A COMPARISON BETWEEN LEAF DIELECTRIC PROPERTIES OF STRESSED AND UNSTRESSED TOMATO PLANTS

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ABSTRACT

Leaf dielectric properties influence microwave scattering from a vegetation canopy. The dielectric properties of leaves are primarily a function of leaf water content. Understanding the effect of water stress on leaf dielectric properties will give insight in how plant dynamics change as a result of water stress, and how radar can be used for early water stress detection over agricultural canopies.

This paper presents *in-vivo* measurements of leaf dielectric properties. Different relationships between leaf water content and leaf dielectric properties were found tomato leaves at various heights. The dielectric properties of live stressed and unstressed tomato plants were measured during a controlled, two-week experiment. A clear difference was found between the leaf dielectric properties of stressed and unstressed leaves, which can be attributed to increase in water stress.

This results of this study show changes in plant dynamics due to water stress lead to a difference in leaf dielectric properties between stressed and unstressed plants.

Index Terms— Dielectric constant, water stress, tomato, microwaves, radar

1. INTRODUCTION

This paper presents observations of leaf dielectric properties of stressed and unstressed tomato plants in the field. The vegetation dielectric properties are a crucial factor that determine the interaction of a canopy with electromagnetic waves. Dielectric properties of individual vegetation components (e.g., leaves, branches, stems, fruit) are therefore an important driver of the impact of vegetation on microwave emission and scattering.

Vegetation dielectric properties depend on e.g., salinity and temperature [1], [2], but are primarily a function of water content [1]. Recent studies have shown that microwave scattering at various frequencies, polarizations and incidence angles, radar backscatter from forest [3] and maize [4] canopies is mainly sensitive to leaf water content, especially during times of water stress. However, behavior of leaf dielectric properties in response to changes in leaf water content and water stress is still poorly understood. This is mainly caused by the lack of *in-vivo* measurements of the dielectric properties [3], [5].

Previous studies have investigated the dielectric properties of vegetation, see for example [1], [2], [5]. However, this has mainly been done using destructive sampling or *in-vivo* on tree trunks [6], [7], but not on leaves. *In-vivo* measurements of leaf dielectric properties should give insight in the effect of changing leaf water content and water stress on leaf dielectric properties. Leaf water content is related to the amount of water present in the soil. However, this relation can be different for various types of crops [8], [9].

A recent paper [4] showed that the leaf water content of maize can change up to 40% between morning and evening at the onset of water stress. This significantly influences the leaf dielectric properties [10]. Detailed *in-vivo* measurements of the leaf dielectric properties will give insight in response of dynamics of different plant species to water stress, allowing further study of how water stress affects radar backscatter.

During a two-week experiment, leaves of both a stressed and unstressed tomato plant were measured throughout per day. Water stress was induced by switching off water supply for one row of tomato plants, while irrigation continued for the other. The goals of this study are to (1) determine the relationship between the sensor response and leaf moisture content, and (2) identify the effects of water stress on leaf dielectric properties of tomato plants.

2. METHODS

2.1. Study site and plant material

The experiment for this study was conducted in the greenhouses at the Wageningen University and Research Center Glastuinbouw, located in Bleiswijk, Zuid-Holland, the Netherlands. Measurements were conducted from November 10 to 22, 2014. All measurements were done on tomato plants (*Solanum lycopersicum*, Tomimaru Muchoo), sown on May 1, 2014 and planted on June 20, 2014 in rockwool. After the emergence of the 8th cluster of fruit, the head of the plant was cut to prevent further growth. Measurements were done in the mature stage of the plant, when all fruits were fully developed. Temperature, relative humidity, CO_2 concentration, and irrigation was all regulated throughout the cultivation of the plants. Each tomato plant had an individual drip irrigation nozzle.

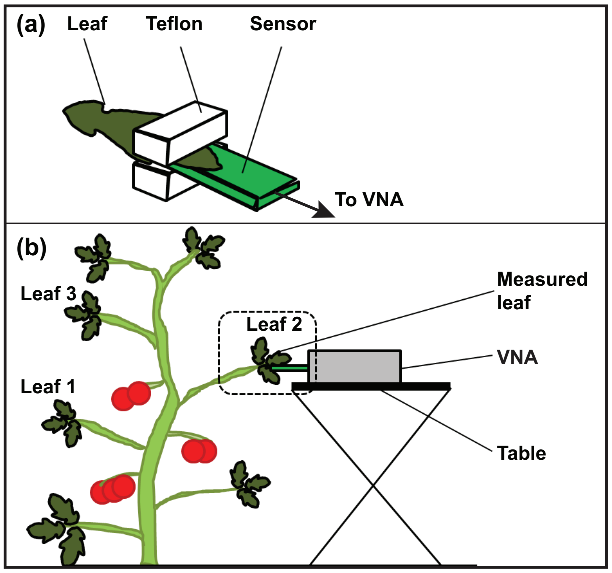

Fig. 1: (a) 3D schematic of the sensor setup for a measurement, (b) measurement set-up. Note that the leaves are numbered from the bottom upwards.

2.2. Dielectric properties measurements

All measurements were done using a microstrip line resonator. The microstrip line resonator was attached to a ZVH8 Cable and Antenna Analyzer (ZVH8, 100 kHz to 8 GHz, Rohde & Schwarz, München, Germany) with the K42 Vector Network Analysis and K40 Remote Control options. For each measurement, the magnitude (dB) of the reflection coefficient S11, which depends on the dielectric constant of the sample, was measured at 1201 frequencies from 2.1 to 4.1 GHz. The resonant frequency is the frequency at which the magnitude of S11 is at a minimum. Because of the dominant influence of moisture content on the leaf dielectric constant, the resonant frequency of the sensor can be related to leaf moisture content. To keep the leaf in place and to provide a stable background signal, one 1 cm thick Teflon block is placed under the sensor and a second block on top of the leaf, see Fig. 1a. The shift in resonant frequency and change in width and depth of the dip is associated with the change in leaf dielectric properties. As a leaf dries out, the difference in resonant frequency between the leaf and the Teflon block, expressed as Δf_r decreases. A high value of Δf_r corresponds to a high value of the dielectric constant, and a low Δf_r corresponds to a low dielectric constant. Therefore, variations in Δf_r can be considered as a proxy for variations in leaf dielectric constant. We express all dielectric properties measurements in terms of Δf_r [GHz]. For more details see Van Emmerik *et al.* [10].

2.3. Calibration experiment

The relationship between Δf_r and leaf gravimetric moisture content M_g depends strongly on the species. A calibration experiment was performed to establish the relationship between the M_g and Δf_r for the measured tomato plants. This was done by taking dielectric measurements of a drying leaf. First one measurement was done when the tomato leaf was attached to the plant. Then, the leaf was cut, measured, weighed, air-dried and measured again. This was repeated for 12 values of M_g. After a dielectric measurement, the leaf was weighed to determine the fresh mass. Finally, the leaf was dried in an oven at 70 °C for 24 hours and weighed again to determine the dry mass. The gravimetric moisture content was calculated using [2]:

$$M_g = \frac{M_w - M_d}{M_w} \tag{1}$$

where M_w and M_d are the fresh and dried leaf weights.

2.4. Dielectric properties time series

For one row of plants, all irrigation nozzles were removed on November 10, 2014 at 9 A.M. For the other row, irrigation continued throughout the experiment. *In-vivo* measurements were taken five times per day (7 A.M., 9 A.M., 11 A.M., 1 P.M., 3 P.M.). At the same time, volumetric moisture content was determined by taking the mean value of 3 measurements along the row. From 10 to 15 November the dielectric properties of an individual irrigated and non-irrigated plant were measured. From 17 to 22 November, another individual irrigated and non-irrigated plant were measured. For every plant, three leaves at different heights were measured, see Fig. 1b. The time series were tested on the presence or absence or trends by calculating Spearman's correlation coefficient [11]. For the two separate weeks, the correlation coefficient was determined of both the stressed and unstressed time series. A trend was considered present if the confidence level was higher than 80%.

3. RESULTS AND DISCUSSION

3.1. Calibration experiment

Fig. 2 presents the results of the calibration experiment for leaf 1, 2 and 3. For every leaf, a different relationship was

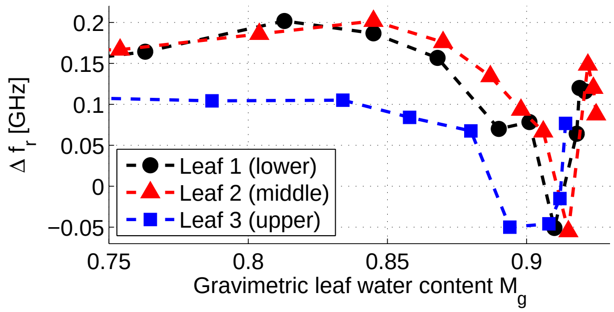

Fig. 2: Relationship between M_g and Δf_r for three leaves: the lower leaf 1 (black circles), the middle leaf 2 (red triangles) and the upper leaf 3 (blue squares).

found between leaf moisture content M_g and Δf_r. Leaf 1 and 2 have a similar relationship, but leaf 3 shows that Δf_r is generally lower. Δf_r first decreases with decreasing water content. If the leaf water content drops below 0.92, the resonant frequency increases steeply. For leaf water content below 0.75, Δf_r is insensitive to changes in M_g. In the case of tomato leaves, the relation between M_g and Δf_r is ambiguous, since the same Δf_r values were measured for two different M_g values.

3.2. Soil moisture

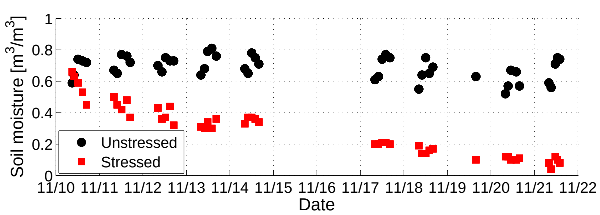

Fig. 3: Volumetric soil moisture measured at the irrigated (black squares) and non-irrigated (red dots) tomato plants.

Fig. 3 presents the soil moisture measured at the irrigated and non-irrigated tomato plants. The soil moisture measurements showed a clear difference between the irrigated and non-irrigated plants. On average, the soil moisture was 0.75 for the irrigated row. Soil moisture at the non-irrigated row dropped directly after irrigated was withheld. After two weeks, soil moisture was lower than 0.1.

3.3. Leaf dielectric properties time series

Fig. 4 (a)-(c) show the leaf water content M_g for leaves 1 to 3. For both the stressed and unstressed plants, M_g appears stable over time. In the second week M_g of the stressed plant is visibly lower than for the unstressed plant. In Table 1 it can be seen that for the stressed plants, all leaves showed a

Table 1: Confidence boundaries for the presence or absence of trends in resonant frequency difference between leaf and Teflon Δf_r and leaf gravimetric moisture content M_g for the stressed and unstressed tomato plants, calculated using Spearman's Rank Coefficient. Positive and negative signs indicate an increasing or decreasing trend, respectively. A (-) indicates no trend was observed. Confidence boundaries were tested for the complete period (November 10 - 21), and for the first (November 10 - 15) and second week (November 16 - 21) seperately.

Leaf No.	Stressed		Unstressed	
	Δf_r	M_g	Δf_r	M_g
	November 10 - 21 (complete period)			
1	0.99	-0.99	0.86	-0.82
2	0.83	-0.97	-	-0.87
3	0.98	-0.98	-	-
	November 10 - 15 (1st week)			
1	-	-	-	-
2	0.84	-	-	-0.84
3	-	-	-	-
	November 16 - 21 (2nd week)			
1	-	-	-0.84	-
2	0.98	-	-	-
3	0.99	-	-0.98	-

strong decreasing trend. The unstressed plant showed a weak decreasing trend in leaves 1 and 2.

Fig. 4 (d)-(f) shows the difference in resonant frequency between leaf and Teflon Δf_r for leaves 1 to 3. All stressed leaves show an increasing trend in Δf_r. For the unstressed plant, only the first leaf shows a weak increasing trend (Table 1). In the first week the values of the stressed and unstressed plant are similar and no trend was observed in both the irrigated and non-irrigated plant. The rockwool contained sufficient water for root water uptake by the non-irrigated plant.

In the second week Δf_r of the stressed and unstressed leaves diverge. Δf_r of stressed leaves is higher than the unstressed leaves, and also strong increasing trends were observed in leaves 2 and 3, while for the unstressed plants only decreasing trends were found for leaves 1 and 3. The calibration (Fig. 2) showed that for Δf_r below 0.85, an increasing Δf_r corresponds to a drier leaf. From November 11 to 22, Δf_r is higher for the stressed leaves than for the unstressed, indicating a lower leaf water content. This is consistent with the lower measured M_g for stressed leaves. From the measurements it is clear that water stress leads to different dynamics in the leaves. Both M_g and Δf_r in the stressed leaves show different trends than the unstressed plants.

Note that the measurements took place in mid-November, during days on which the incoming radiation was around 10 % of typical summer values. Also, the plants were restraint

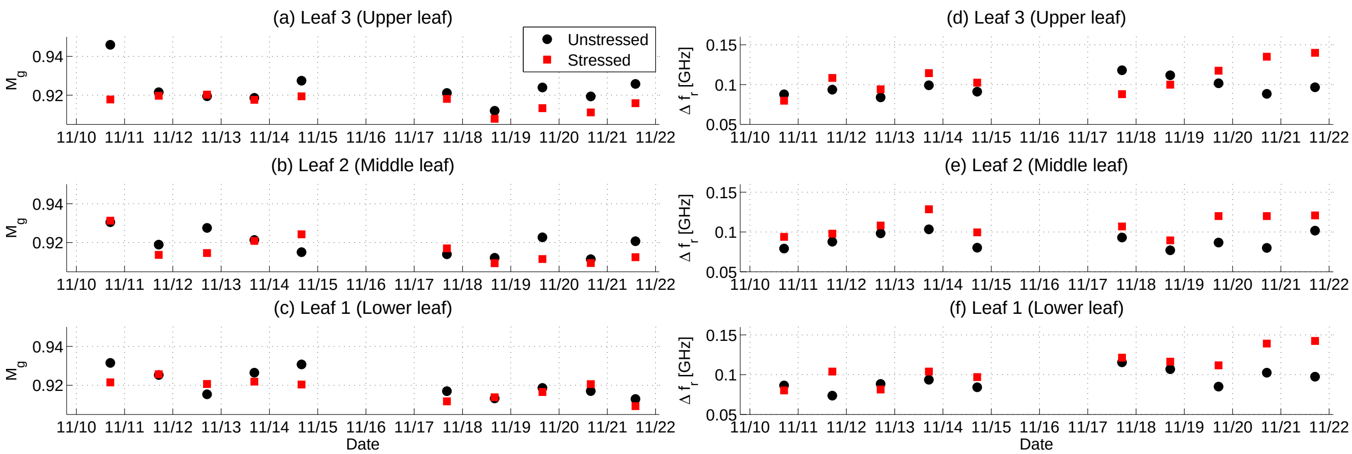

Fig. 4: Gravimetric leaf moisture content M_g of (a) leaf 3 (upper leaf), (b) leaf 2 (middle leaf) and (c) leaf 1 (lower leaf), and the difference in resonant frequency between leaf and Teflon Δf_r of (d) leaf 3 (upper leaf), (e) leaf 2 (middle leaf) and (f) leaf 1 (lower leaf). M_g and Δf_r of the unstressed plants are shown as black dots, the stressed plants as red squares.

from growing further and all fruits were developed. The photosynthetic activity was therefore most likely very low, leading to low transpiration, and hence water loss rates. Even during these times of low plant activity a difference in Δf_r was found. In case a similar experiment would be done in the vegetative or early reproductive stage (fruits are developing), the effects of water stress would probably be noticable not only earlier, but also to a greater extent.

4. CONCLUSIONS

Measurements using a microstrip line resonator were used to show that the dielectric properties of tomato leaves are affected by (mild) water stress.

Considerably different trends in leaf water content M_g and Δf_r were observed for stressed and unstressed tomato plants, suggesting a similar difference in leaf dielectric constant. This shows that the impact of water stress on plant dynamics results in dynamics in leaf dielectric properties.

This study shows a difference in dielectric properties between irrigated and non-irrigated tomato plants as a result of water stress. With this paper, we aim to contribute to the development of a better understanding of the relation between water stress, leaf water content, and leaf dielectric properties.

5. ACKNOWLEDGEMENTS

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