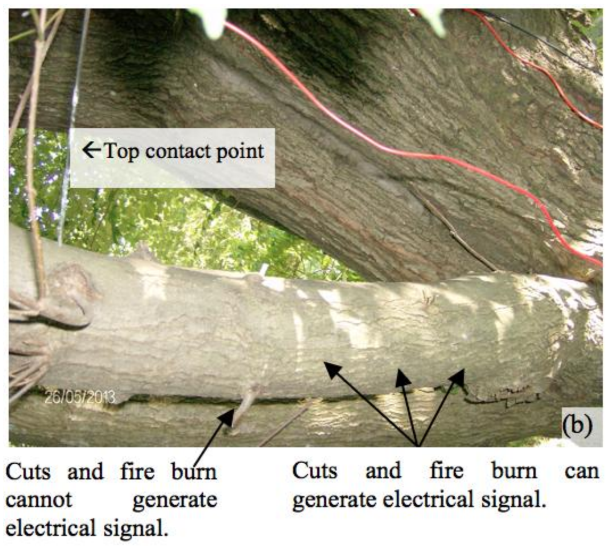


Fig. 3 Measurements are done on a branch of a maple wood. One electrode is connected to the soil as the ground. The other (red wire) electrode is connected to a metal probe, which is inserted into the tree branch.

potential change. Each cutting or burning contributes a small amount of potential changes and the measured total bio-potential change was from ~336 mV to ~325 mV.

Apparently, larger trees are less sensitive to wounding/damage. The experiment result further showed that for another small branch that is likely to be outside the sap flow path leads to the top electrode, a fire burn or cut cannot produce any signal even that branch is thicker than that of all 3 other above mentioned branches. Apparently in these wound generation cases sap flows may play an important role in electrical signal generation [28]. A more comprehensive circuit model will be described later.

3. Cell-Based Plant Electricity

With the observation that smaller plants can be more sensitive to external stimulation, we were attracted to the idea that if we cut a section of a plant maybe we can still obtain some part of the system potential useful for detection of stimuli. We found, to our surprise, that after we cut out a segment from a tree branch, roughly the same amount terminal voltage was still measured on each one of the two separated sections. The amount of voltage did not show evidence of being reduced and in several cases, it even increased. Even more surprising is that if we further subdivide each plant branch section, each new and successively smaller piece seems to be able to reproduce nearly the same amount of terminal voltage. We continuously cut them to smaller and shorter pieces and each new piece can provide around 200-300 mV maximum voltage if their two contacts are somehow adjusted to “ideal positions”, though at this moment we do not fully understand what the “ideal positions” are, which will be studied and understood in this continuing work. Investigations are currently focused on connecting electrical probes to both ends of a certain sap flow pathway, and plotting these results with successively more distant pathways.

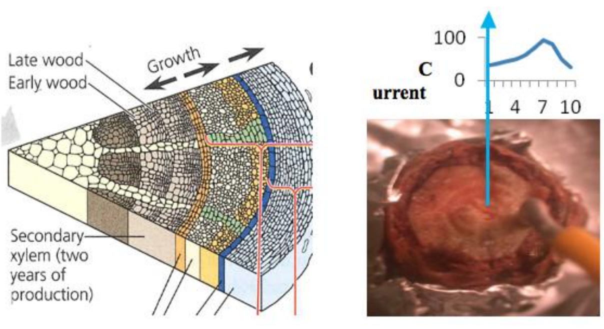
To understand the source of this bio-electricity, we cut a slice of pine trunk as shown in Fig. 4b. We pasted one side of the disk with silver epoxy and covered it with alumina foil to form an electrode. We then measure the generated short circuit current with a silver coated probe and a Keithley 6487 pico-ampere meter (Keithley Inst., Cleveland, OH), capable of obtaining 1,000 low-current readings per second. System voltages were obtained using electrodes positioned at specific target locations in each plant sample, and recorded using a high input-impedance digital multi-meter computer interface (Kaito Electronics Inc., California).

We found that the maximum current was coming from close to the vascular cambium belt area, as shown in Fig. 4a. The measured short circuit current is mapped along the radius from center to the perimeter of the circle as shown in Fig. 4b.

From the current plot, it seems that the source of the bio-electricity is generated from living cells close to the vascular cambium and secondary xylem and phloem areas. The rest of the dead cell areas (first xylem and phloem areas) are producing voltage or current mainly because leakage current is flowing through these dead cell areas due to their high-water content, although these areas can produce current by themselves through capillary effect when they are still inside a living tree.

4. Circuit Model

Plant bio-potential may be modeled as a Norton



(a) (b)

Fig. 4 (a) The cross section of plant structure; (b) A cross section of a pine tree disc with one side contacted with silver epoxy and aluminum foil and the other side contacted with silver coated probe. Inset shows the generated current profile as a function of distance from the center to the edge of vascular tissue.

equivalent power source with an ideal current source in parallel with a resistor as shown in Fig. 5. As described above, the living cells are the sources of the electricity. When the segment is inside a living plant, the xylem and phloem can behave like current sources through capillary effect-produced ion flows. However, for dissected segments, the flows are cut off and only passive resistance banks are modeled into the full system to account for wet leaky paths that remain.

In either case, all the sources and resistors can be converted to a single Norton equivalent source and parallel resistor. The measured short circuit current is typically in the range of a few tens to a few hundreds of nA. The equivalent parallel resistor is large and estimated to be in the range of a few to a few tens of MOhms. Thus, we determine, if the measurement tool input impedance is not high enough, the measured output voltage will suffer significant reduction in amplitude.

5. Serially-Connected Voltage Sources

Short circuit current and open-circuit voltage was observed to increase when sections were connected in series (Fig. 6). Probe placement and connection is critical for serially-connected plant sections, and resulting output is on the order of 100's mV increase for multi-section, serially-connected groups in comparison to individual sections, for all woody and herbaceous plant varieties included in our testing.

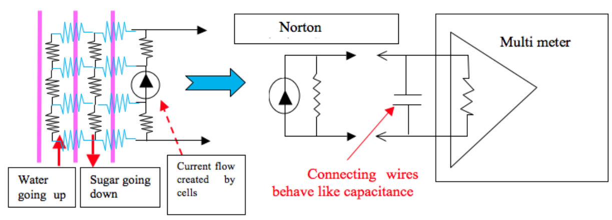


Fig. 5 The equivalent circuit diagram of the plant potential generator and the input circuit of the multi-meter.

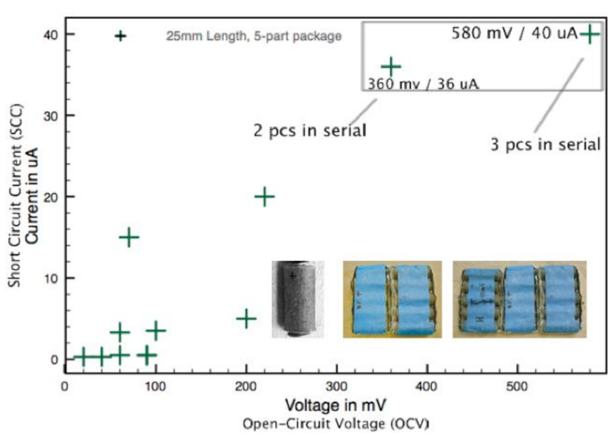


Fig. 6 Open-circuit voltage in hundreds mV was observed for plant sections connected in series.

6. Voltage Sources Connected in Parallel

For plant sections connected in parallel, we observed little increase in open-circuit voltage, on the order of only 10's mV per 25 mm × 10 mm cylindrical section added to a set. This may result from unstable probe connections or possibly from leakage or competing pathways within the vascular tissue. These results indicate that it may be more advantageous to connect plant vascular tissue sections in series.

7. Additional Considerations

A question raised during our experiments was whether the system potential could be affected by light incident on the plant tissue. For preliminary testing, we chose laser light sources with wavelengths of 820 nanometers and 1,200 nanometers. System voltage measurements were obtained from branch sections of *Acer negundo* while illuminated with continuous-wave laser light (Fig. 7) from the sources, in succession. A small rise in system voltage was measured for both

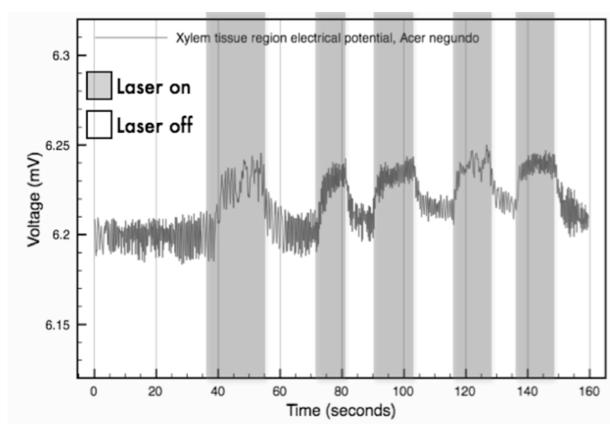


Fig. 7 System voltage derived from probes placed in xylem tissue region of 11 mm diameter branch section of *Acer negundo*, showing response to near-IR (820 nm) CW laser illumination.

types of illumination. Further investigation is needed to determine the true reason for this phenomenon.

8. Conclusions

Our study concentrated on the study of localized electrophysiological phenomena in a variety of herbaceous and woody plant stems and branches. Probes placed in plant vascular tissue confirmed presence of electrical potential and identified polarity of plant tissue as a function of growth direction. Some woody branch sections exhibited the same voltage output even after halving or quartering the overall length of the original section, for reasons not yet understood. We then established a basic map of internal resistance present in xylem tissue.

Open circuit voltages of up to 350 mV were observed from small woody branch segments. When assembled according to polarity in packs of multiples, and connected in serial or parallel arrangements, these plant sections have the potential to supply electrical current on the order of tens of microamperes.

Our preliminary study seems to suggest that obtaining electricity from plants holds promise as a sustainable, alternative energy source warranting further investigation.

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