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Field assessment of wood stake decomposition in forest soil

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Abstract

A pulse-echo acoustic method was investigated for evaluating wood stake decomposition in the field. A total of 58 wood stakes (29 loblolly pine, *Pinus taeda*, and 29 aspen, *Populus tremuloides*) that were vertically installed (full length) in forest soils were non-destructively tested by means of a laboratory-type acoustic measurement system. The same acoustic measurements were also conducted on the wood stakes after they were removed from the soil. Compression (parallel to grain) tests were then performed on the stakes in the laboratory to obtain residual elastic and strength properties. The results indicate that the pulse-echo acoustic method is a good approach to characterize wood stakes that are fully inserted into mineral soils. Statistical analysis showed good relationships between acoustic parameters (number of pulse echoes and in-ground acoustic velocity) and percentage weight loss, modulus of elasticity in compression, and residual compressive strength. The pulse-echo acoustic method could be used as a monitoring tool to assess progressive levels of wood stake decomposition in forest soil.

Keywords: acoustic wave; biodegradation; decomposition; modulus of elasticity; pulse echo; residual compressive strength; weight loss; wood stake.

Introduction

Organic matter in soil is a key to maintaining site productivity because of its roles in water availability, nutrient supply, soil aggregation, and disease incidence or prevention (Harvey et al. 1987). Decomposition of organic matter is controlled by the same factors that affect tree growth. Forest management practices can greatly impact organic matter decomposition, which also influences tree growth (Grigal 2000). Consequently, organic matter decomposition has been used as an index in long-term soil productivity research concerning effects in forest management in various parts of North America and Canada (Powers 1991).

In a recent study (Jurgensen 2002; Jurgensen et al. 2006), standard wood stakes (25 mm×25 mm×300 mm) were used as an organic matter substrate in forest soil. Their decomposition process was studied at various sites and in a wide range of soil conditions in terms of temperature and moisture. The decomposition rate is currently determined by examining physical and mechanical properties. Stake samples are periodically removed and mechanical compression tests are performed on small segments cut from each stake. Comparison of the results of these destructive tests is only possible with results for suitable controls. This evaluation procedure requires the preparation of large numbers of replicate samples installed in the field. Subsequent sampling and tests are labor-intensive and time-consuming. It is desirable to develop a field method for non-destructive evaluation of wood stake decomposition without removing stakes from the soil.

The determination of weight loss is the criterion most frequently used to assess decay in wood and wood-based materials (Hardie 1980). Weight loss determination is usually a simple procedure, but a drawback is the lack of sensitivity in the early stages of decay. Decomposition processes are not always reflected by weight loss from the very beginning. Strength loss, on the other hand, has been found to be a better measure of biodeterioration (Hardie 1980).

In an earlier study, Armstrong and Savory (1959) exposed beech (*Fagus* spp.) to soft-rot organisms and observed an immediate reduction in impact strength before any appreciable loss in dry weight was recorded. They also found that a 5% weight loss for beech corresponded to a 60% decrease in impact-bending strength and an 18% decrease in static-bending strength. Similarly, Liese and Pechmann (1959) reported a 50% decrease in impact-bending strength of wood after a 5% reduction in weight. Nicholas and Jin (1996) evaluated radial compression strength loss in soil block tests and concluded that strength loss analysis provided a more sensitive measure of decay than weight loss.

The advantages of strength loss determination are (1) it provides more accurate assessment of biodeterioration than weight loss, and (2) it can easily be carried out in laboratories equipped with routine mechanical testing machines. The drawback lies in its destructive nature. As such, it is only possible to measure strength loss by reference, on a statistical basis, to suitable controls.

The high potential of the pulse-echo acoustic wave technique in assessing biodegradation of various wood members has been demonstrated (Pellerin et al. 1985; Ross et al. 1997; DeGroot et al. 1998). However, no research has been carried out on field wood stakes that are fully inserted into forest soil. The goal of the present research was to determine if the pulse-echo acoustic method is a viable approach to test in-ground wood stakes and assess wood decomposition in forest soils.

The specific objectives of this research are: (1) to examine the acoustic characteristics of loblolly pine (*Pinus taeda*) and aspen (*Populus tremuloides*) sapwood stakes fully embedded in forest soils and undergoing a wide spectrum of degradation; and (2) to establish fundamental relationships between acoustic parameters and progressive levels of wood decomposition as indicated by weight loss, modulus of elasticity in compression, and residual compressive strength of the wood stakes.

Materials and methods

Wood stake samples

A total of 58 wood stakes were subjected to the acoustic test while they were still in the ground. The samples included 29 loblolly pine stakes and 29 aspen stakes, which were selected from 12 micro-plots that represent a wide range of soil temperature and moisture conditions.

The micro-plots are on the Long-Term Soil Productivity (LTSP) site in the Umpqua National Forest in Medford, OR (USA). The LTSP site was established in 1998 by the USDA Forest Service to investigate possible effects of soil compaction and organic matter removal on long-term site productivity. The LTSP design consists of three levels of compaction: (1) none, (2) moderate, and (3) severe, and three levels of organic matter removal: (1) stem-only harvest, (2) whole-tree harvesting, and (3) whole-tree plus forest floor removal. In our study, the stakes were tested in soils with compaction levels 2 and 3, levels 1 and 3 of organic matter removal, and unharvested controls.

In these plots, both loblolly pine and aspen sapwood stakes were used to compare different lignin and cellulose contents of softwood and hardwood trees. A total of 25 wood stakes (25 mm×25 mm×300 mm) of each species were installed in the surface mineral soil layer at each micro-plot in May 2001. These stakes had following strict quality criteria: straight grain, sapwood only, 6–10 rings, free of any defects, and ±5% deviation of the mean density (Jurgensen 2002). The wood stakes were spaced 40–50 cm apart. The tops of the stakes were level with the mineral soil surface. The upper ends of the stakes were sealed. The basic properties (initial weight, moisture content, specific gravity, and ring width) of the stakes were established before installation.

One set of wood stakes of each species was removed from each micro-plot every 6 months. Field acoustic measurements were conducted in October 2002 during routine field data collection and stake removal.

Field acoustic measurement

Wood stakes were tested acoustically in two positions: (1) in-ground (stakes were still installed in the soil), and (2) out-of-ground (stakes were removed from the soil). For each measurement, a clamp containing a spring-loaded impactor and a piezo-film sensor was fixed to one end of the stake. For in-ground tests, the clamp was attached by exposing the top end of each stake. A single impact wave was induced in the stake. The repeated passage of the wave past the piezo film as the wave reciprocated from end to end was detected and recorded with a portable ScopeMeter (Fluke 99 ScopeMeter, Fluke Corporation, Everett, WA).

The acoustic waveforms typically observed consisted of a series of sine-shaped pulses for which the magnitude decreased with time. The number of pulse echoes in each measurement was recorded and the time between pulses (peak to peak, Δt) was determined through cursor measurement. The acoustic velocity (C) was then calculated from the following equation:

$$C=2L/\Delta T, \tag{1}$$

where L is the stake length.

After each stake was removed from the soil, it was immediately weighed on a portable electronic balance. Then all stakes were shipped to the Forest Products Laboratory (FPL) in Madison, WI for laboratory tests.

Compression parallel to grain test

In the laboratory, stakes were conditioned to 12% equilibrium moisture content (EMC) in an environment of 24°C and 66% relative humidity. All samples were weighed again when the EMC was reached.

A compression test was conducted on each stake parallel to grain according to ASTM D198-98 (ASTM 1999). To ensure short column behavior (i.e., failure by crushing), a support jig was used to provide adequate lateral supports. The jig consisted of four 41-cm galvanized telescoping tube columns welded to a steel base-plate. A steel connecting L-beam was also welded on top of the columns to increase lateral support. Twelve roller supports were used to laterally hold the specimens on the jig. This procedure ensured that each stake was loaded uniformly and axially. The dimensions (length and cross-section) of the stakes were measured before the test. Load-deflection data were obtained using a data acquisition system.

Data analysis

The weight loss of each wood stake was expressed as percentage of the initial weight (before installation) and defined as follows:

$$\text{Weight loss}=(W_0-W_i)/W_0\times 100\%, \tag{2}$$

where W_0 is the initial weight of a stake before installation (12% EMC), W_i is the weight measured immediately after the stake was removed from soil or the weight after the stake was reconditioned to 12% EMC in the laboratory.

The modulus of elasticity (MOE) in compression and residual compressive strength (RCS) of each stake was determined based on the load-deflection curve using the following equations:

$$\text{MOE}=F'/A\varepsilon \tag{3}$$

$$\text{RCS}=F/A, \tag{4}$$

where F' is the compressive load at the proportional limit (N), A is the cross-sectional area (mm^2), ε is the strain at the proportional limit (mm mm^{-1}), and F is the maximum compressive load (N).

For field acoustic measurements, the wave attenuation rate of the acoustic signals was not obtained because of instrumental limitations. Instead, we recorded the number of pulse echoes on the waveform observed for each stake sample. Both the acoustic velocity and the number of pulse echoes obtained for in-ground stakes were analyzed and compared with the percentage weight loss, MOE, and RCS determined under laboratory conditions. Quantitative relationships between acoustic velocity and weight loss were determined by statistical regression analysis. The relation between acoustic velocity and residual elastic and strength properties was evaluated in the same way.

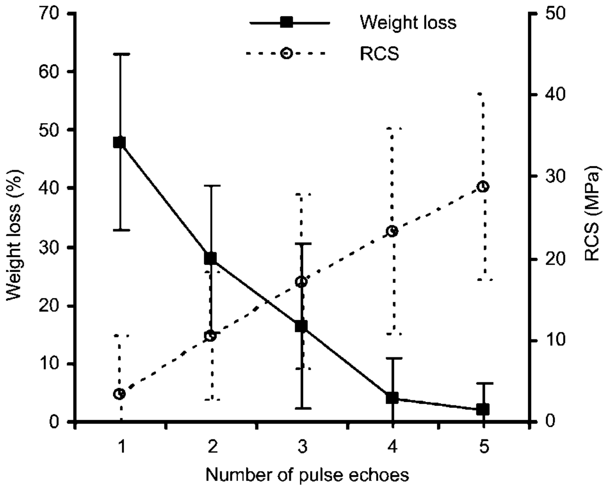

Figure 1 Number of pulse echoes observed from in-ground measurement in relation to weight loss and residual compressive strength (RCS).

The stakes tested in this study showed a broad spectrum of deterioration. Some stakes had decomposed to the extent that they were either broken during handling or too weak to be mechanically tested. In these cases, the stakes were assumed to have a zero value for both MOE and RCS.

Results and discussion

Acoustic waveform analysis

Acoustic waves obtained for in-ground measurements had significantly fewer wave pulses and higher wave attenuation than those for out-of-ground measurements. This reflects a significant loss of acoustic energy through absorption in soil. The number of pulse echoes recorded for in-ground stakes was typically 1–5. For a few stakes, no echo could be obtained because the stakes were decomposed to the extent that they separated into two parts when extraction was attempted.

The number of pulse echoes in in-ground stakes tended to decrease as the amount of decay increased. This decrease was associated with increased weight loss and decreased RCS (Figure 1). For instance, stakes yielding one pulse echo had an average of 48% weight loss. Stakes that had more than four pulse echoes generally had less than 10% weight loss. RCS, on the other hand, decreased almost linearly as the pulse-echo number decreased. A reduction of one pulse-echo in the acoustic signals corresponded to a loss of 6.3 MPa in average stake RCS. These findings are similar to the observations reported by DeGroot et al. (1998).

The general decrease in pulse-echo number with progressive wood decomposition reflects a loss of signal energy through absorption or damping. From an ecological perspective, the inclusion of pulse echo count may prove to be a valuable component of the decomposition analysis for periodic monitoring. However, the large variation for weight loss and RCS at each pulse-echo level indicates that pulse-echo count alone is not sufficient for this type of assessment, especially when between-stake or cross-plot comparisons are performed.

Acoustic velocity

The acoustic velocity for in-ground and out-of-ground wood stakes is summarized in Table 1. Both loblolly pine and aspen stakes showed a wide acoustic velocity range after they had been installed in mineral soil for 17 months. The acoustic velocity of in-ground stakes ranged from 569 to 2428 m s^{-1} for loblolly pine and from 635 to 2342 m s^{-1} for aspen. This velocity range is significantly lower than the normal acoustic velocities for solid green wood (Wang et al. 2001, 2004). Although the initial acoustic velocity distribution of the stake specimens was unknown (stake specimens were not acoustically tested before installation), we suppose that the original stakes had a narrow velocity band because they were selected under strict quality criteria and had low density variation. Therefore, it is very likely that the wide range of acoustic velocities for the stakes reflects various levels of wood decomposition due to microbial activity for different levels of soil compaction and organic matter removal. Figure 2a compares acoustic velocities for in-ground and out-of-ground stakes. Regression analysis yielded a strong linear relationship ($R^2 = 0.96$). This proves the applicability of acoustic measurement for stakes still imbedded in forest soil.

Weight loss in relation to in-ground acoustic velocity

Figure 2b shows the percentage weight loss for wood stakes in relation to in-ground acoustic velocity. Wood stakes installed in mineral soil had gained a significant amount of moisture, which has to be deduced in calculations concerning weight loss due to deterioration. The moisture content (MC) of in-ground stakes in soil can be estimated after re-equilibration to 12% EMC in the laboratory. Figure 3 illustrates MC distributional characteristics of loblolly pine and aspen in-ground stakes. It is apparent that MC of all in-ground stakes was above the fiber saturation point (FSP), except one aspen stake that had an MC of approximately 14%. The majority of the stakes surpassed the minimum MC (22–24%) for fungal decay development. The large MC range found in the stakes was the result of different soil conditions at each micro-plot.

Table 1 Acoustic velocity of loblolly pine and aspen stakes measured in the field.

Species	Acoustic velocity (m s^{-1})							
	In-ground stakes				Out-of-ground stakes			
	Mean	Min	Max	SD	Mean	Min	Max	SD
Loblolly pine	1779	569	2428	526.4	1758	467	2393	525.8
Aspen	1574	635	2342	440.8	1574	472	2325	475.9

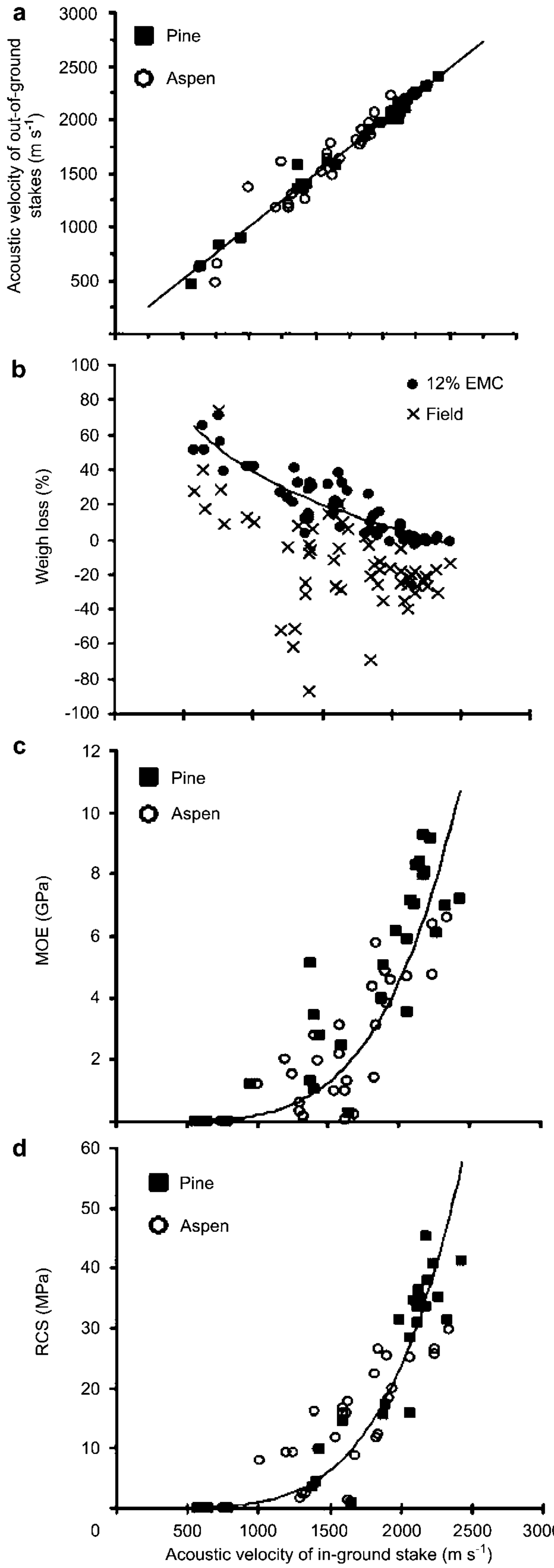

Figure 2 Loblolly pine and aspen stakes were installed in mineral soils for 17 months and tested in several ways. (a) Comparison of acoustic velocities of in-ground and out-of-ground wood stakes. (b) Weight loss of wood stakes in relation to in-ground acoustic velocity. (c) Relationship between acoustic velocity of in-ground stakes and modulus of elasticity (MOE). (d) Relationship between acoustic velocity of in-ground stakes and residual compressive strength (RCS).

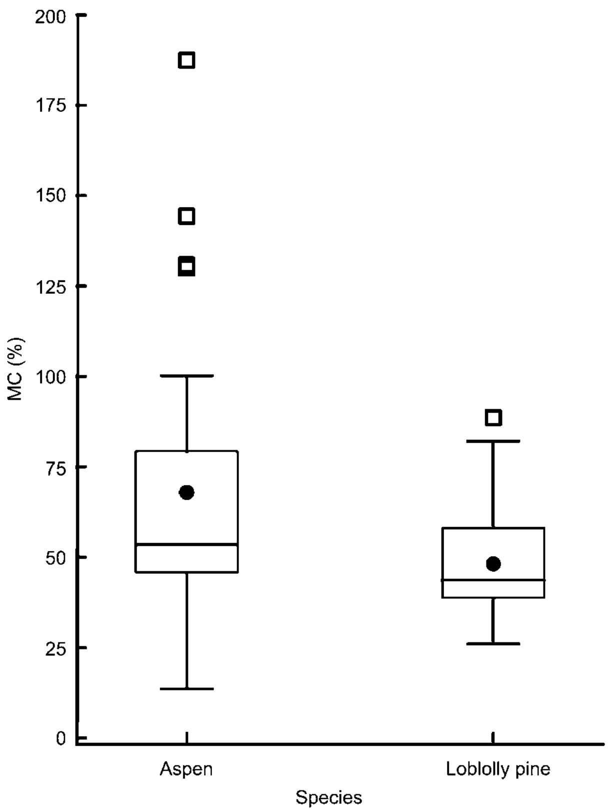

Figure 3 Moisture content (MC) of in-ground wood stakes at the time of field testing.

Weight gain from moisture uptake reached values as high as 40% for loblolly pine and 87% for aspen (Figure 2b). Clearly, weight loss and gain measured in the field show no good correlation with in-ground acoustic velocity.

The percentage weight loss for wood stakes after re-equilibration ranged from -2.9% to 51.6% for loblolly pine and from -0.6% to 65.3% for aspen. This weight loss was primarily caused by the reduction of wood polysaccharides (and partly lignin) in the stakes. The small negative values for weight loss in some stakes were probably caused by the hysteresis effect, a common source of error in wood decay experiments (Zabel and Morrell 1992).

The experimental data demonstrate a good correlation between weight loss determined in laboratory conditions and in-ground acoustic velocity. Regression analysis indicates that a logarithmic regression equation best fits the data sets. When comparing all stakes as a group, the regression model (% weight loss $=$ -46.648 ln $C+361.2$) could explain approximately 80% of the variation in weight loss. As shown in Figure 2b, the percentage weight loss generally increased as acoustic velocity decreased. Weight loss changed less significantly in the higher velocity range than in the lower velocity range.

MOE and RCS in relation to in-ground acoustic velocity

The MOE in compression and RCS of loblolly pine and aspen stakes are presented in Table 2. Of the 58 stakes removed from the soil, six stakes (three loblolly pine and three aspen) were severely decayed and had lost over

Table 2 Modulus of elasticity (MOE) and residual compressive strength (RCS) of loblolly pine and aspen stakes measured at 12% EMC.

Species	MOE (GPa)				RCS (MPa)			
	Mean	Min	Max	SD	Mean	Min	Max	SD
Loblolly pine	4.94	0	9.26	3.102	23.37	0	45.23	14.486
Aspen	2.40	0	6.63	2.093	13.44	0	29.79	9.255

50% of their initial weight. The deterioration of these stakes was so advanced that some of them broke during handling. Mechanical tests were not possible and values of 0 were assigned for MOE and RCS.

The maximum RCS of the stakes was almost the same as the strength values given in the Wood Handbook (Forest Products Laboratory 1999). We suppose that little or no decomposition had occurred for some of the stakes. This is likely due to either compaction or organic matter removal in the micro-plot. The wide range of MOE and RCS values shown in Table 2 is an indication of diverse decomposition levels in the micro-plots where the stake samples came from.

Decomposition levels of the wood stakes can also be demonstrated graphically by a cluster of load-deflection curves (Figure 4). The mechanical behavior of the stakes is typically characterized by load and deflection at failure, changes in the slope of the curve, and maximum load. Higher maximum load corresponds to higher compressive strength, and higher slope of the curve (within the proportional limits) indicates higher MOE. The load-deflection curves in Figure 4 not only show a wide range of mechanical properties, but also represent different in-ground acoustic velocity levels. The maximum load and slope of the curve are generally in the same rank as acoustic velocity for the stakes. As the maximum load and slope decreased, the acoustic velocity also decreased.

There is a strong correlation between in-ground acoustic velocity and compression properties, as shown in Figure 2c,d. When comparing all stakes as a group, a power regression model ($y=ax^b$) was found to best fit the experimental data. The regression models developed could explain approximately 73% of the variation in MOE and approximately 84% of the variation in RCS.

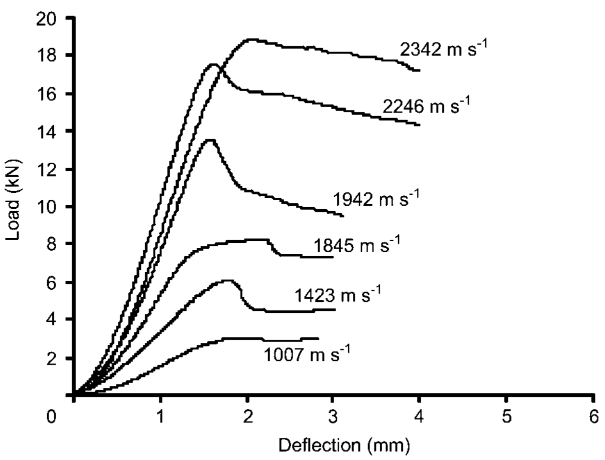

Figure 4 Load-deflection curves of aspen stakes with different acoustic velocities.

The regression equations for predicting MOE and RCS using in-ground acoustic velocity are as follows:

$$MOE=10^{-14}\ C^{4.4414}\ (GPa),\ R^2=0.726$$

$$RCS=2\times10^{-14}\ C^{4.5967}\ (MPa),\ R^2=0.836.$$

The velocity-decomposition relationship can be characterized into three regions. In the range $C>2000$ m s^{-1}, both MOE and RCS decreased significantly as in-ground acoustic velocity decreased. A velocity drop of 100 m s^{-1} in this region would result in an average decrease of 1.55 GPa in MOE and 8.96 MPa in RCS. In the range 1000–2000 m s^{-1}, stake decomposition further progressed, as indicated by weight loss (Figure 2b). However, the magnitude of MOE and RCS changes in this region was less dramatic. When acoustic velocity dropped to 1000 m s^{-1} and lower, stake decomposition was so advanced (weight loss >40%) that MOE and RCS approached zero.

The curvilinear relationships between elastic and strength properties and in-ground acoustic velocity of wood stakes may be the result of different decomposition mechanisms (leaching, microbial mineralization, cellulose loss, and lignin degradation) commonly found in wood-substrate decomposition processes. From an ecological perspective, it is important to follow the degradation of wood stakes to completion in field research. The in-ground acoustic velocity seems to be well suited to this purpose.

Conclusions

Wood stake decomposition can be evaluated by a pulse-echo acoustic method when stakes are fully imbedded in forest soil. The number of pulse echoes observed for in-ground stakes was associated with both weight loss and RCS of the stakes. Good relationships existed between acoustic velocity and residual elastic and strength properties. The pulse-echo acoustic method could be used as a monitoring tool in soil productivity research to assess the decomposition rate of wood stakes. A standard procedure should be established for this approach.

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