TELKOMNIKA, Vol. 11, No. 8, August 2013, pp. 4841~4846
e-ISSN: 2087-278X

Bioelectricity in Standing Trees-A Potential Energy for Wireless Sensor Networks

Zhibin Hao, Wenbin Li*, Jiangming Kan, Liyuan Jiang, Chao Feng
School of Technology, Beijing Forestry University, Beijing 100083, China
*Corresponding author, e-mail: leewb@bjfu.edu.cn

Abstract

It has been observed that there are sustained electrical potential difference and current between a tree trunk and its surrounding soil, which have bright application prospects for powering wireless sensor networks in forests. But the mechanism of the bioelectricity has remained controversial. In order to provide more comprehensive data for further researches and to analyze the relationship between the bioelectricity in tree trunks and their surrounding environmental parameters, an experiment has been made. The output power of selected trees, xylem pH, as well as the environmental parameters such as air temperature, air relative humidity, soil temperature, soil moisture and soil pH were measured. Results supported the hypothesis that bioelectricity in xylem has a significant relativity with soil pH. Moreover, it was found that air relative humidity, soil temperature and material of electrode affected the bioelectricity in the xylem.

Keywords: *bioelectricity, standing tree, wireless sensor networks, xylem, soil pH*

Copyright © 2013 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction

Recent researches have showed that there are sustained electrical potential difference and current between a tree and its surrounding soil while the mechanism of the bioelectricity has remained controversial [1]. It has great potential in powering the low-power devices in forests [2], especially to the wireless sensor networks for the lack of perfect power supply. Therefore, exploring the characteristics and mechanism has a large necessity. Many hypotheses and experiment schemes have been proposed [3-5] because the bioelectricity has been detected in different parts of the trees [6-8].

A large portion of researchers have paid attention to the xylem where sustained electrical potentials were detected by a metal electrode. Most of them have assumed that the electrical potentials were due to transpiration and sap flow [3, 5, 9]. The xylem has capability of transporting water and ions including K^+ [10], H^+, Na^+ [11] and Ca^{2+} [12]. The ions in the sap flow attach to the electrode inserted into the xylem, which probably generate the electrical potentials between the electrode and surrounding soil. But a recent research has found that only a few potential was attributed to the sap flow, whereas, the pH difference between xylem and soil had a clear relationship with the voltages measured from a potted *ficus benjamina* tree [1].

However, the output power of trees may be a more significant physical quantity to reflect the magnitude of the bioelectricity compared with the voltage or the current separately. In order to find more comprehensive relationships between the bioelectricity in trees and their surrounding environmental parameters, an experiment was made in different regions and in the natural environment. In the experiment, output power of selected trees, xylem pH, as well as the environmental parameters were measured. The environmental parameters contained air temperature, air relative humidity, soil temperature, soil moisture and soil pH.

2. Research Method

2.1. Experiment Regions and Tree Species

Four experiment regions located in four cities respectively were selected, including Yinchuan, Hangzhou, Liuzhou and Beijing with different kinds of soil and climates. The

Received March 23, 2013; Revised May 28, 2013; Accepted June 6, 2013

experiment was divided into two sub-experiments, named *E1* and *E2* respectively. *E1* was made in Yinchuan, Hangzhou and Liuzhou in summer and lasted 19 days. Yinchuan is in the west of China, having alkaline soil and dry climate in summer. Hangzhou is in east-central China, having neutral soil and wet climate in summer. Liuzhou is in the south of China, having acidic soil and very wet climate in summer. The purpose of the sub-experiment in above three regions was to obtain comprehensive data in different growth conditions for further researches. *E2* was made in Beijing in the early winter and lasted 20 days. Beijing is in the northeast of China, having alkalescent soil and dry climate in early winter. A large number of trees and measurements were selected and made in *E2* to analyze the relationship between the bioelectricity in trees and their surrounding environmental parameters. In each experiment region, several healthy trees were selected randomly (Table 1).

Table 1. Experiment Regions and Tree Species

Experiment region	Tree number	Tree specie
Yinchuan	1	Populus tomentosa Carr
Yinchuan	2	Salix babylonica
Yinchuan	3	Ulmus pumila L.
Yinchuan	4	Populus tomentosa Carr
Yinchuan	5	Populus tomentosa Carr
Yinchuan	6	Populus tomentosa Carr
Yinchuan	7	Sophora japonica L.
Hangzhou	1	Chinese sweet gum
Hangzhou	2	Chinese sweet gum
Hangzhou	3	Salix babylonica
Hangzhou	4	Salix babylonica
Hangzhou	5	Populus euramevicana cv.
Hangzhou	6	Populus euramevicana cv.
Liuzhou	1	Micheliamacclurel
Liuzhou	2	Micheliamacclurel
Liuzhou	3	Schima spp.
Liuzhou	4	Pinus massoniana Lamb
Liuzhou	5	Cunninghamialanceolata
Beijing	1	Platanus acrifolia
Beijing	2	Platanus acrifolia
Beijing	3	Platanus occidentalis Linn.
Beijing	4	Platanus occidentalis Linn.
Beijing	5	Populus canadensis Moench
Beijing	6	Populus canadensis Moench
Beijing	7	Fraxinus chinensis
Beijing	8	Fraxinus chinensis
Beijing	9	Eucommia ulmoides
Beijing	10	Eucommia ulmoides
Beijing	11	Koelreuteria pdepthaniculata
Beijing	12	Koelreuteria paniculata
Beijing	13	ginkgo
Beijing	14	ginkgo
Beijing	15	Pinus tabuliformis
Beijing	16	Pinus tabuliformis
Beijing	17	Sabinachinensis (Linn.) Ant.
Beijing	18	Sabinachinensis (Linn.) Ant.
Beijing	19	Pinus bungeana Zucc.
Beijing	20	Pinus bungeana Zucc.

2.2. Power

Three ferric electrodes (5mm diameter) were inserted into the xylem at different heights (50cm, 100cm, and 130cm) of each selected tree. Another electrode was planted into the adjacent soil (15cm under the earth). Fixed-length wires were connected to the electrodes. A load resistance was joined into the circuit between the electrode in the tree and the electrode in the ground through the wires. The voltage and current of the load resistance were measured at the same time by same multimeters (FLUKE 17B, FLUKE, America). The power was calculated after each measurement.

In *E1*, the electrode in soil was replaced by negative terminal of the multimeter, which was connected to soil at the corresponding depth directly. The terminal was made of cuprum. In

E2, the same ferric electrode was used. The purpose was to observe the influence of electrode material to the experiment.

2.3. Xylem pH

Xylem samples were collected from each selected tree and stored in plastic bags for several days. The xylem pH was measured in accordance with standard GB/T 6043-1999.

2.4. Environmental Parameters

Air temperature and air relative humidity were measured by JWSK-SC Temperature & Humidity Meter (ColliHigh, China). The probe of JWSK-SC hung free until display was stable and the data was recorded. Soil moisture was measured by SK-100 Multi-purpose Moisture Meter (SK, Japan). Soil temperature and soil pH were measured by HI 99121 pH & Temperature Meter (HANNA, Italy). The probes of SK-100 and HI 99121 were planted into soil simultaneously until displays were stable and the data was recorded. The HI 99121 was calibrated by pH 7.01 buffer solution (HI 7007, HANNA, Italy) before each individual measurement.

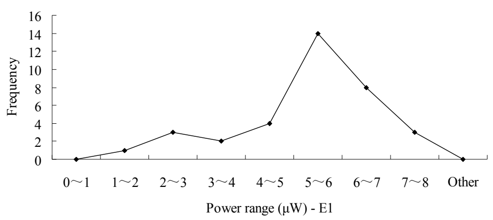
3. Results and Analysis

3.1. Power Distribution

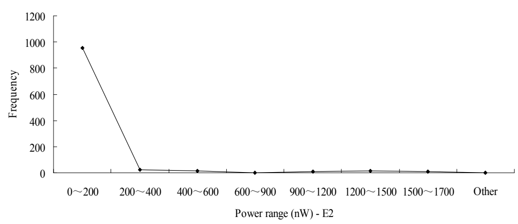
Thirty-five groups of data were obtained in *E1*, and one thousand and twenty-six groups of data were obtained in *E2*.

Figure 1 shows the value distributions of power obtained in *E1* and *E2*. X-axis is the power ranges which have a close-interval on the left and an open-interval on the right. Y-axis is the frequency of power in each range. In A, the 35 groups of data were obtained in Yinchuan, Hangzhou and Liuzhou in summer. The electrode in soil was the negative terminal of the multimeter. Most of the power values were in the range from 5μW to 6μW. In B, the 1026 groups of data were measured in Beijing in early winter, in which the peak fell in the range from 0nW to 200nW.

It is obvious that the power values in *E1* were larger than those in *E2*, which suggests that the magnitude of bioelectricity in trees probably fluctuates with changes of electrode in soil. To exclude the possibility of seasonal influence, a counter-experiment was made in *E2*. Using negative terminal of the multimeter to replace the electrode in soil, larger power values were observed while they were still less than those in *E1*. Seasonal change may be another influential factor, but not significant in our experiment.



(a)



(b)

Figure 1. Power Distribution

3.2. Different Heights

Some relevant literatures have observed that there is no change in the voltage difference between the xylem and soil with the changing position of electrodes in xylem [1, 3]. However, the power was greatly influenced by the height of electrodes in our experiment. But no precise relationship was found.

Three heights (50cm, 100cm, and 130cm) were selected in each tree in our experiment, where same electrodes were inserted into the xylem separately. Three power values were obtained in different heights in each individual tree. Figure 2 shows the comparison of power values among the three heights. *D (100-50)* is the set of power differences between the height 100cm and 50cm in all trees. Similarly, *D (100-130)* is the set of power differences between the height 100cm and 130cm in all trees. All data used were measured in Beijing. X-axis is the ranges of *D (100-50)* or *D (100-130)* which have a close-interval on the left and an open-interval on the right. The coordinate intervals selected are not uniform, but convenient to understand the comparison. Y-axis is the accumulative percent of the data numbers in each interval. In A, at the interval (0.1, 1], the percentage barely gets 50%, which indicates that in over half of the measurements the power values at the height 100cm were larger than those at 50cm. In B, similarly, at the interval (-0.1, 0], the percentage reaches 50.29%, which means that in majority of the measurements the power values at the height 130cm were larger than those at 100cm. Figure 2 suggests that larger power values were observed at the height 130cm in most of the measurements.

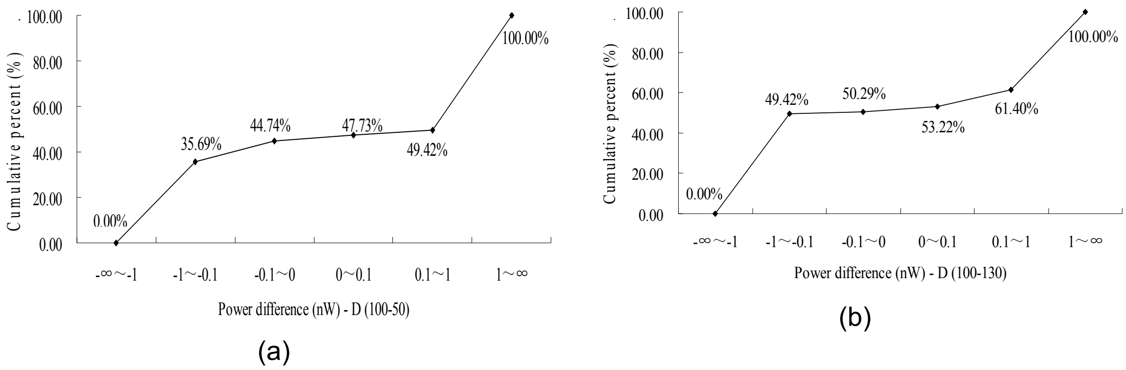


Figure 2. Comparison of Power Values among Different Heights

Table 2 shows the variances of power values at different heights.It is obvious that the variance of power values obtained at 130cm was the minimum, which suggests that individual differences of power values are more inconspicuous at 130cm than those at other heights.

Table 2. Variance of Power Values at Different Heights.

Electrode height (cm)	Variance of power (nW^2)
50	231.8
100	316.4
130	24.5

3.3. Environmental Parameters

It was found that the values of xylem pH had little changes while those of soil pH varied with experiment region changes. Although the xylem pH in each experiment region had a fluctuation, the averages were all around 6 (Figure 3). The soil pH (diamonds) shows that soil samples measured in Yinchuan, Hangzhou and Liuzhou were alkaline, approximate neutral and acidic respectively. But the averages of xylem pH (squares) were around 6 in all experiment regions. The same value has been obtained from the xylem of a potted ficus benjamina tree in Christopher's experiments [1]. The consistent value may be due to the resistance of plants. An exact relationship between the bioelectricity magnitude and the pH difference between xylem and soil has been observed. A similar hypothesis was postulated in our experiment due to the consistent value of xylem pH: there is a significant relationship between the bioelectricity magnitude and soil pH.

Considering above analyses, seventeen groups of data (tree 14, 130cm, Beijing, Figure 4) were selected to find the relationship between the bioelectricity in trees (xylem) and their surrounding environmental parameters. The data were measured at one-day intervals over a seventeen-day period.

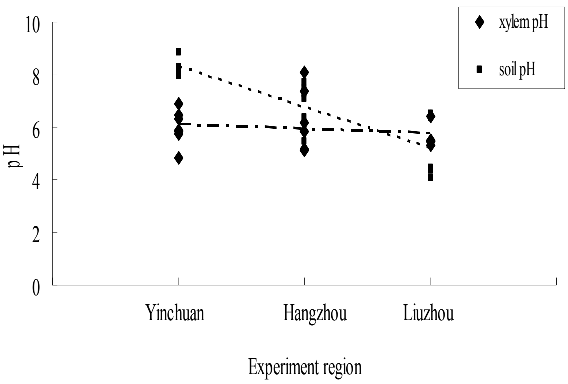


Figure 3. Xylem pH and Soil pH

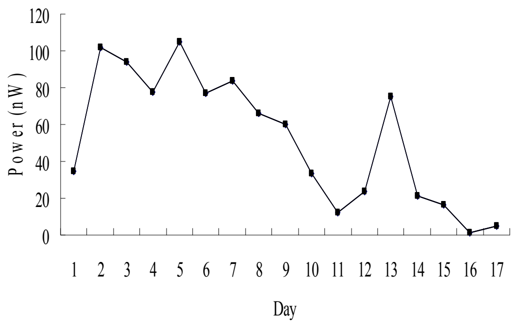


Figure 4. Power Curve

It was found that there was a significant correlation between the power measured in the xylem and the pH of surrounding soil (Table 3). Moreover, air relative humidity and soil temperature had significant influences on power, although the correlation coefficients were smaller. The symbol ** means that correlation is significant at the 0.01 level (2-tailed). The symbol * means that correlation is significant at the 0.05 level (2-tailed).

Table 3. Correlations

Model	Power	Soil pH	Air temperature	Air relative humidity	Soil temperature	Soil moisture
Pearson Correlation	1	0.873**	0.213	-0.491*	0.628**	0.215
Sig. (2-tailed)		<0.001	0.412	0.045	0.007	0.406

Table 4 shows the result of regression analysis among power, soil pH, soil temperature and air relative humidity. The dependent variable was power. The independent variables were soil pH, soil temperature and air relative humidity. An equation of linear regression was given:

$$P = 196.699Sp + 15.055St - 0.714Arh - 1475.803 \quad (1)$$

P is the power. *Sp* is the soil pH. *St* is the soil temperature. *Arh* is the air relative humidity. R^2 is 0.861.

Table 4. Regression Analysis

Model	Unstandardized Coefficients	Standardized Coefficients	t	Sig.
Constant	-1475.803		-3.721	0.003
Soil pH	196.699	0.542	2.826	0.003
Soil temperature	15.055	0.385	-2.292	0.014
Air relative humidity	-0.714	-0.298	3.593	0.039

4. Conclusion

In relevant literatures, the voltage difference was measured and used to analyze the mechanism of the bioelectricity in trees. In our experiment, the voltage on the load resistance and the current in the circuit were measured simultaneously in each individual measurement. In all analyses related to the bioelectricity, the parameter power was used. But the measurement of the power needs a close-circuit which leads to the power consumption. Considering reducing the consumption on wires and precision of the current measurement, a 12KΩ load resistance was selected.

It has been observed that there is a clear relationship between the voltage and the pH difference between xylem and soil, which closely follows the Nernst equation [1]. A consistent value of xylem pH was found in our experiment. Therefore, the pH difference between xylem and soil was replaced by soil pH approximatively in our analyses. The result indicated that the power measured in xylem has a significant correlation with soil pH, which partly supported the hypothesis of Christopher J. Love, Shuguang Zhang and Andreas Mershin. Moreover, soil temperature and air relative humidity also had a relationship with power magnitude in our experiment. The positive correlation between power and soil temperature suggests the rise of soil temperature leads to an increase of power. A warm temperature probably promotes the exchange of electric charge between soil and the electrode in soil. The negative correlation between power and air relative humidity may be due to the inhibition to transportation of electric charge by moisture in the air.

The material of electrode in soil greatly influenced the magnitude of power in our experiment. More experiments should be done to observe the relationship between power obtained from trees and electrode material. The seasonal change may be another influence on the power values measured in the experiment. The physiological characteristics of trees in winter possibly restrain the transportation and exchange of electric charge. But the conclusion remains to be further researched.

No clear correlation between the power and electrode height was found in our experiment. But the values at the height 130cm showed a greater stabilization than others. More detailed experimentation should be done to find the optimum position where more electric energy can be obtained for application.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 31170669).

References

[1] Christopher J Love, Shuguang Zhang, Andreas Mershin. Source of sustained voltage difference between the xylem of a potted Ficus benjamina tree and its soil. *PLoS ONE.* 2008; 3(8): e2963.
[2] Carlton Himes, Eric Carlson, Ryan J Ricchiuti, David W Taylor, Brian Otis, Babak A Parviz. Using plants for directly powering nanoelectronic circuits. *Nanotechnology Perceptions*. 2010; 6: 29-40.
[3] Dominique Gibert, Jean-Louis Le Mouel, Luc Lambs, Florence Nicollin, Frederic Perrier. Sap Flow and Daily Electrical Potential Variations in a Tree Trunk. *Plant Science*. 2006; 171: 572–584.
[4] William Gensler, Tai lai Yan. Investigation of the Causative Reactant of the Apoplast Electropotentials of Plants. *Journal of the Electrochemical Society*. 1988; 135(12): 2991-2995.
[5] Anthony Labady Jr, D'Jahna Thomas, T atiana Shvetsova, Alexander G Volkov. Plant bioelectrochemistry: effects of CCCP on electrical signaling in soybean. *Bioelectrochemistry*. 2002; 57(1): 47-53.
[6] John P Wright, Donald B Fisher. Measurement of the Sieve Tube Membrane Potential. *Plant Physiology*. 1981; 67(4): 845-848.
[7] Lars H Wegner, Ulrich Zimmermann. Simultaneous recording of xylem pressure and trans-root potential in roots of intact glycophytes using a novel xylem pressure probe technique. *Plant, cell and environment*. 1998; 21(9): 849-865.
[8] O Ksenzhek, S Petrova, M Kolodyazhny. Electrical Properties of Plant Tissues: Resistance of a Maize Leaf. *Bulgarian Journal of Plant Physiology*. 2004; 30: 61-67.
[9] András Koppán, András Fenyvesi, László Szarka, Viktor Wesztergom. Measurement of electric potential difference on trees. *Acta Biologica Szegediensis.* 2002; 46(3-4): 37-38.
[10] Lars H Wegner, Ulrich Zimmermann. On-line measurements of K^+ activity in the tensile water of the xylem conduit of higher plants. *The Plant Journal*. 2002; 32: 409-417.
[11] AH DeBoer, V Volkov. Logistics of water and salt transport through the plant: structure and functioning of the xylem. *Plant, Cell, and Environment.* 2003; 26: 87-101.
[12] Silke Lautner, Thorsten Erhard Edgar Grams, Rainer Matyssek, Jörg Fromm. Characteristics of electrical signals in poplar and responses in photosynthesis. *Plant Physiology*. 2005; 138: 2200-2209.