Species-Specific Prediction Model of Wood Moisture Content Based on Electromagnetic Wave Propagation Time

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Laboratory and field experiments were performed to examine the feasibility of using Time Domain Reflectometry (TDR) to monitor moisture content (MC) of wood and standing trees. The TDR was used to detect the electromagnetic wave propagation time of four tree species (*Betula platyphylla*, *Tilia tuan*, *Picea asperata*, and *Fraxinus mandshurica*) at different MCs. During the TDR test, effects of probe insertion depths on MC predictive accuracy were considered. The best results were obtained at an insertion depth of 8 cm. At the selective 8 cm insertion depth, a species-specific MC prediction model ($0.94 \leq R^2 \leq 0.98$), a generalized model for the four species ($R^2 = 0.65$), and a hybrid model for the species with similar densities ($0.80 \leq R^2 \leq 0.96$) were constructed, respectively. Overall, the species-specific MC prediction model showed good predictive ability for both tree and wood disc samples, including that TDR can be used to detect wood and standing tree MC. If possible, the hybrid model can be used for species with similar density.

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INTRODUCTION

Time Domain Reflectometry (TDR) is an electronic measurement technique that measures electrical parameters such as the dielectric constant and resistivity of a medium by measuring the propagation time of an electromagnetic pulse (Hernández-Santana *et al*. 2008; Schimleck *et al*. 2011; Dahlen *et al*. 2015). As a new detection technology, TDR, has been widely applied in soil MC testing. Because the bulk permittivity of a composite material (*e.g*., a porous medium) is a composite average of the permittivity of the components in the composite, it is usually simulated by a dielectric mixing model. Water, however, has a high dielectric constant, much higher than that of the other soil components, so soil MC can be measured by the reflected signal of the TDR input transmission line pulse signal (Jones *et al*. 2002).

Theoretically, TDR can be applied to monitor MC in any porous material, such as a standing tree (Dahlen *et al.* 2015). A standing tree can be regarded as a three-phase inhomogeneous system of wood-water-air, and at room temperature the dielectric constant of water (80) is much higher than that of dry wood (2 to 6) and air (1), making the TDR also suited for measuring MC in trees (Ishida *et al.* 1959; Schimleck *et al.* 2011).

Researchers have been working to determine the feasibility of the TDR for detecting MC in standing trees. In 1996, Wullschleger *et al.* used TDR equipment to monitor the MC of a total of 160 sample trees of several hardwood species over a long period of time. They established a general calibration equation for MC *versus* dielectric constant, where $R^2 = 0.89$ (Gao *et al.* 2019; He *et al.* 2021). Schimleck *et al.* (2011) investigated the effect of irrigation and other storage or environmental factors on MC of wet-stored logs using TDR equipment to continuously monitor wet-stored logs, demonstrating that TDR can accurately respond to changes in MC. While each of these studies showed potential for TDR as a means of measuring MC in standing trees, it should be noted that probe length can have an impact on the results in different experiments. In most studies, the probe length of the TDR equipment ranged from 2 to 20 cm) (Xu and Wang 2014). Probe length affects the effectiveness of the detection, with long probes resulting in signal attenuation and short probes resulting in lower signal resolution (Guo *et al.* 2023; He *et al.* 2021; Jones *et al.* 2002; Schimleck *et al.* 2011). In order to accurately use TDR to detect trunk MC, a probe of at least 10 cm needs to be used. However, TDR probe lengths can be limited by trunk diameter, and long probes are difficult to insert into the trunk. Existing calibration equations may not apply if measurements are made with short probes (Gao *et al.* 2019). Therefore, in order to implement TDR as a basis for monitoring standing trees MC, it was first necessary to determine what probe length is the most conducive for predicting MC and carry out a calibration study (Castiglione *et al.* 2006).

The aim of this study was to attempt to establish a species-specific MC prediction model to accurately monitor standing trees MC in real time using TDR, on the basis of analyzing effects of different probes insertion depths and MCs on the test results, which may provide data support for estimating the MC of all tree species.

EXPERIMENTAL

Materials

Four tree species, *Betula platyphylla*, *Tilia tuan*, *Picea asperata*, and *Fraxinus mandshurica* were used in this study. All samples were obtained from Yichun City, Heilongjiang Province, China. Standing trees with a diameter at breast height of 120 to 160 mm were selected from sample plots of an artificial forest aged 30 to 50 years, 25 trees of each species. Then, for each tree species, five wood disks with a thickness of 50 mm at breast diameter were selected for indoor experiments, and the rest of the standing trees were used for outdoor experiments.

Methods

Fresh wood discs were stored in a refrigerator at -5 °C, from which all samples of one species were taken at a time for the experiment. Firstly, the disc samples were taken and placed in a cool place to thaw for 24 h. Wood samples were hydrated in a saturation tank for one month prior to the start of the experiment. Following saturation, wood sample weight was measured. Then, two small holes with a depth of 120 mm were drilled at the middle height of the disk using an electric drill, with the diameter (3.5 mm) and spacing (30 mm) of the holes matching the diameter and spacing of the two probes of TDR, and probe orientation was parallel to the grain. The TDR equipment used for the experiment was a CS616 moisture sensor (double probe, 30 cm long) and CR800 data collector (Fig.1). Once the holes were drilled, the double probe was inserted, the insertion depth was increased sequentially (4, 6, 8, 10, and 12 cm), and the first waveform readings were taken at each insertion depth. The samples were then allowed to dry naturally and weighed every 12 h. When the sample mass was reduced to less than 50 g within 12 h, the sample was dried in an oven at 105 °C for 24 h each time. After each drying and weighing, the TDR test procedure was repeated until the sample was absolutely dry. The absolute dry mass was recorded and the corresponding MC was calculated.

Boreholes were drilled at the breast diameter of standing trees and TDR tests were performed in the same way as in the indoor experiment. MC of standing trees was measured using growth cones to take cores.

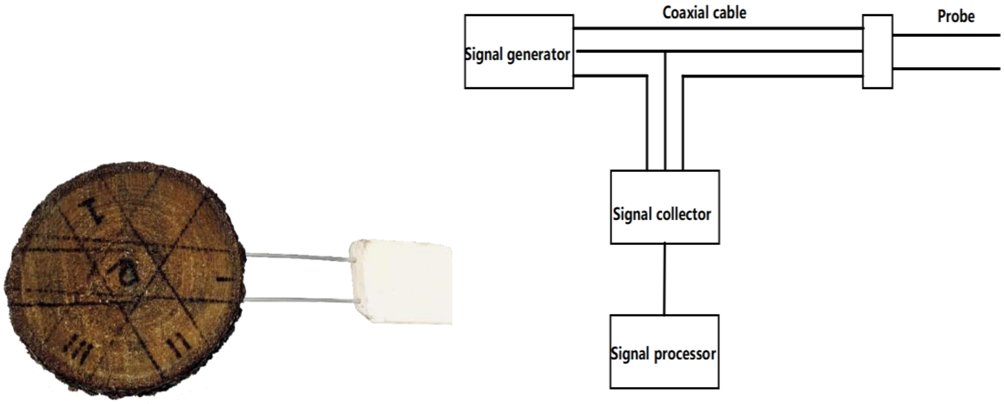

Fig. 1. Schematic diagram of experiment

RESULTS AND DISCUSSION

Construction of Species-specific MC Prediction Model

The regression models (linear, quadratic polynomial, logarithmic, exponential, and power function models) of MC and electromagnetic wave propagation time (EWPT) were computed and analyzed using statistical analysis, and the coefficient of determination (R^2), residual sum of squares (Q), F-value, and significance (Sig.) were selected as the indicators for evaluating the models.

The R^2 of the regression models for the four tree species at different insertion depths of the probes are shown in Table 1. Both linear and quadratic polynomial models showed R^2 greater than 0.90, so these models were chosen.

To investigate the effect of TDR probe insertion depth on model construction, the evaluation indices of different tree species were compared at 4, 6, 8, 10, and 12 cm depths, and Sig. of all models were obtained < 0.01. R^2 and F-values were largest at insertion depths of 8 cm or 10 cm, which means that the inversion model fits better at these two insertion depths (Table 1).

Considering the difficulty of drilling holes, reducing the damage to trees and other practical issues, the data of 8 cm insertion depth was chosen to construct a species-specific MC prediction model, as follows,

$$y = ax^2 + bx + c \tag{1}$$

$$y = dx + e \tag{2}$$

where y is the MC, x is the EWPT. The coefficients a, b, and c are given in Table 2.

For the four tree species, the relationship between EWPT and MC and the two species-specific MC prediction models are shown in Fig. 2. The strong correlation between EWPT and MC can be visualized in Fig. 2. The fitting of the two models for each tree species was also relatively similar, but there were differences in the models for different tree species. Under the same EWPT, the MC from largest to smallest was always: *Picea asperata*, *Tilia tuan*, *Betula platyphylla*, and *Fraxinus mandshurica*.

Table 1. R^2 for Different Models for 4 Tree Species at Different Insertion Depths

Species	Depth	Linear	Quadratic	Logarithmic	Exponential	Idempotent
Picea asperata	4	0.962	0.981	0.944	0.791	0.830
	6	0.977	0.980	0.933	0.858	0.848
	8	0.942	0.945	0.944	0.791	0.831
	10	0.955	0.955	0.953	0.810	0.853
	12	0.942	0.942	0.939	0.805	0.851
Tilia tuan	4	0.936	0.976	0.924	0.777	0.833
	6	0.959	0.973	0.948	0.868	0.855
	8	0.981	0.980	0.974	0.777	0.833
	10	0.979	0.980	0.967	0.803	0.862
	12	0.973	0.976	0.955	0.825	0.884
Betula platyphylla	4	0.961	0.971	0.965	0.746	0.890
	6	0.977	0.978	0.976	0.798	0.830
	8	0.984	0.985	0.978	0.825	0.861
	10	0.978	0.981	0.968	0.840	0.879
	12	0.979	0.980	0.957	0.858	0.899
Fraxinus mandshurica	4	0.936	0.973	0.935	0.867	0.884
	6	0.965	0.959	0.955	0.880	0.907
	8	0.971	0.971	0.963	0.886	0.884
	10	0.972	0.976	0.958	0.909	0.937
	12	0.963	0.973	0.943	0.919	0.944

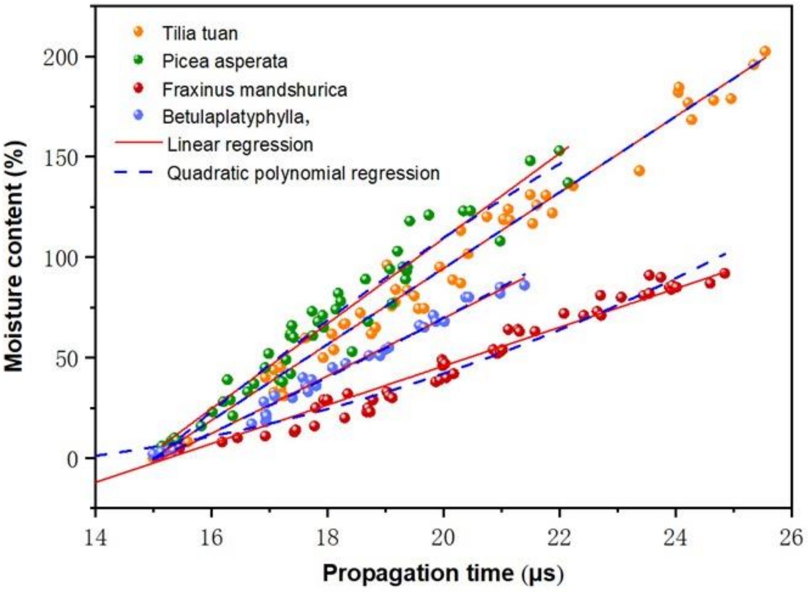

Fig. 2. Linear and quadratic polynomial species-specific MC prediction models

Table 2. Coefficients of Selective Models for Four Tree Species at 8 cm Insertion Depths

Species	Species	Quadratic polynomial models a	Quadratic polynomial models b	Quadratic polynomial models c	Linear models d	Linear models e
Tilia tuan	Tilia	-0.001	0.229	-3.212	0.189	-2.841
Picea asperata	Spruce	-0.005	0.401	-4.861	0.213	-3.163
Fraxinus mandshurica	Ash	0.005	-0.104	0.478	0.097	-1.471
Betula platyphylla	Birch	0.002	0.061	-1.437	0.144	-2.179

Construction of Generic MC Prediction Model

The species-specific MC prediction model is only applicable to certain tree species, which limits the application of TDR. During the analysis, it was found the species-specific MC models were different for different tree species, but the variation pattern of EWPT with MC is identical. For a generic MC prediction model that can be widely applied for four tree species, a quadratic polynomial model was constructed, as follows.

$$y = -0.0003x^2 + 0.124x - 1.853 \tag{3}$$

The ANOVA of the generic MC prediction model is shown in Table 3, where Sig. < 0.01, indicating a significant model. R^2 was 0.65, and the goodness-of-fit was lower than that of the species-specific MC prediction model.

Table 3. ANOVA of Generic MC Prediction Model

	Variance sum	Df	Ms	F	Sig
Regression	23.078	2	11.539	176.024	0
Residuals	12.258	187	0.066	—	—
Total	35.336	189	—	—	—

When comparing the physical properties of tree species, the differences between four species-specific MC prediction models were related to air-dry density. The air-dry densities of the four species tested were, in decreasing order, 0.70 g/cm^3 for ash, 0.60 to 0.70 g/cm^3 for birch, 0.42 to 0.56 g/cm^3 for *Tilia tuan*, and 0.40 to 0.52 g/cm^3 for spruce. In the species-specific MC prediction model, the predicted values of MC at the same EWPT for different tree species showed a negative correlation with density. In this case, the difference in air-dry density between ash and spruce was large, so it resulted in a lower goodness of fit for the generic MC prediction model. The differences between the species-specific MC prediction models for ash and spruce, and the generic MC prediction models for the four tree species are shown in Fig. 3.

Based on the above analysis, birch (0.60 to 0.70 g/cm^3), *Tilia tuan* (0.42 to 0.56 g/cm^3) and *Picea asperata* (0.40 to 0.52 g/cm^3) species with similar air-dry densities were selected, and a hybrid model was established between each two species. The three hybrid models and their evaluation indexes are shown in Table 4. The R^2 of the three hybrid models were all greater than 0.8, indicating a high degree of fit and much higher than the generic MC prediction model. However, compared with the *Picea asperata-Tilia tuan* and *Tilia tuan-Betula platyphylla* hybrid models, the R^2 and F-values of the *Picea asperata-*

Betula platyphylla hybrid model were lower, and the Q value was twice that of the other two hybrid models. The was attributed to the relatively large difference in the air-dry densities of spruce and birch. Therefore, if the air-dry densities of different tree species are essentially the same, a generic MC prediction model can be constructed.

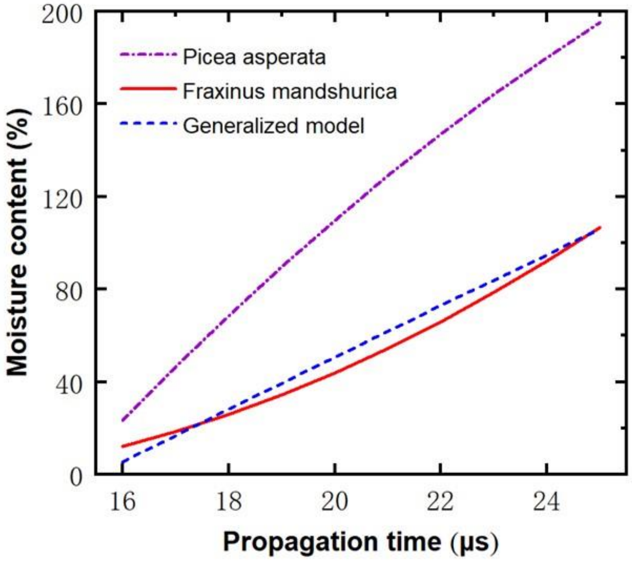

Fig. 3. Species-specific MC prediction models for ash and spruce and a generic MC prediction model for the four tree species

Table 4. Hybrid Models and Evaluation Indicators

Name	Model	R^2	Q	F
Picea asperata-Tilia tuan	$y = -0.003x^2 + 0.296x - 3.812$	0.96	1.012	1139.1
Tilia tuan-Betula platyphylla	$y = -0.0037x^2 + 0.044x - 1.499$	0.95	1.033	901.8
Picea asperata-Betula platyphylla	$y = -0.0003x^2 + 0.194x - 2.813$	0.80	2.156	158.2

Field Calibration of Species-specific MC Model

To accurately monitor MC of standing trees in real time, four species-specific MC prediction models were applied to the field tests. The relationship between EWPT and actual values of MC in standing trees, as well as the predicted values of the species-specific MC prediction models are shown in Fig. 4.

The relationship between EWPT and MC in standing trees showed a similar trend to that of the indoor experimental data, which also supports the feasibility of using TDR to monitor the MC of standing trees. Using the species-specific MC prediction model obtained from the indoor experiments to calculate the predicted values of standing trees MC, the results showed that the predicted values of white birch had the smallest difference from the true values, with an average difference of 10.8%, and the predicted values of spruce had the largest difference from the true values, with an average difference of 58.8%. In addition, the predicted values of all tree species were larger than the true values, which may be induced by many factors, such as complex environmental factors, loss of sap during drilling process and relative concentrated MC variation range of standing tree. In addition, the distribution of moisture in standing trees can be very different from that in progressively drying discs of wood after soaking, so the indoor model can produce large errors when used as a predictor for outdoor experiments. Thus further study is needed for accurately estimating tree MC. Overall, field test data proved that TDR can be used to detect tree MC.

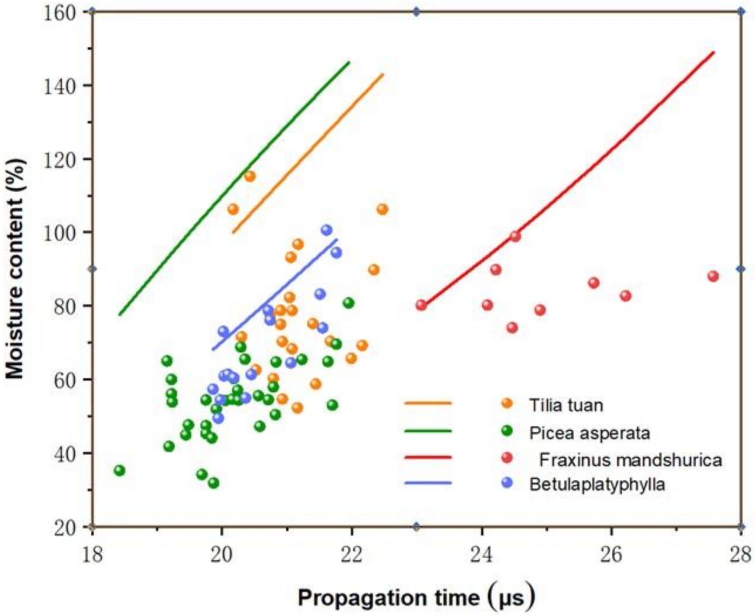

Fig. 4. Actual (point) *vs*. predicted (line) MC of standing trees

CONCLUSIONS

1. Indoor and field experiments on moisture content (MC) detection of *Betula platyphylla*, *Tilia tuan*, *Picea asperata*, and *Fraxinus mandshurica* showed that there was a strong correlation between electromagnetic wave propagation time (EWPT) and MC, and the correlation was affected by the insertion depth of the probe.
2. Species-specific MC prediction models with different insertion depths were constructed based on the data from the indoor experiments. The results showed that the linear and quadratic polynomial models constructed at an insertion depth of 8 cm were highly predictive.
3. The quadratic polynomial model was utilized to construct a generic MC prediction model for the four tree species, but with a lower accuracy (R^2 = 0.65). This may be related to the differences in air-dry density of different tree species. The data of tree species with similar air-dry density were used to construct P*icea asperata-Tilia tuan***,** *Tilia tuan-Betula platyphylla***,** and *Picea asperata-Betula platyphylla* hybrid models, and the R^2 was 0.96, 0.95, and 0.80, respectively. This means that the same MC prediction model could be used for tree species with similar density.
4. In the field experiments, the EWPT and MC also had a similar trend to the indoor experiments, but the MC calculated using the species-specific MC prediction model was higher than the actual value, which may be related to environmental factors and sap loss after drilling.
5. The natural variability and density differences in the trunks of different tree species can lead to variations in trunk moisture distribution, resulting in large differences in MC,

which makes time domain reflectometry (TDR) field monitoring difficult. The indoor model constructed in this paper cannot be used for all tree species in the field, but it can provide a reference for the detection of water content in standing trees. In order for TDR to be accurately applied to MC detection in standing trees, a large number of experiments need to be conducted in the field.

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Author Contributions

Peng Wang and Huadong Xu designed the experiments; Jiedong Wei and Peng Wang, performed laboratory test; Jiaxing Guo, Peng Wang, and Ruixia Qin performed data curation and investigation; Peng Wang and Ruixia Qin wrote the paper. These authors contributed equally to this work. Huadong Xu reviewed the manuscript.

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