Comparison of decay classification, knife test, and two penetrometers for estimating wood density of coarse woody debris

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Abstract: Inventories of the necromass of coarse woody debris typically involve measurements of density (e.g., kilograms per cubic metre) on a sample of logs, with densities of other logs estimated based on assignment to decay classes. Here, we compare two new devices for assessing density of woody debris, a spring penetrometer and a dynamic penetrometer, with the traditional decay classification and knife test in terms of the strength of the relationship with measured density and the consistency in measurements by four different people. Our evaluation was conducted in a diverse tropical forest and involved only a brief training period in each method. Classifications or scores from all four methods were only weakly correlated with measured density, and consistency among technicians in the measurement–density relationship was highest for the dynamic penetrometer. Therefore, we conclude that when training time is limited and the sampled logs can reasonably be assumed to be representative of all of the logs (e.g., an inventory of one site at one time), it is best to simply assume that the average density of the sampled logs is representative of nonsampled logs. For inventories involving multiple people, limited training, and cases where the sample average is likely to be unrepresentative, we recommend the dynamic penetrometer.

Résumé : Les inventaires de nécromasse des débris ligneux grossiers nécessitent habituellement la mesure de la densité (p. ex. kilogrammes par mètre cube) d'un échantillon de billes alors que la densité des autres billes est estimée en les répartissant dans des classes de décomposition. Dans cet article, nous comparons deux nouveaux appareils pour évaluer la densité des débris ligneux : un pénétromètre à ressort et un pénétromètre dynamique, avec le test traditionnel du couteau et l'utilisation de classes décomposition sur la base de la robustesse de la relation avec la densité mesurée et de l'uniformité des mesures prises par quatre personnes différentes. Notre évaluation a été réalisée dans une forêt tropicale diverse et comportait seulement une brève période de formation pour chaque méthode. Les classements ou les résultats obtenus avec les quatre méthodes étaient seulement faiblement corrélés avec la densité mesurée. L'uniformité de la relation entre les mesures des techniciens et la densité était la plus élevée avec le pénétromètre dynamique. Par conséquent, nous concluons qu'il vaut mieux simplement assumer que la densité moyenne des billes échantillonnées est représentative des billes non échantillonnées lorsque la durée de la formation est limitée et qu'on peut raisonnablement assumer que les billes échantillonnées sont représentatives de toutes les billes (p. ex. dans le cas d'un inventaire effectué à un seul endroit et à un seul moment). Lorsqu'un inventaire implique plusieurs personnes, que la durée de la formation est limitée et dans les cas où la moyenne des échantillons n'est probablement pas représentative, nous recommandons d'utiliser le pénétromètre dynamique.

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Introduction

Woody debris is important in nutrient cycling and water retention in forest ecosystems around the world (Harmon et al. 1986). Coarse woody debris (CWD) (with a diameter over 20 cm excluding standing dead trees) represents a significant portion of the fuel load in many forest fires (Hély et al. 2000) and is an important resource and microhabitat for many forest organisms (Martikainen et al. 2000). In recent decades, increasing attention has focused on the role of CWD in carbon budgets (Brown 2002). Not only is CWD itself an important carbon pool, it also often significantly influences the much larger carbon pool in soil.

Conceptually, the simplest way to carry out an inventory of CWD involves taking, drying, and weighing samples from all individual pieces of CWD (hereafter "logs"), a process that is time-consuming and requires specific equipment (a chain saw and drying oven). The simplest way to reduce the effort involved is to sample only a random selection of logs and assume that the average density of the sample applies to the whole inventory (all densities are dry mass per fresh volume). Of course, the average density may vary over time and among sites due, for example, to differences in the average age of logs and changes in the species composition of living trees. Thus, caution must be used in extrapolating from one set of samples to other places and times.

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Despite Brown's (2002) wish for "Development of an objective, non-destructive portable tool for measuring the density of dead wood regardless of its decomposition class" in her highly cited review, qualitative decomposition classification (hereafter "decay classification") is still commonly used (Canadian Forest Innovation Council 2004). The idea is to classify each log into one of several decay classes based on visual examination (sometimes supplemented by probing with feet or hands) and then use class-specific mean densities to compute mass per unit area. Typically, the first, low-decay classes are defined based on observations of whether leaves and bark are attached and the last, high-decay classes are based on friability of the logs. This approach has the potential to lower the size of the inventory required to reach a given level of confidence and to allow quantification of variation in density over time or space. However, the potential gain in efficiency is often small or nonexistent because in many inventories, a large majority of logs belong to a single class (the class of no bark but solid wood) (Keller et al. 2004). More importantly, the classifications are inherently subjective, raising questions about repeatability. Such questions are of particular concern because in practice, the class definitions themselves often fail to clarify how to assign logs that are decomposing in an unusual way (e.g., bark still attached but can be broken by kicking).

Some of the problems related to the use of decay classification for estimation of the mass of woody debris can be avoided by applying a "knife test" commonly used in northern Europe. This involves pressing a knife into a log and classifying the log according to the penetration (Rouvinen et al. 2002). However, the knife type, sharpness, applied force, and location and orientation of the blade relative to the wood fibers are typically unspecified, despite the fact that these make a difference in penetration. Thus, such measurements presumably remain quite variable, and this test too may lack repeatability.

It is technically simple to construct devices that standardize the penetration force to reduce the subjectivity of this method. Therefore, it is surprising that we are aware of only one journal article documenting use of such methods. Creed et al. (2004) used an inexpensive "penetrometer" designed for soil science and an expensive "resistograph" designed for living trees. As neither of the instruments was designed to study dead wood, they both had problems with detection limits. The penetrometer explained very little of the intraspecific density variation ($r^2 = 0.07$–0.15) due to an overly low upper detection limit and the resistograph somewhat more ($r^2 = 0.23$–0.32) but had an overly high lower detection limit.

Here, we critically evaluate various standard and alternative methods for woody debris inventories, specifically focusing on precision, repeatability across different technicians, and time requirements. Our main objective is to compare four indirect methods for assessing the density of CWD, including two traditional methods and two penetrometers developed for this study. Our focus is on the subjectivity of the methods and the associated potential for systematic differences in measurements among technicians, which in turn could cause systematic errors if different technicians conduct inventories in different areas or time periods. Because we are interested in the potential of these

methods to be applied to standing dead trees as well as fallen woody debris, we also compare penetration of the dynamic penetrometer at a 45° angle and vertical. Finally, to complete our investigation of errors and efficiency in woody debris inventories, we quantify how the precision of total necromass estimates is affected by measuring the height of logs in addition to the width of the cross section.

Methodology

Study area

We carried out the field inventories and sampling in moist tropical forest in Barro Colorado Nature Monument in central Panama (9.15°N, 75.85°W). The average daily minimum temperature was 23.2 °C and the average maximum was 31.1 °C, with little variation between monthly averages at a weather station 60 m above sea level (Leigh et al. 2004). The average annual rainfall was 2600 mm with January, February, and March receiving less than 100 mm. Due to the dry season, the forests are semideciduous. For practical reasons, we worked first in Gigante Peninsula in an area that was relative open agricultural land in the beginning of the 20th century and is now old secondary forest (hereafter "secondary forest") and that is at approximately the same altitude as the weather station. We then moved to the 50 ha forest dynamics plot in Barro Colorado Island, which is an area that has not been opened by humans for centuries (hereafter "primary forest") that is nearly 100 m above the weather station. Despite the very different history, the forest structure in the two sites is indistinguishable to a nonexpert. However, CWD dynamics may differ due to the lack of large trunks of slow-growing and decay-resistant species in the secondary forest.

The forests at the study site are very species-rich, with wide variation in wood characteristics among species. In the forest dynamics plot on Barro Colorado Island, there are on average 53.6 (±4.7 SD) species above 20 cm in diameter per hectare; in the secondary forest in Gigante, the corresponding number is 46.2 (±6.5 SD) (S.J. Wright, personal communication). Wood density of living trees varies widely among these species, from 190 to 880 kg/m³, with a mean of 550 and an SD of 140 (S.J. Wright, personal communication). Some species have distinct heartwood with higher wood density; others have higher wood density on the outside of the trunk (P. Hietz, personal communication). Bark form and thickness, branch architecture, and life history all vary widely (Croat 1978).

General CWD inventory procedures

The field work was carried out between August and November 2008. The work was carried out in three stages in all of which we either carried out (43 samples taken in primary forest) or mimicked (for efficiency, 37 samples taken in the secondary forest) the line-intersect inventory method in which the measurement is taken not on a whole log but just on a point along the log and its immediate proximity (Warren and Olsen 1964). We did not want to take the common approach of combining the line-intersect method and measurements on the whole log, as samples were taken only at the intersection point and we expected all methods to perform best if estimates of density were also based on

Fig. 1. Dynamic penetrometer composed of five stainless steel parts. The moving weight is 1 kg (the total weight of all other parts including nuts is 0.3 kg), the dropping distance of the moving weight is 250 mm, and the diameter of the pin penetrating a log is 5 mm. The point is sharpened like a pencil with the tapering part 10 mm (measured vertically) and is sharp enough to mark a human nail. Additional technical specifications are available on the Web site of the CTFS Global Forest Carbon Research Initiative (www.ctfs.si.edu/group/Carbon/Protocol+Documents).

Moving weight

Can use nuts to tighten here
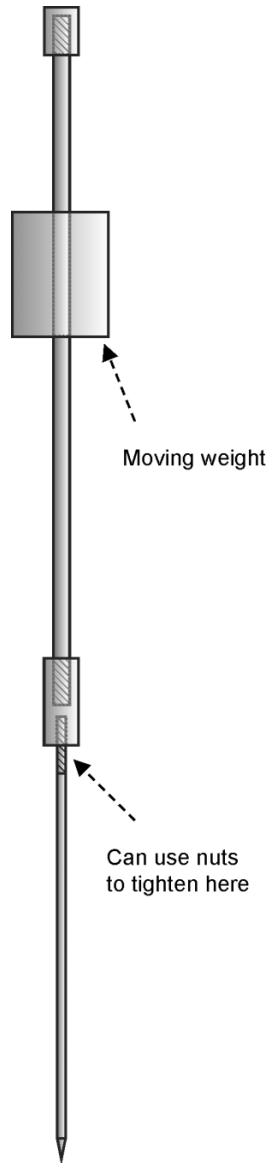
this area of the log. At each measurement point, each of four people measured the density using each of the four methods. In addition, we recorded the width of the cross section (i.e., horizontal diameter with a Haglöf Mantax caliper for 0–127 cm) on all pieces and the height in addition in the primary forest (height was measured on both sides with an identical caliper except that the nonsliding arm was removed). We cut a disc-shaped sample with a chain saw, weighed it with portable balance (Pesola mechanical spring scale for 0–5 kg), and measured its thickness with a digital caliper (0–20 cm). We then took a wedge-shaped subsample

in a randomly chosen direction, weighed it, and transported the subsample back to the laboratory where it was dried at 60 °C to determine the moisture content. The nominal volume of each disc, the volume including void space (which was not measured), was calculated under the assumption of circular cross section, except for the comparison of precision based on circular and elliptic cross section. The density of each piece was then calculated as dry mass per nominal volume (with dry mass calculated as (fresh mass) × (1 – water content]).

To obtain independent assessments by the four field technicians, we first explained each of the four indirect methods for assessing wood density (described below), spending approximately 10 min on each. To assure that the methods were understood, we then located subjectively a log and a point along it and each test technician assessed density with the four indirect methods (one with two variants as described below), while the other three test technicians waited far enough away so as not to be able to see or hear us, with the "trainer" verifying that everything was done correctly. The technicians could subsequently continue to ask us questions and even see others assessing density but it was made clear that they should focus on their independent work and not "learn" from what others were doing.

To efficiently collect data in which all four people measured density on the same logs, we identified locations in the secondary forest with several logs close by to minimize waiting time and obtained data on 37 logs in total. Because we subsequently modified the data collection methodology for the dynamic penetrometer when applied at an angle of 45°, we obtained data on this aspect on only 28 logs. Even though the logs and the location along the log were subjectively chosen, we tried to reach a similar distribution of size classes and stages of decomposition as along randomly chosen transects. We then moved to the primary forest to take advantage of a CWD inventory that was beginning there. In this area, the logs and the locations along the log were selected based on systematically placed transects, and we measured the height in addition to the width of the cross section. As comparison of the indirect methods was very laborious, we continued it for only 43 more logs, and therefore, the data included data on indirect methods on a total of 80 logs. To obtain additional data on the marginal gain provided by measuring the height (vertically) of the cross sections, we continued to make these measurements as we continued the CWD inventory, obtaining width and height data on 137 logs in total.

The educational level of the field technicians varied but all had at least some experience in scientific field work in the forests in question. All were Panamanian citizens and only one of them would have been able to read the English language written protocols, so we translated these orally to them. Due to the absence of one test technician, another similarly trained technician replaced him for nine logs.

For three of the technicians and 13 logs, we measured the time needed for each measurement, starting from when they were standing next to the log with equipment at hand to the time when the measurement was complete. The timing started when all three people had experience with at least 16 logs, after which time the speed did not significantly improve.

Table 1. Summary information on the four methods for assessing wood density.

	Manufacture of the instrument	Approximate price ($US) based on information from Panama, Singapore, and the United States	Average time (range) (s) needed (extremes of three people and 13 logs)
Decay classification	No instrument		8 (2–21)
Knife test	Ready-made	10	20 (4–50)
Spring penetrometer	Mostly ready-made	120	31 (12–63)
Dynamic penetrometer	Custom-made	80	52 (2–86)

Indirect methods for assessing wood density

The decay classification method that we used was nearly identical to that published in Palace et al. (2007) and was similar to dozens of published classifications that have been used throughout the world. The idea is first to examine visually then, if the bark is not attached, to kick the log, and finally, if the log yields on kicking, to grab it with bare hands and determine whether pieces can be broken off with fingers alone. On this basis, the log is assigned to one of the following classes: (1) newly fallen solid wood with leaves and (or) fine twigs still attached, (2) solid wood with intact bark but no fine twigs or leaves, (3) solid wood with bark rotten or gone and no fine twigs or leaves, (4) rotten wood that could be broken when kicked, and (5) highly friable and rotten wood that could be broken apart with bare hands.

The idea was to visually observe the whole log but limit the kicking and grabbing to the immediate proximity of the cross-section of interest. The test technicians kicked and grabbed the logs approximately 0.5 – 1 m from the cross-section of interest in a location looking similar in friability.

In the knife test, technicians inserted a knife vigorously but not with full force and estimated the penetration. The classification was simplified from Mäkinen et al. (2006), which included other information that might contradict with knife penetration. If the blade penetrated fully, we grabbed the log as in the decay classification and used the following five classes: (1) knife penetrates 0–5 mm, (2) knife penetrates 5–20 mm, (3) knife penetrates over 20 mm but not all the way, (4) knife penetrates all the way but wood cannot be broken with the hand, and (5) knife penetrates all the way and wood can be broken with the hand.

As the technicians had a ruler at hand for the third and fourth indirect methods, they often measured the penetration even though we encouraged them to just estimate it. This might be partly due to the fact the Panamanians are more used to inches than metric units and could not easily estimate the thresholds. We instructed the technicians to press the knife on highest points of cross sections up to 0.2 m from the studied cross section to lower the risk that several technicians would apply the knife in exactly the same location. In the secondary forest, the technicians used a stainless steel foldable pocket knife with blade dimensions of 65 mm × 12 mm × 2 mm. The same knife was not available in the primary forest and they used a similar knife but with a significantly wider blade (62 mm × 26 mm × 2 mm).

The spring penetrometer consisted of a Pesola spring scale with pin attached to measure compression. Technicians pushed on this scale to apply 20 kg (or more correctly, 204 N) of force to the pin. The custom-made stainless steel pin was round in cross section, 4.7 mm in diameter, and 590 mm long and had a point sharpened like a pencil (like the dynamic penetrometer in Fig. 1 but 16 mm long instead of 10 mm long) sharp enough to mark a human nail (Table 1). The location was chosen as in the knife test. The instrument was pressed vertically with a force of 20 kg on the scale, a dot marked with a marker, pin pulled out, and the penetration measured with a ruler. The pin had a permanent mark at 200 mm and if the penetration reached this with a smaller force than 20 kg, then the force was recorded. The logarithm of the penetration in millimetres per newton was used in the analyses.

The dynamic penetrometer utilizes a moving weight to apply a standardized force to a point (Fig. 1). Milton N. Garcia (Smithsonian Tropical Research Institute, Panama) suggested the idea of testing a penetrometer with a moving weight and assisted us in designing the instrument. We manufactured it in a workshop in Panama from stainless steel bars of various diameters (Table 1). It is composed of five main parts and a few nuts (Fig. 1) and used in much the same way as the spring penetrometer. A weight of 1 kg was dropped a distance of 250 mm 20 times and the penetration measured as with the spring penetrometer. If the penetration reached 200 mm in 20 or fewer hits, the number of hits required to reach this penetration was recorded instead of the distance. The logarithm of the penetration in millimetres per hit was used in the analyses. To evaluate the potential of the dynamic penetrometer for use with standing dead trees, we also ran tests of the dynamic penetrometer when applied at an angle of 45° angle from vertical and from the central axis of the log.

Analysis

For the decay class and knife test methods, we calculated arithmetic mean woody debris densities for each class. For the spring penetrometer and dynamic penetrometer, we fitted models with two touching linear sections (i.e., piecewise linear models). The joint of the sections was at 200 mm (with 204 N with the spring penetrometer or 20 hits with the dynamic penetrometer), meaning that the left part of each model is based on partial penetration and the right part on full penetration.

To compare the precision of the indirect methods, evaluated as the deviation of the estimate from real density, we computed the average deviation for an individual log over our 80 samples and calculated confidence intervals on this average by bootstrapping (80 data points, 1000 bootstraps). Specifically, we computed 95% confidence intervals as the 2.5 and 97.5 percentiles of the average deviation across the bootstrap samples. Therefore, if the error bars do not over-

lap, the probability that the difference is not real is $2 \times 0.025^2 = 0.00125$ or less.

To compare the potential for systematic error of the different methods, we calculated the absolute value of the deviation of the estimate generated by using the model of one technician and the measurement of another from the estimate generated when using the model and measurement from the same technician. Confidence intervals were calculated by bootstrapping as above. To compare the precision based on circular and elliptic cross section, we calculated the average deviation for an individual log over our 137 samples and computed confidence intervals as above (137 data points, 1000 bootstraps).

Results and discussion

The diameters (width of the cross section) of logs averaged 266 mm (range 201–433 mm) in the secondary forest and 387 mm (201–1674 mm) in the primary forest. The density of logs averaged 323 kg/m^3 (78–714 kg/m^3) in the secondary forest and 276 kg/m^3 (25–1024 kg/m^3) in the primary forest. It is surprising that we had a higher average density in the secondary forest given that living trees there on average have lower wood density; it is possible that very decayed logs were underrepresented in our secondary forest sample because these are difficult to spot. There was no relationship between diameter and wood density.

Comparing methods for assessing wood density

The technicians rapidly grasped the basics of the four indirect methods. The most difficult aspect was remembering the classifications in the decay classification and knife test. However, this is not a serious problem in a normal inventory in which the technicians need to remember just one classification and can carry notes in the field. Decay classification was much faster and the dynamic penetrometer much slower than the knife test and spring penetrometer (Table 1). However, the time difference in an inventory of 500 logs between the slowest and fastest method is only 6.1 person-hours, which is in most cases an insignificant proportion of the total time needed in the inventory. If several measurements are made at different locations on each log, then the difference in extra time required for the dynamic penetrometer becomes relatively more substantial.

In all four methods, the classification or measurement was correlated with wood density, but considerable variation in density remained unexplained (Fig. 2). Due to the large scatter, all four methods perform weakly if the objective is to lower the needed transect length and number of logs sampled to decrease the uncertainty in the estimated total mass. When the density of an individual log is estimated using measurements made by the same technician who took measurements for the regression model fitted based on destructive sampling, on average the estimate is about 40% off with little difference between the four methods (Fig. 3). The more time-consuming quantitative methods ranked higher in precision (lower in error), but the differences are small (Fig. 3). When only the average density is used, the average deviation is somewhat larger average measured density in Fig. 3). Assuming a normal distribution of the amount of woody debris along transect sections, one would

need a 22% larger sample with the decay classification to get the same precision as could be obtained with the dynamic penetrometer or a 76% larger sample if average density alone is used. Not surprisingly, both tested penetrometers performed better than the two instruments tested by Creed et al. (2004), which were not designed for CWD.

We would expect that all methods would be better predictors of density if the sample were restricted to trees of one species or to trees with less variation in wood density and other wood traits, as it would be if it had been taken in a monodominant or low-diversity forest. Thus, it is not surprising that other studies focusing on a single species, Norway spruce (*Picea abies* (L.) Karst.), have found much lower scatter around regressions similar to those in Fig. 2 for both decay classification (Næsset 1999) and a dynamic penetrometer (T. Aakala, personal communication).

The impetus to design and test penetrometers came from attempts to lower the subjectivity of the methods and thus the potential for systematic errors that could obscure differences (or similarity) in wood densities among sites and over time. An examination of the lines representing the fitted functions for different people in Fig. 2 shows that the lines vary the most for the decay classification and the least for the dynamic penetrometer. This suggests that if one technician does the decay classification and the same densities are assumed for logs classified by another technician in the same area and time, the results will suffer from more systematic error than if the same procedure were followed with the dynamic penetrometer. We quantified this by computing the deviations of densities estimated using models fit for a different technician. Decay classification and the knife test were approximately equal in subjectivity (Fig. 4). The dynamic penetrometer was much better and the spring penetrometer intermediate between the best and worst methods (Fig. 4).

In an actual inventory situation when one technician collects data for model calibration and another collects data to which the model is applied, this results in additional systematic error that cannot be eliminated by increasing sample size. The reduction in subjectivity further means that the penetrometer measurements themselves could more reliably be compared among data sets collected by different people. It is important to note that some of the deviation reported in Fig. 4 was not caused by subjectivity but by within-log variation in wood properties. As the technicians had to focus on somewhat different locations, the scores inevitably vary even without subjectivity. Our data do not allow us to quantify this error, but its relative contribution to the total deviation in Fig. 4 is likely to be the highest for the dynamic penetrometer because inherent subjectivity is lowest for this instrument.

Although the dynamic penetrometer emerged as the best method in our comparison, it is far from perfect. Logs of similar density vary significantly in penetration of the dynamic penetrometer (Fig. 2d). This is not surprising, as hollow logs can be covered in strong bark and solid heartwood can be surrounded by decayed, soft sapwood. It is obvious that resistographs modified from those used in arboriculture that would penetrate to the center of the log would reveal more about density, but the dynamic penetrometer is a good

Fig. 2. Density estimated based on width of intersections of pieces of coarse woody debris and (*a*) class of decay classification, (*b*) class of the knife test, (*c*) value of the spring penetrometer, and (*d*) value of the dynamic penetrometer. The circles represent data points of one randomly selected test technician. The lines represent class averages and (*a* and *b*) connecting broken lines and (*c* and *d*) fitted models of the four test technicians. The solid lines are based on the data indicated by circles.
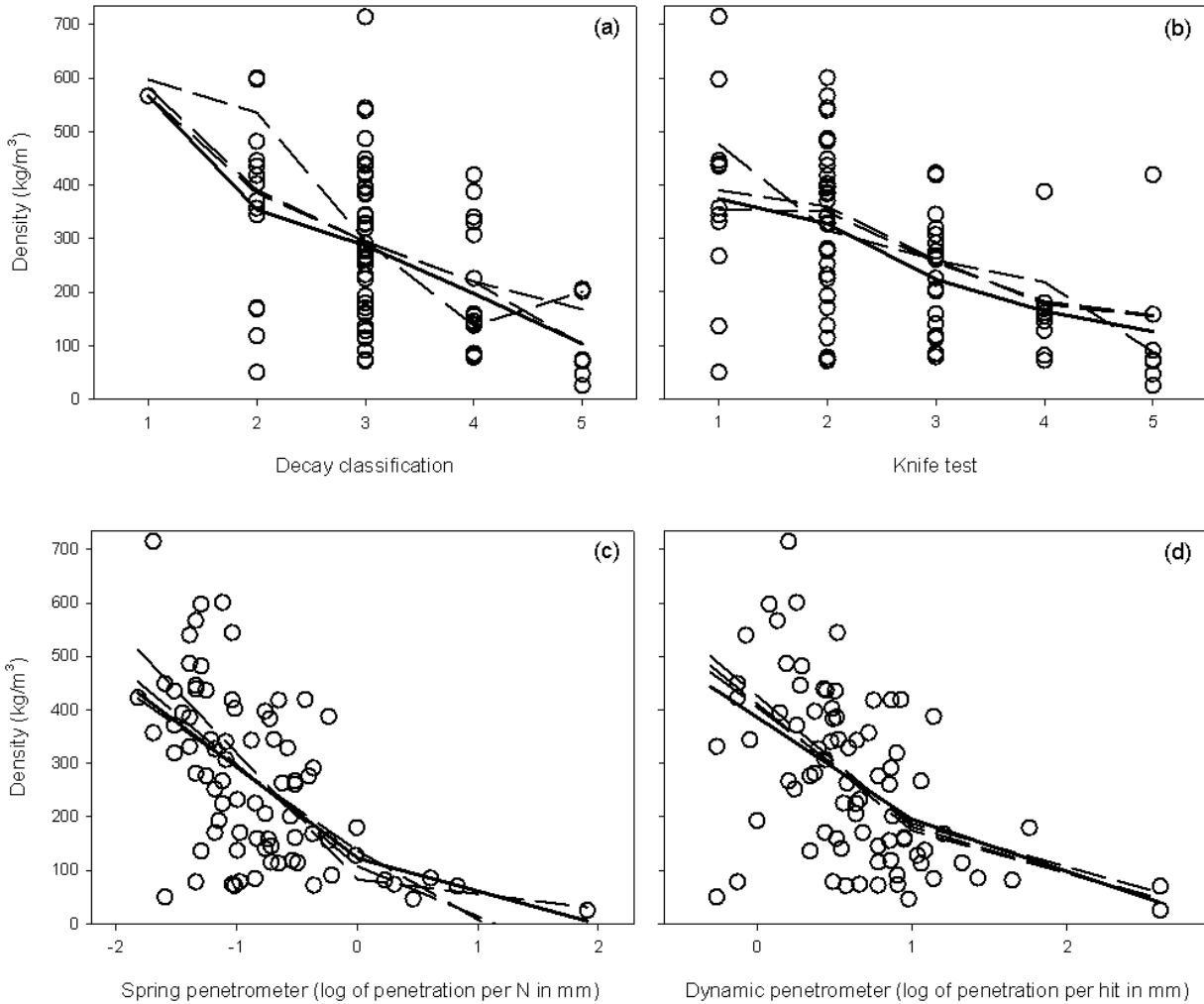
Fig. 3. Precision of the methods evaluated as the deviation of the estimate from real density: averages (columns) and 2.5 and 97.5 percentiles (bars).
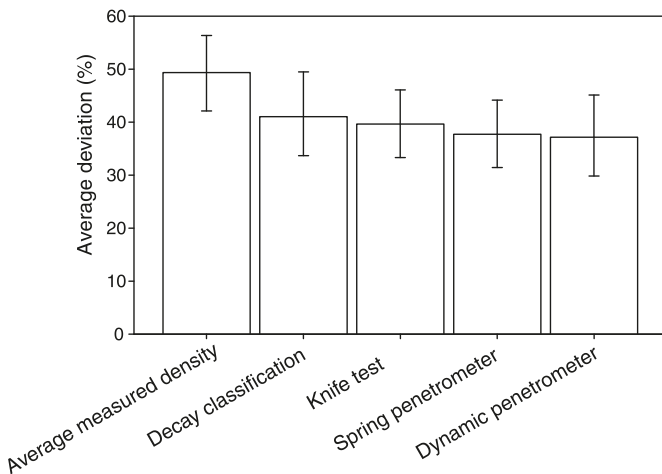
compromise between technical simplicity, low cost, ease of use, and quality of data. We do not know what is the cause of the greater subjectivity of the spring penetrometer measurements relative to the dynamic penetrometer measurements, but it could be caused by the variable level of efforts to keep the pin straight to oppose bending.
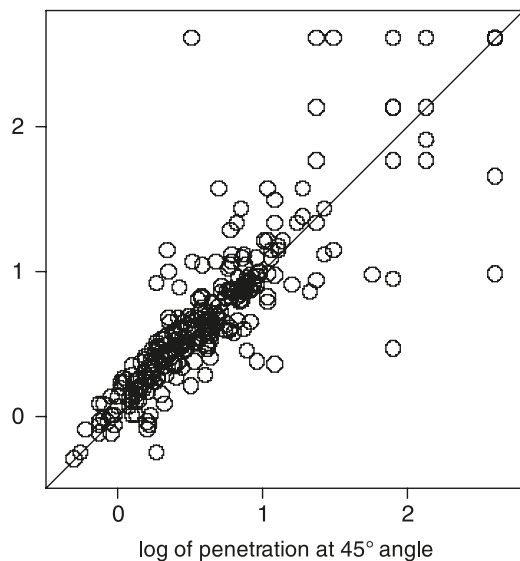
The knife used in the secondary forest was significantly different from the one used in the primary forest. Compared with using a single knife, this increases the scatter in Fig. 2*b* and deviation in Fig. 3. However, it does not increase the subjectivity and deviation in Fig. 4, as all technicians used the same knife for a given log. The lack of a standardized knife type for the knife test causes extra variation that we did not quantify. Therefore, with more variable knife types, the performance of the knife test would have been worse (greater deviance) in Fig. 4.

Our results on the relative precision and subjectivity of the methods are most relevant to situations where technicians receive relatively brief training in the methods. In our study, technicians had approximately 10 min of training on each of the four indirect methods. Longer training periods for the decay classification and knife test, training such as

Fig. 4. Potential for systematic error of the different methods evaluated as the absolute value of the deviation of the estimate generated by using the model of one technician and the measurement of another from the estimate generated when using the model and measurement from the same technician: averages (columns) and 2.5 and 97.5 percentiles (bars).
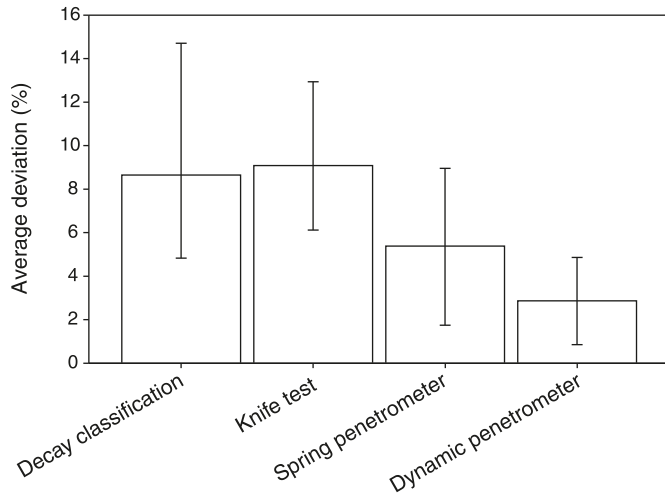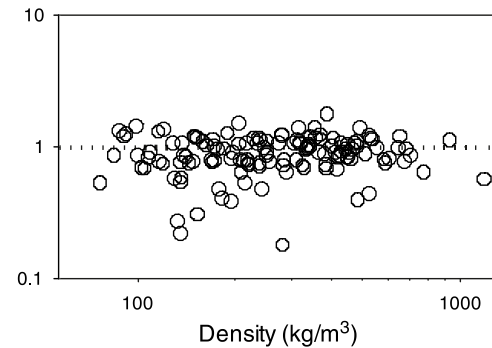

Fig. 5. Relationship of penetration at 90° and 45° angles of the dynamic penetrometer for 72 intersections and four test technicians. The line represents where the data points would fall if penetration were identical at both angles.

Fig. 6. Ratio of cross-section height and width of 137 logs. The data points would fall on the dotted line if height and width were equal. The density here is not based on circular cross section as normally in the article but on a symmetric and elliptic cross section.

Fig. 7. Precision of the methods evaluated as the absolute value of the deviation of the estimate from real density: averages (columns) and 2.5 and 97.5 percentiles (bars). "Circular" refers to density calculated based on only the width of cross sections and "elliptic" to density calculated based on both width and height.
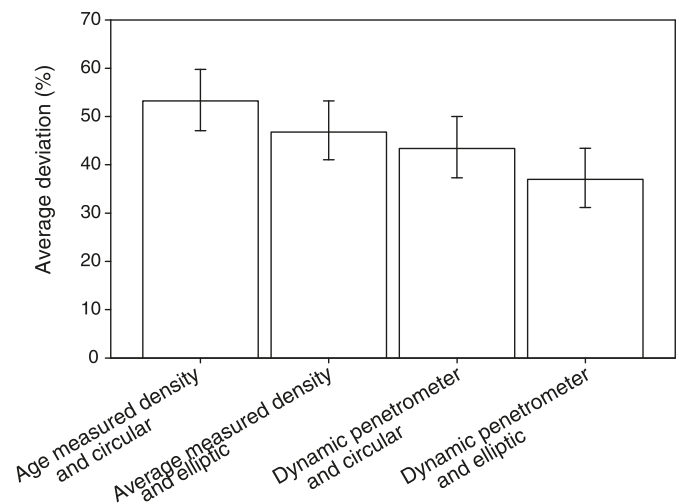
cluding longer written descriptions, photographs, and videos, that can be used consistently across sites and over time.

Dynamic penetrometer at 90° and 45° angles

The penetration of the dynamic penetrometer was nearly identical in both 90° and 45° angles. Data points fell nearly symmetrically on both sides of the equal penetration line (Fig. 5). We also plotted the data on which Fig. 5 is based separately for the four test technicians and did not visually notice deviation from the symmetry seen in Fig. 5. This is surprising, as the potential energy converted to kinetic energy is 29% lower in the case of the 45° angle even with no friction taken into account. The increased penetration relative to energy available in a 45° angle is probably due to the fact that the pin penetrates more easily more parallel to fibers running parallel to the central axis of the log. Our data suggest that the relationship between 90° penetration and density can also be used to estimate density from measurements of standing dead trees taken at a 45° angle.

that often conducted prior to major inventories, would surely have reduced the average deviations of these methods in Fig. 4, especially if they included many exemplary logs of all species in all decay stages. Of course, even longer training periods risk the possibility of systematic differences among technicians, as there may be systematic variation among trainers in classifications or techniques, drift over time in the classifications of a given trainer, differences in the sample of logs encountered and corresponding differences in perceptions, etc. Perhaps the best option to reduce subjectivity and potential for variation and drift in methods such as the decay classification and knife test is to produce and use more extensive documentation of the protocols, in-

Width and height or width only?

We measured the height of the cross section of a log from both sides if we were not able to fit the nonsliding arm under the log. We were able to measure the height with a normal two-armed caliper in only 31% of the logs. In the remaining cases, the higher height was on average 21% or 34 mm higher than the lower, even though the study area was relatively flat. The average height (hereafter "height") per width is 89%. Before collecting data, we correctly hypothesized that height is lower than width. However, we incorrectly hypothesized that this is caused by both tendency of freshly non-circular logs to lie on their flat side and flattening of decaying pieces. If the latter would be common and a significant portion of variability in wood density is caused by the decomposition stage (and not by the wood density of a living tree), we would expect to see lower height to width ratios at lower densities (because density decreases over time); Fig. 6 shows no indication of such a pattern. In contrast, a Swedish study showed a dramatic drop to average heights equal to only 38% of widths in the last decay class (Fraver et al. 2007). This drop is partly explained by the fact that elliptical shape was in the definition of the last decay classes but probably mainly caused by true flattening in the decomposition process.

We quantified the additional value of measuring the height in the same way as we compared the four methods and the use of just the average density in Fig. 3. However, the columns based on circular density in Fig. 7 are not identical to the respective bars in Fig. 3, as the data are for different logs. Measuring the height in addition to width lowers the average deviation (Fig. 7). Equivalent precision in mean density estimates can be achieved without measuring heights by increasing the inventory size: when using a dynamic penetrometer, the required increase is 37%, while it is 29% if no decay classification or quantification is used. Measuring heights improves precision but it is not clear whether the increase in precision is worth the extra work.

Conclusions

In the diverse forest studied here, much of the variation in CWD density remained unexplained by all four indirect methods that we tested. Therefore, for a one-time inventory in such a forest in which a representative destructive sample can be taken, it is best to simply assume that the average density of sampled logs applies also to nonsampled logs. If a representative destructive sample cannot be taken (e.g., heterogeneous landscapes or repeated inventories), use of the average density leads to systematic error. Based on our results, we recommended using the dynamic penetrometer in these cases, especially if multiple people are involved in data collection and the training period is brief. This recommendation is based on the potential of the dynamic penetrometer to quantify shifts in average wood density in space and time due to changes in species composition and (or) the mean age of logs combined with its high repeatability even with minimal training.

Large-scale woody debris inventories such as those carried out by the US Forest Service almost always employ decay classifications, but in combination with extensive training and in areas of lower tree diversity (compared with our study). The repeatability of the decay classification method would no doubt be considerably higher when conducted by experienced personnel. Further, the correlation of decay scores with density might also be higher in forests having fewer tree species. However, even in these conditions, we would expect the decay classification method to be inferior to penetration-based methods in capturing variation in woody debris density due to shifts in the wood density of living trees (as opposed to shifts in the proportions of logs in different decay stages). Future studies should evaluate the overall performance of the dynamic penetrometer compared with traditional decay classification in contexts typical of these large-scale inventories.

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