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Microwave backscatter response of pecan tree canopy samples for estimation of pecan yield in situ using terrestrial radar

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ABSTRACT

Accurate estimates of pecan yield prior to harvest are critically important for marketing and production management decisions such as nut thinning, irrigating and nutrition supplementing. Current methods of estimating pecan yield in situ are not sufficiently accurate and are time consuming. Research using satellite based microwave imaging has enabled scientists to identify trends in orchard crop condition but precision is inadequate for yield sensing. Ground based radar schemes using antenna within the orchard resolve many of the power, resolution and sensitivity limitations of satellite radar imagery. The objective of this research is to determine if pecan nuts can be quantified in situ using backscattered microwaves from antenna located in the orchard. Pecan tree canopy samples (leaves and secondary branches) and nuts were collected at five growth stages and placed in a polystyrene foam test fixture located between horn antennae spaced 1 m apart. Reflection and transmission measurements were recorded with a vector network analyzer at frequencies from 1 to 18 GHz while the amount of nuts were varied from 0% to approximately 30% of the canopy mass. Regression analysis revealed no specific frequencies to quantify nut mass however response to total canopy water and dry mass over a wide range of frequencies had $R^2 > 0.63$ and 0.78 respectively. This relationship combined with range finding and appropriate crop model algorithms may ultimately be the basis for developing pecan yield monitoring technology.

1. Introduction

Accurate estimates of pecans in an orchard prior to harvest are critically important for both production management decisions and marketing. Current methods of estimating pecan yield in situ include empirically derived formulas and sampling techniques where a subset of nuts are visually counted in the orchard (Wright et al., 1990). These methods are not sufficiently accurate nor do they provide cost effective yield information on a per tree basis that is needed for precision agriculture applications. Technological innovations to improve the accuracy and/or speed of infield pecan estimates will have direct benefit to producers, processors and marketers. Precision agricultural practices, including in situ yield estimates, have been applied successfully to a variety of field crops and pecans represent a similar opportunity (Lee et al., 2010). Furthermore, if successful in pecans, the technology has potential for extension to other orchard fruit and nut crops.

Microwaves can penetrate vegetation and thus may be appropriate for yield monitoring of pecan. Satellite based radar images of vegetation consist of a composite of backscattered electromagnetic energy. Some energy is directly reflected back to the receiver by leaves, stalks/stems or soil while a portion undergoes multiple reflections before returning. Early investigations of vegetation by backscattered microwaves used models that assumed the vegetative layer was a cloud of absorbing material over the soil surface (Ulaby et al., 1984). Refinements have been incorporated into microwave backscatter models for forest canopies that include reflections from leaf, branch, trunk, and soil layers (de Jong and Herben, 2004; Ulaby et al., 1990). In these models, the trunk is represented as a single vertical cylinder while branches commonly take the form of semi-randomly oriented cylinders of various sizes. Individual thin disks or a cloud of material can represent leaves. In general, leaves and small branches result in isotropic reflections and the trunk and primary branches have directional reflections. Imagery from satellite synthetic aperture radar (SAR) investigations has shown the ability to provide canopy level information correlating with density of stems and leaves, leaf area and understory canopy type (Imhoff, 1995; Kovacs et al., 2008). Detecting differences in the nut content at the tree or orchard level with satellite based radar remains well beyond the sensitivity and resolution of current technology.

The dielectric properties, or permittivity, of a material determine how the electric field of an electromagnetic wave interacts with it. The dielectric constant (K) of a material is the ratio of the material's permittivity over the permittivity of free space. Water has a very high K, usually given as 80 at 1 GHz. Free space, by

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definition, has a dielectric constant of one. Materials containing water generally have a high *K*. The *K* of a leaf increases as it takes on water and decreases as it dries out (Shrestha et al., 2007). Solutions containing sugars, ions and lipids have unique *K* values. As the concentration of these changes over time, the electromagnetic response of the plant changes. The state of water in a tissue also influences *K*. Water can exist in a free state or it can be chemically bound in tissues. Each tissue in a plant has its own electromagnetic signature that is dependent on its chemical makeup, structure, quantity and state of water.

Mature pecan nuts, like many seeds, are high in lipids and have a lower *K* value than leaves and stems (Nelson, 1991; Nelson et al., 1992). The developing pecan nut expands to near its full size early in development, called the "water stage", where it is dominated by a large central vacuole filled with an aqueous solution containing elemental ions and sugars. The edible embryo and cotyledons of the pecan develop and expand to fill the liquid filled void (Wells and Wood, 2008). Thus, the dielectric properties of the developing nut change as it matures. Likewise, as nutrients are diverted from other tree tissues to the developing kernel, there may be sensible changes in canopy dielectric properties necessitating different models to predict pecan load throughout the season. Accurate yield estimates at the water stage are important because fruit thinning decisions are generally made at this time before significant plant resources are diverted to development of the kernel.

Short range, terrestrial backscattered microwaves can resolve many of the resolution and sensitivity limitations of satellite radar imagery. Radar receiver signal power is inversely proportional to the distance from the receiver to the target raised to the fourth power. By placing the transmitter/receiver closer to the target, higher received signal strengths, and thus, increased sensitivity, are attainable. Another related advantage that close proximity of the antenna to the pecan tree provides is that reflections from the far side of the tree are much further from the antenna relative to reflections from the front side. Reflected signals from the backside will be weaker by the ratio of distances to the fourth power.

Lower frequencies tend to be preferred on satellite-based radars because the reflected power of short wavelengths is lower unless the target is tuned to specific wavelengths. In most cases, satellites have limited power available; a problem that ground based systems can generally overcome. Another advantage of dedicated ground based radar is that imagery can be taken when needed from orientations not dictated by set satellite orbits. Imaging of the pecan canopy could use horizontal or upward looking radar, which removes reflections from the soil in the returned signal. All models that use satellite imagery must account for the confounding effects of reflections from the ground. Ground reflections are influenced by soil moisture from rainfall and irrigation, vegetation cover and soil conditions.

McDonald et al. (1991) investigated microwave backscatter response of a walnut orchard to ground based X band (9.6 GHz) radar. The configuration used in the experiments of McDonald et al. employed a boom-mounted antenna pointed towards the ground at an angle of 35–50°. Diurnal water response of the tree was detectable with their configuration. Their antenna also received reflections from the soil but the effects were less influential than in satellite systems because of the proximity of the antenna to the tree canopy and ground resulted in less interference with canopy backscatter. This study illustrated the ability to detect relatively minor physiological differences in a tree with short-range ground based radar.

The ability of microwave energy to penetrate through vegetation has enabled satellite-based radars to identify trends in orchard crop condition but precision is inadequate for pecan yield sensing. Short-range ground based radars resolve many of the power, resolution and sensitivity limitations of satellite radar imagery and are a potential technology for estimation of pecan nut yield. The objective of this research is to determine if pecan nut mass can be quantified in situ using backscattered microwaves from horizontally aimed antenna located in the orchard. The specific experimental objectives of this study were to obtain baseline empirical microwave backscatter response of pecan tree canopy samples in a laboratory setting and identify spectral features that may allow quantification of nuts in situ. This information will assist in specifying radar systems and experiments for future research efforts.

2. Materials and methods

2.1. Plant materials

Pecan nuts and canopy samples were collected from the Oklahoma State University Cimarron Valley Research Station near Perkins, OK. The orchard contained 26-year-old 'Maramec' trees on 'Apache' seedling rootstocks in a Teller sandy loam soil (fine-loamy, mixed, active, thermic Udic Argiustoll). Trees were diagonally spaced 24.4 by 24.4 m with Bermudagrass [*Cynodon dactylon* (L.) Pers.] ground cover. A 3 m wide vegetation-free area was maintained the entire row length with herbicides. Natural rainfall of 51.9 cm from January through October 2011 was supplemented by traveling gun irrigation. Mean daily temperatures were 4.0 °C above average during June through August 2011. Commercial management for pests and fertilization were used. Diammonium phosphate and urea were each applied in a band application at rate of 482 kg ha^{-1} in March of 2011. Specimens were collected periodically from water stage through harvest to determine the effects of ontogeny on electromagnetic properties. On each collection date canopy samples from three trees, randomly selected at the start of the study, were cut where the branch diameter reached approximately 2 cm. Samples were taken from trees approximately 2–4 m above the ground. Additional nuts were collected from the same trees to supplement nuts in the canopy samples. Plant materials were immediately placed over ice in coolers until tested.

2.2. Vector network analyzer measurements

Microwave response to the pecan canopy samples was observed at the Biosystems and Agricultural Engineering Sensor lab at Oklahoma State University in Stillwater, Oklahoma. Microwave reflection and transmission measurements of test samples in various configurations were taken using a vector network analyzer (VNA) (model N5230A PNA-L, Agilent, Santa Clara, CA) attached to double-ridged waveguide horn antennae (model 3117, ETS-Lindgren, Cedar Park, TX). The antenna supported a frequency range of 1–18 GHz. The antennae were mounted vertically facing each other 1 m apart in a PVC frame with a midlevel specimen support shelf (Fig. 1). Port 1 of the VNA was connected to the bottom antenna. To minimize reflections from the tile covered concrete floor a microwave absorbent panel 61 by 61 cm was positioned under the antenna set (model C-RAM LF-79, Cuming Microwave, Avon, MA). The VNA was calibrated with a SOLT (short-open-load-through) procedure prior to taking measurements on pecan canopy samples. This procedure consisted of sequentially connecting a short circuit, open circuit and matched load to each of the VNA ports to calibrate reflection response. After this, the antennae were connected to the VNA ports to calibrate the transmission response in empty space. Temperatures were between 21 and 23 °C for all tests.

For each configuration tested, the magnitude of scattering matrix parameters S11, S22, S21 and phase of S21 were collected. Scattering matrix parameters S11 and S22 were used for statistical analysis of backscattered microwaves for nut detection. Through