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European Journal of Soil Biology 42 (2006) 23–31
EUROPEAN JOURNAL OF SOIL BIOLOGY
www.elsevier.com/locate/ejsobi

Original article

Wood strength loss as a measure of decomposition in northern forest mineral soil

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Received 27 May 2005; accepted 8 September 2005

Available online 11 October 2005

Abstract

Wood stake weight loss has been used as an index of wood decomposition in mineral soil, but it may not give a reliable estimate in cold boreal forests where decomposition is very slow. Various wood stake strength tests have been used as surrogates of weight loss, but little is known on which test would give the best estimate of decomposition over a variety of soil temperature conditions. Our study showed that radial compression strength (RCS) was a better indicator of wood strength change in southern pine (*Pinus* spp.) and aspen (*Populus tremuloides* Michx.) than surface hardness or longitudinal shear. The suitability of using the RCS to measure wood decomposition in boreal mineral soils was tested in six Scots pine (*Pinus sylvestris* L.) plantations along a North–South gradient from Finland to Poland. After 3 years RCS losses ranged from 20% in northern Finland to 94% in central Poland, compared to dry weight losses of 3% and 65%. RCS was a sensitive indicator of initial wood decomposition, and could be used in soils where decomposition is limited by low temperature, lack of water or oxygen, or where a rapid estimate of wood decomposition is wanted.

Keywords: Wood strength; Scots pine; Lignin; Cellulose; C/N ratio

1. Introduction

Organic matter (OM) decomposition is a critical factor in assessing the possible impacts of future climate change on soil carbon (C) pools [21,23,26]. Temperature is a main driver of soil OM decomposition, and is especially important in high latitude (> 50°N) forests where future temperature increases are projected to be the greatest [24,34]. Northern latitude forests are thought to be net atmosphere C sinks, but could shift from C sinks to C emission sources if soil OM decomposition rates increase [40]. Such a change would have significant implications for global C cycling and sequestration [29,33]. Most studies on OM decomposition in northern forest soils have focused on the litter layer e.g. [4,7]. In contrast, relatively little work has been done on OM decomposition in mineral soil [25], which is largely a result of sampling difficulties (e.g. disturbance) and the large variation in mineral soil horizon depths and properties [14]. The mineral soil in northern forests contains large amounts of C [13,33], although its contribution to total forest C pools will vary depending on the soil depth sampled.

Differences in OM quality (lignin content, C/N ratio, etc.) make it difficult to compare decomposition results across a range of forest soils and climate regimes [3,38]. By using the same “standard” organic substrate in different soils, OM quality is held constant and decomposition is a function of soil

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doi:10.1016/j.ejsobi.2005.09.001

abiotic (moisture, temperature, O_2/CO_2 levels, redox potential, nutrient content, pH) and biotic (microbial biomass, functional diversity) conditions. Various substrates, such as cellulose strips, cotton cloth, museum board, and wood dowels, have been used to investigate OM decomposition in mineral soil [16,25,30,36]. However, wood stakes seem best suited for long-term studies, since decomposition can be measured at different soil depths and very little soil disturbance occurs during installation. Wood is a normal component of forest soils (surface residue, stumps, large roots), and integrates changes in temperature and moisture conditions over long time periods during decomposition [18].

Weight loss is usually used as a measure of wood decomposition [42], but it may not be sensitive enough in northern forests, where OM decomposition is limited by low soil temperature [39]. Changes in mechanical wood properties, as measured by various wood strength tests, have been used as an alternative to dry weight loss [31,35,41]. Wood strength is primarily a function of lignin, cellulose and hemicellulose content in cell walls, which decreases as these cell components are degraded by soil microorganisms [11]. Wood strength tests are often conducted on small wood blocks decayed by pure cultures of white-rot and brown-rot fungi growing under laboratory conditions [2]. In field studies, wood stake decomposition is estimated by visual field ratings [10] or by measuring strength loss or failure (e.g. static bending) for the entire stake [1]. However, little is known about which wood strength test is the best indicator of weight loss over a variety of soil conditions. Therefore, we conducted a pilot wood stake decomposition study using several wood strength tests, and then compared one test to wood weight loss in northern European forest soils over a 3-year period. Our specific objectives were to: 1) assess the effectiveness of three mechanical wood strength tests in measuring weight loss in early decay stages, and 2) determine if wood strength loss could be used as an index of wood decomposition over a temperature gradient from northern Finland to central Poland.

2. Methods

2.1. Assessment of wood strength tests

Since we wanted to measure wood decomposition at different soil depths, it was necessary to choose tests that could be used with relatively small samples taken along the length of a wood stake. The tests chosen were surface hardness, radial compression strength (RCS), and longitudinal shear strength. All of these tests are common procedures and can be performed on equipment available in many university and commercial testing laboratories. The first two tests measure wood strength near the wood stake surface, while the shear test is a measure of bulk wood properties. Stakes made from aspen (*Populus tremuloides* Michx.) and southern pine (*Pinus* spp.) were used to compare the performance of these three tests on wood with different lignin types, cellulose contents, and anatomical structures.

Sapwood boards of aspen and southern pine (two to four annual growth rings per cm) were cut into 40, 2.5 × 2.5 × 33 cm (radial × tangential × longitudinal) field stakes, which had growth rings oriented parallel to one longitudinal face. Since we wanted to compare the wood strength tests on wood decayed under optimal soil moisture and temperature conditions, we installed pine and aspen stakes (30 each) in a 3 m × 3 m grass plot at the Michigan Technological University wood preservative test site near Hilo, Hawaii (23 °C mean annual temperature, 325 cm mean annual rainfall). In order to reduce soil compaction and damage to the stakes during installation, each stake was placed in a hole made by a 2.5 cm^2 coring tool. Stakes of each species were randomly inserted 40–50 cm apart with the top of the stake level with the mineral soil surface. Ten additional stakes were used as unexposed controls (time = “0”). Five stakes of each species were removed every 2 weeks for 3 months and shipped to Michigan Technological University for analysis. Each stake was air-dried, conditioned to 12% equilibrium moisture content (EMC), and marked into six test samples (2.5 cm blocks) cut as shown in Fig. 1A.

The three wood strength test methods followed American Society for Testing and Materials procedures [1]. Sample blocks 1, 3, and 5 were used for hardness and longitudinal shear evaluations, while samples 2, 4, and 6 were subjected to the RCS test. The hardness test was conducted before wood blocks were cut from the stakes to minimize the effects of a cut surface on wood strength properties. The load was applied at a rate of 0.64 cm/min, and recorded when the ball (1.13 cm in diameter) penetrated to one half its diameter on a tangential surface. Wood block surface area was measured before shear strength tests were carried out, and maximum load was recorded using a crosshead speed of 0.061 cm/min. RCS was determined by measuring the stress at 5% thickness compression in the radial direction applied at a rate of 0.03 cm/min [5].

Wood strength variability in aspen and pine stakes, as measured by the hardness, shear strength, and RCS tests, were used to estimate 95% confidence intervals for each mean wood strength value. The variability from each wood strength test ($N = 5$) was also used to estimate confidence interval width for different field sample sizes, and determine the relative gain in precision by increasing the number of stakes sampled. The statistical power, or the likelihood of detecting a change in wood strength, was used to determine the sensitivity of wood stake sample size to detect changes in wood strength as a result of decomposition.

2.2. Boreal forest soil study

In 1998 a wood stake study was established in six Scots pine (*Pinus sylvestris* L.) plantations from northern Finland to central Poland to test the effectiveness of RCS to measure wood decomposition under different temperature conditions (Fig. 2). Average annual air temperatures ranged from –1 °C in northern Finland to 8 °C in central Poland. Yearly precipi-

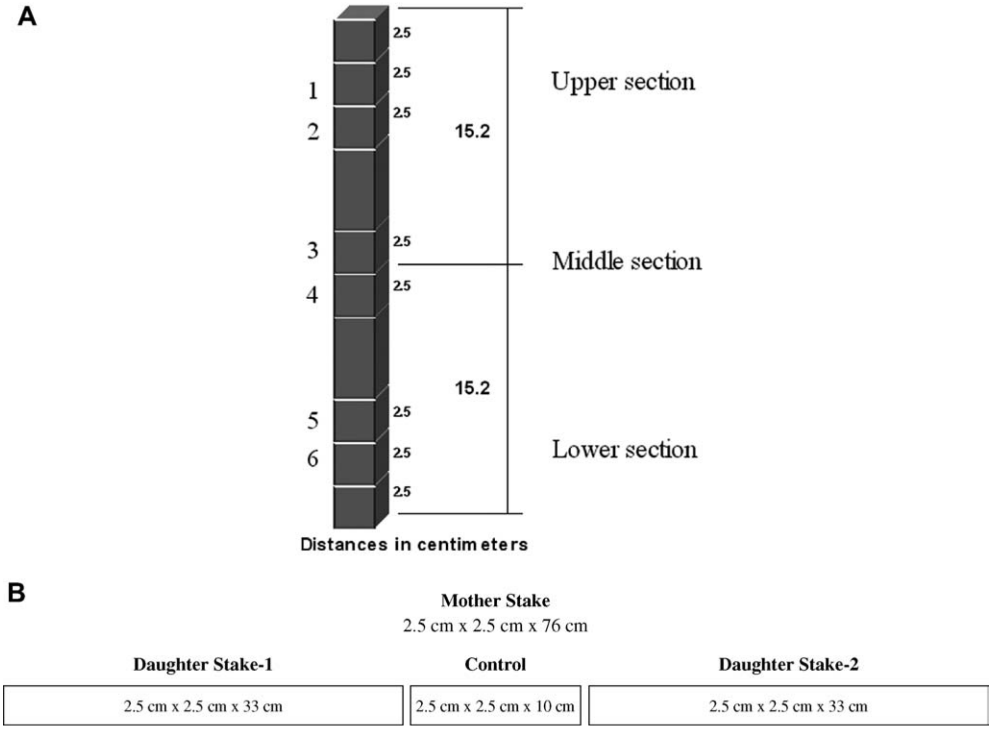


Fig. 1. Wood blocks used in laboratory wood strength tests (A) and wood stakes used in the European North–South temperature gradient study (B).

tation on the study sites averaged from a low of 450 mm in northern Finland to a high of 630 mm in Lithuania. These stands were part of a comprehensive study on Scots pine ecosystem response to climate change in northern Europe [32], and were similar with respect to tree species composition, stand age, and basal area. All soils were sands or loamy sands, classified as either podzols or rusty podzols (Entic haplorthods), and had similar horizon development and pH [13].

Southern pine was selected as the standard wood for our study since it is widely used in soil tests of wood preservative formulations [10]. Field ("daughter") stakes were cut from defect-free pine sapwood "parent" stakes (Fig. 1B). The top of each field stake was treated with a wood sealer to reduce evaporation after installation. The 10 cm center section from each parent stake was used to determine initial mechanical and chemical properties of the two field stakes (time = 0). In September 1998, stakes were installed in a 2 m × 2 m plot that was representative of each Scots pine stand: 10 stakes in Finland (FN1, FN2, and FN3) and five stakes Lithuania (LI1) and Poland (PL1, PL2). The forest floor in each plot was carefully removed, and the stakes inserted in holes 40–50 cm apart made by a 2.5 cm^2 coring tool. The stakes were placed level with the mineral soil surface and the forest floor replaced. In September 1999, five stakes were removed from each of the three Finnish sites, and five stakes were removed from all six sites in September 2001. The stakes were sent to the School of Forest Resources and Environmental Science at Michigan Technological University for processing.

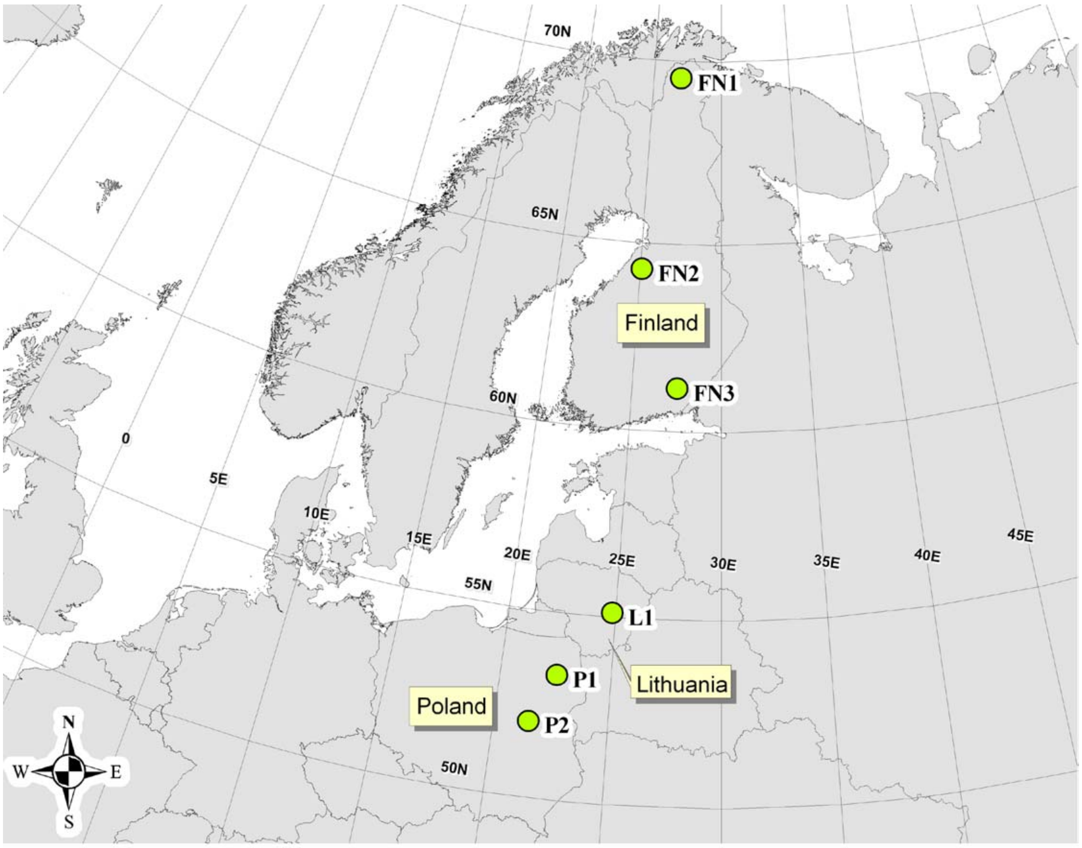
In the laboratory, all wood stakes were air-dried, conditioned to 12% EMC, cut into three 2.5 cm blocks corresponding to block numbers 1, 3, and 6 in Fig. 1A, and RCS determined as described earlier. After the RCS test, all blocks were dried at 105 °C for 48 hours and weighed. RCS tests and dry weight measurements were also conducted on 2.5 cm blocks cut from the center of each 10 cm parent stake control section. The relationship of RCS loss to changes in wood chemical properties was examined by determining total C, total N, lignin, cellulose, and hemicellulose content in one representative stake (and its associated control) taken from each stand 3 years after installation [12,15].

Regression analysis was used to examine the relationship of field stake dry weight loss and RCS loss in the six soils along the North–South temperature gradient. The regression intercept value was interpreted to be the RCS loss that occurred prior to measurable weight loss. The sensitivity of dry weight and RCS to measure wood decomposition in these soils was evaluated by "t" tests that compared RCS loss and dry weight loss in field stakes after one and 3 years incubation to their corresponding controls (time = 0).

3. Results and discussion

3.1. Assessment of wood strength tests

The RCS measurement of our Hawaiian aspen stakes showed the least variability (i.e. narrowest confidence inter-



Site	Elevation (m.a.s.l.)	Average Annual Air Temperature (°C)	Average Annual Precipitation (mm)	Stand Age (years)	Trees (ha^{-1})	Basal Area ($m^2\ ha^{-1}$)	Forest Floor Depth (cm)
FN1	90	-1	450	178	442	11.2	7.7
FN2	52	2	500	98	525	16.6	5.9
FN3	78	4	550	66	508	12.8	4.8
LI1	123	6	600	116	317	26.6	3.4
PL1	92	6	760	114	658	27.0	4.2
PL2	102	7	550	90	292	24.5	4.0

Fig. 2. European Scots pine stands used in the temperature gradient study. Climate and stand values from Reed and Nagel [33] and forest floor thickness from Degórski [14].

val) of the three test methods, and would likely be the best indicator of changes in wood physical properties during initial decay (Fig. 3). If five stakes are sampled, as occurred in our study, RCS would give estimates within 10% of the mean, compared to 14% for shear strength and 28% for hardness. If 15 stakes are taken, RCS estimates would be within 5% of the mean, compared to 8% for shear strength and 12% for the hardness test. Similar results were found with the pine stakes (results not shown). RCS has a low correlation with other wood stake properties, such as number of annual rings, % of summerwood, ray volume, and radius of annual ring curvature [35], which increases the robustness of the test to detect wood strength loss from decay. Our field sample size of five stakes taken every 2 weeks resulted in a 95% probability of detecting wood strength loss as low as 10% (Fig. 4). However, other estimates of statistical precision and power may vary depending on the study sampling design, the experimental material used, and wood decay conditions in different soils.

3.2. Boreal forest soil study

Differences in wood decomposition at the six Scots pine stands along the North/South temperature gradient were clearly shown by changes in wood strength (Fig. 5). RCS

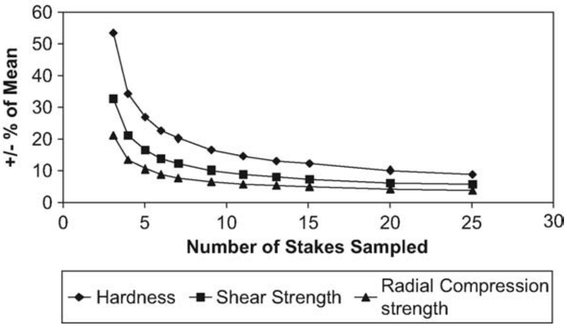


Fig. 3. Estimated 95% confidence intervals widths for wood hardness, shear strength, and RCS in aspen stakes as a function of number of stakes sampled.

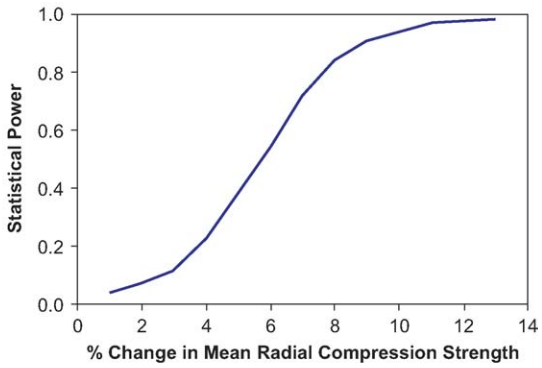


Fig. 4. The statistical power or likelihood of detecting a difference at alpha = 0.05 as a function of % change in mean southern pine RCS ($N = 5$).

loss at the 5 cm soil depth after 3 years ranged from 20% in northern Finland to 95% in central Poland, and closely follow differences in mean annual temperature (Fig. 2). Similar results were found with dry weight loss, which ranged from 3% in northern Finland to 65% in Poland. While the six sites had some differences in average annual precipitation, temperature was the main driver of surface litter decomposition along this North/South gradient [8]. Studies on surface litter and woody residue decomposition in other forest ecosystems have also shown that temperature usually controls OM decomposition in soils where microbial activity is not moisture-limited [6,27,38]. Both RCS and weight loss decreased as stake depth in the soil increased, which likely reflects lower soil temperatures at these depths. Capillary movement of water in the stakes from lower soil depths could also have increased decomposition near the surface, but we do not know if, or to what degree, this occurred during our study.

Mineral soil temperatures would also be affected by forest floor depths, which decreased from FN1 to FN3 in Finland (Fig. 2). Soil temperature would likely increase as the forest floor thickness decreases, and increase the North–South soil temperature differentials among these three stands. In contrast, forest floor thickness was similar in LI1, PL1 and PL2, and does not appear to be a factor in wood stake decomposition differences among the Lithuanian and Polish stands.

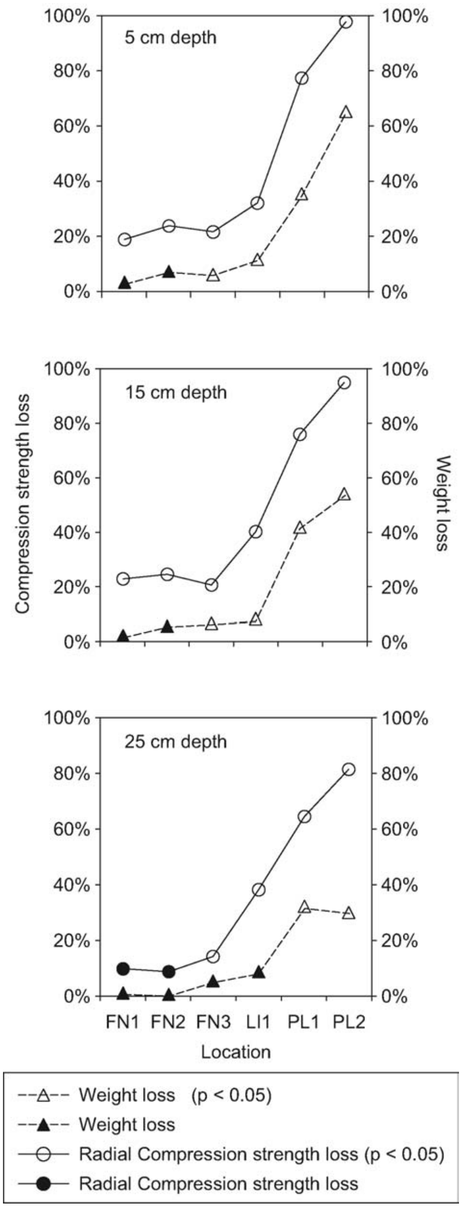


Fig. 5. Dry weight (Δ) and wood strength compression loss (o) for southern pine stakes after 3 years in the mineral soil of Scots pine stands from northern Finland to central Poland. Observations with filled symbols were not significantly different ($P < 0.05$) from control values ($t = 0$) (see Fig. 2 for location abbreviations).

While both RCS and weight loss were good indicators of wood decomposition in the warmer, southern soils (Lithuania and Poland), RCS was more sensitive in colder Finnish soils (Fig. 6). After 1 year, significant RCS loss was found at the 5 cm depth in all three soils. After 3 years, significant RCS losses were found at all soil depths, except 25 cm in northern and central Finland (FN1, FN2). In contrast, no weight loss had occurred in any of the three soils after 1 year, and the only significant weight loss after 3 years was found at

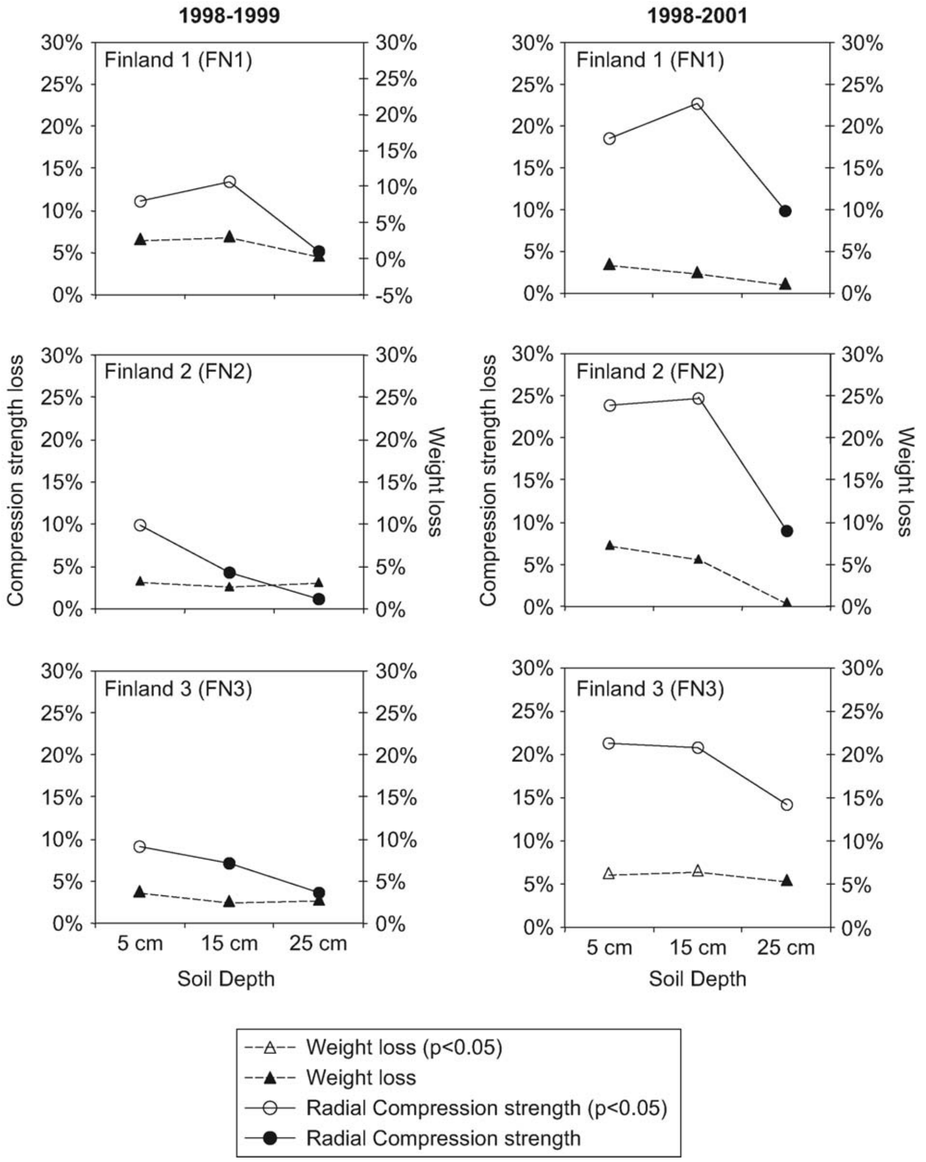


Fig. 6. Dry weight (Δ) and wood strength compression loss (o) for southern pine stakes after one and 3 years in the mineral soil of three Finnish Scots pine stands. Observations with filled symbols were not significantly different ($P < 0.05$) from control values ($t = 0$).

the 5 and 15 cm soil depths in southern Finland (FN3). Microbial attack of cell wall components (lignin, cellulose and hemicellulose) early in the wood decay process can reduce RCS without any detectable change in dry weight [34]. A cubic polynomial equation (RCS loss % = $a + b\ x + c\ x^2 + d\ x^3$ (where x is % dry weight loss) showed the best relationship between RCS and weight loss. No significant differences in regression coefficients were found among the three soil depths, so all the data were combined to develop one RCS/weight loss regression equation (Fig. 7). The intercept from this regression indicated that a RCS loss of ~9% (95% confidence interval of 4–14%) occurred without measurable weight loss. Once dry weight loss began, RCS was highly correlated to weight changes in dry weight, with a ~4:1 RCS loss/weight loss ratio during the initial wood decay stage, defined as a weight loss of up to 10% [40]. Above 10% weight loss, cell walls were so degraded that the RCS/weight loss ratio decreased to < 1:1, and RCS showed little change above 40% weight loss. Similar RCS/weight loss results for southern pine were also reported by Curling et al. [11]. At weight loss > 50%, the stake became very weak and often broke during extraction, but could usually be removed with careful digging. However, if the stake was so decomposed that only broken pieces could be obtained, weight loss could be estimated from specific gravity measurements of the wood fragments (unpublished results).

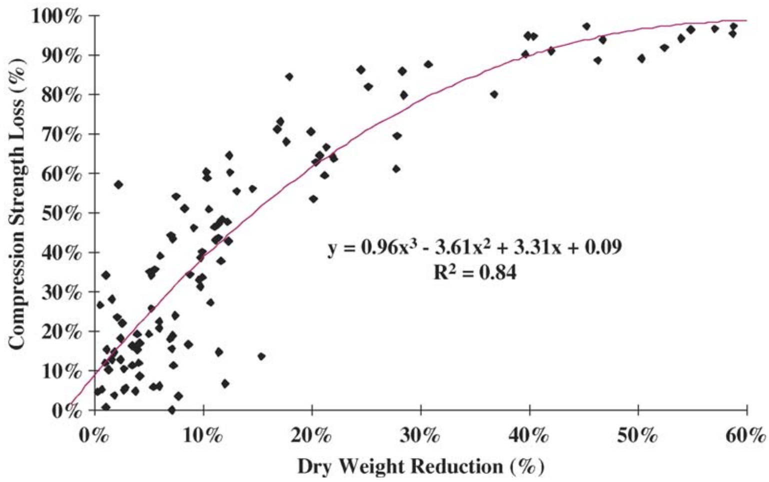


Fig. 7. Relationship of southern pine stake weight loss to change in RCS (N = 135).

While RCS is more sensitive to wood decomposition in early decay stages than weight loss, the RCS to weight loss ratio is affected by the fungal communities that colonize wood. White-rot decay fungi remove all three cell wall structural components, and generally show a smaller RCS/weight loss ratio than brown-rot fungi, which remove only cellulose and hemicellulose [37,41]. While both white- and brown-rot decay can occur in pine sapwood, brown-rot fungi usually predominate [41]. We did not do any fungal isolations, but chemical analysis of our wood stakes, representing a range of RCS and weight loss from the six Scots pine soils, indicated very little change in lignin, cellulose, and hemicellulose concentrations (Table 1). However, when these cell wall components were expressed on a dry weight loss basis, lignin, cellulose, and hemicellulose content showed a proportional decrease as decomposition progressed, which is indicative of white-rot fungal decay [28].

Similar to cell wall components, C concentrations showed little change during decomposition, while total C content decreased (Table 1). In contrast, both wood N concentration and content increased as decay progressed, which was reflected in declining C/N ratios. After 3 years, the N content of wood stakes from northern Finland (FN1) increased by 17%, while the highly-decayed stakes from central Poland (PL2) contained nearly 300% more N than when the stakes were installed. These N gains could come from a combination of microbial N_2-fixation in the wood itself, and N brought in from the surrounding mineral soil by fungal hyphae [9,22,42]. Since both N_2-fixation and N mineralization rates increase as soil temperature increase [19,39], more N would

Table 1
Relationship of RCS loss and weight loss to changes in southern pine cell wall components (A), and carbon and nitrogen concentration and content (B) after 3 years in the mineral soil of Scots pine stands from northern Finland to central Poland (average of three soil depths)

A

Location	Lignin (%)	Cellulose (%)	Hemi-cellulose (%)	Strength loss (%)	Weight loss (%)	Lignin loss (%)	Cellulose loss (%)	Hemi-cellulose loss (%)
FN1	29.6	41.2	21.6	10.5	2.7	2.0	4.3	1.2
FN2	29.3	42.8	20.2	8.9	4.2	1.4	0.8	0.1
FN3	26.4	45.3	20.4	21.3	6.2	9.2	5.7	12.6
LI1	28.4	43.5	20.0	36.5	19.2	10.9	7.8	13.7
PL1	27.6	41.5	20.0	91.2	42.0	44.7	46.8	47.9
PL2	29.4	40.0	18.2	97.7	58.8	61.0	64.5	64.9

B

Location	Carbon (%)	Nitrogen (%)	C/N ratio	Carbon loss (%)	Nitrogen gain (%)
FN1	50.7	0.057	890	0.4	17.0
FN2	51.2	0.049	1045	4.1	20.3
FN3	n.a	n.a	n.a	n.a	n.a
LI1	51.4	0.061	845	12.6	71.4
PL1	51.6	0.107	482	35.1	107.9
PL2	51.3	0.229	224	59.7	295.5

likely be available to wood decay fungi in the Lithuanian and Polish soils. Nitrogen fixation rates also increase as wood becomes more decayed [17], which could supply more N to fungi in the warmer soils. Differences in soil N contents can also affect wood stake decomposition rates [20,43], but no North–South soil N pattern was evident among the six stands [13].

4. Conclusions

Results of our studies show that standard wood stakes can be used to measure wood decomposition at different depths in northern forest mineral soil. The RCS test was a more sensitive indicator of initial wood decomposition (< 10% dry weight loss) than weight loss. However, the strength components of cell walls (lignin, cellulose, and hemicellulose) are so degraded above 10% weight loss that RCS becomes less sensitive to wood decay, and a direct measure of weight loss is a better measure of decomposition. Consequently, the RCS test is best suited for soils where OM decomposition is slow (limited by low temperature, water or oxygen), or in other soils where an estimate of wood decomposition is wanted within a relatively short-time period.

Acknowledgements

We thank Joanne Tirocke, Jennifer Hensiek, Mark Davis (USDA Forest Service), Josh Reed, Melissa Powers, and Mike Hyslop (Michigan Technological University) for their help in laboratory analyses and computer graphics. We also thank Alicja Breymeyer (Polish Academy of Sciences) for her support in all phases of this project.

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