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Moisture content correction: Implications of measurement errors on tree- and site-based estimates of biomass

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ABSTRACT

Accurate estimates of biomass are required for relating ecosystem functioning to atmospheric carbon regulation. Biomass may be directly measured through field sampling, which can then be used to calibrate biomass predictions from remote sensing and/or modelling. Field sampling generally entails measuring the fresh mass of individual trees or shrubs and then estimating the moisture contents of a representative sub-samples, which are then used to calculate dry mass. Because any errors in the estimation of the moisture content (MC) correction are translated proportionally to the biomass prediction of an individual tree or shrub, care is required to ensure MC estimates are unbiased and as precise as possible. There are numerous different protocols currently applied to attain MC, with these differing in accuracy (bias and precision) and cost of implementation. A dataset of MC of above-ground biomass (AGB) of 1396 individuals (trees or shrubs) was used to assess which protocols for within- and among-individual sampling are likely to provide the most cost-effective estimates of MC within acceptable bounds of accuracy. Monte-Carlo analysis was used to explore key sources of error in within-individual MC estimation. Results suggest these MC estimates may be based on at least the bole and crown components of AGB, with bias resulting if MC is based on stem wood only, particularly in young (or small) individuals. Little gain in accuracy was attained with more intensive sub-sampling (e.g. into foliage, twig, branches, bark, and stem wood components). Moreover, further efficiencies may be gained by applying existing empirical models to estimate the proportion of AGB that is crown based on easily measured variables such as stem diameter, thereby avoiding the resource-intensive process of partitioning to obtain fresh weights measurements of components. However to minimise bias, it is important to undertake MC sampling at each study site, and to stratify sampling among-individuals by both appropriate taxonomic grouping (e.g. plant functional type) and age-class. For a given plant functional type-by-size (or age) strata at a given site a precision of about 4% coefficient of variation of the average MC estimate can be achieved with intensive within- and among-individual sampling. However a precision of 8–10% is achievable using our recommended less intensive but more efficient protocol; derive an average MC for at least six individuals, and for each individual, intensively sub-sample bole and crown components for MC, which is then applied to the fresh weights of these components. This latter estimate may be obtained from partitioning of the AGB, or for the highest efficiency, from predictions obtained from the application of existing representative empirical relationships of partitioning based on the size of the individual.

1. Introduction

In recent decades there has been an increasing demand for accurate quantification of terrestrial biomass carbon to contribute to the mitigation of climate change, and to ensure viable access to carbon markets for vegetation management projects. To facilitate efficient quantification of biomass (high accuracy-to-cost ratio), there has recently been increased scrutiny of field sampling protocols (e.g. Paul et al., submitted for publication). Many workers have assessed the errors in biomass estimates that are attributable to application of allometric models (i.e. biomass of an individual tree or shrub is predicted based on an easily measured variables such as stem diameter) or selection of plots for inventories of variables such as stem diameter to which the allometric models are applied (de Gier, 2003; Chave et al., 2004; Samalca, 2007; Molto et al., 2013). But few workers have considered errors in individual tree or shrub biomass *per se* (i.e. errors in inputs to allometric models). Of those that have (Molto et al., 2013; Magalhães and Seifert, 2015), individual-based errors were assessed in the context of esti-

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mating biomass of the wood via applying stem wood density (ρ, g m^{-3}, or basic wood density) estimates to estimates of stem volume. None of these error propagation studies included errors associated with full direct (i.e. destructive) biomass measurements; namely those associated with correction of fresh mass measurements to estimates of dry mass of above-ground biomass (AGB) via sampling for moisture content (MC_{AGB}, expressed as a proportion of fresh mass).

As estimates of MC_{AGB} are directly multiplied to measurements of fresh weights, any bias in MC_{AGB} estimation directly transfers to bias in estimates of AGB. Despite its potential for introducing bias in biomass estimates, little work has been done to provide justified recommendations on sampling protocols for MC_{AGB}. Moreover, the sampling required to determine MC_{AGB} are perhaps the most expensive (resource-intensive) aspect of direct sampling for AGB, with both within- and among-individual sampling required (Fig. 1).

Determining an efficient protocol to minimise errors in MC is of particular interest for complex sites with mixed-species and age-classes. If protocols required MC_{AGB} estimates for numerous replicate individuals of each age (or size) class of each species present, with each of these being based on detailed within-individual sampling (e.g. picking leaves off twigs to determine the fresh mass of the foliage component), this may often be cost-prohibitive operationally (e.g. costs of quantifying biomass carbon may outweigh any revenue obtained through a carbon market). Hence, recommended protocols for stratified sampling of MC_{AGB} within- and among-individuals need to be as efficient as possible, particularly when seeking to incentivize mixed-species revegetation projects that provide additional environmental benefits, yet attract much less carbon revenue than equivalent monoculture plantings (e.g. Paul et al., 2015).

The most accurate approach to within-individual sampling would entail placing the entire individual in the oven to directly determine dry weight of biomass, thereby avoiding sub-sampling errors. But this is impractical for all but the smallest individuals. Hence, within-individual sub-sampling for MC_{AGB} is generally required. The AGB is partitioned into components which are each weighed fresh, and then randomly sub-sampled to determine the MC of the component ($MC_{Component}$). When $MC_{Component}$ are combined with the fresh weights of the component, the moisture content of AGB (MC_{AGB}) is derived (Briggs et al., 1986). Protocols used for within-individual sub-sampling are described in detail by Picard et al. (2012), with some common approaches listed in Table 1.

Table 1
Alternative protocols for measurement of MC_{AGB}. I, indicates a method used to directly measure the MC_{AGB} of the specific individual; A, indicates a method used to estimate MC_{AGB} of an individual based on applying an average value attained from sampling MC_{AGB} of other individuals of the same strata.

Method	Description of method
I_A	*Detailed multi-component sub-sampling*. Sub-samples of each component of AGB; namely stem wood, bark, branches (including a dead wood component), and foliage
I_B	*Simple multi-component sub-sampling*. Sub-samples of each component of AGB; namely stem wood, bark, branches (including a dead wood component), and foliage. But with the foliage and small branch components being estimated from the total crown mass (foliage plus branches of diameter <4–5 cm), based on the measured proportion of these in representative sections of the crown that are sampled (e.g. 3 or 4 typical canopy branches are partitioned)
I_C	*Two-component sub-sampling*. Sub-samples of AGB bole and crown (which is foliage plus smaller branches of diameter <4–5 cm) components. Note: When sampling small shrubs, only the crown are sampled as there is not a significant bole component
I_D	*One-component sub-sampling*. Sub-samples of AGB stem wood component only, with no sub-sampling of any crown components
A_A	Average of Method I_A applied across other individuals within the site
A_B	Average of Method I_B applied across other individuals within the site
A_C	Average of Method I_C applied across other individuals within the site
A_D	Average of Method I_D applied across other individuals within the site

Some workers (Auclair, 1986; Picard et al., 2012) have suggested that as the different components of a tree do not have the same MC (e.g. Auclair and Metayer, 1980), the finer the stratification, the more precise the biomass estimation. To inform efficient stratified sampling of an individual (i.e. number of components), data is required on which AGB components typically differ in MC, and the variability in these MCs. If resources for field work are limited, an increased stratified sampling within-individuals may come at the cost of decreased sampling intensity among-individuals. Hence as stated by Cunia (1986), for the same budget of site-based sampling of biomass, there is likely to be a trade-off between the number of sampled individuals, and the intensity of sub-sampling within those sample individuals.

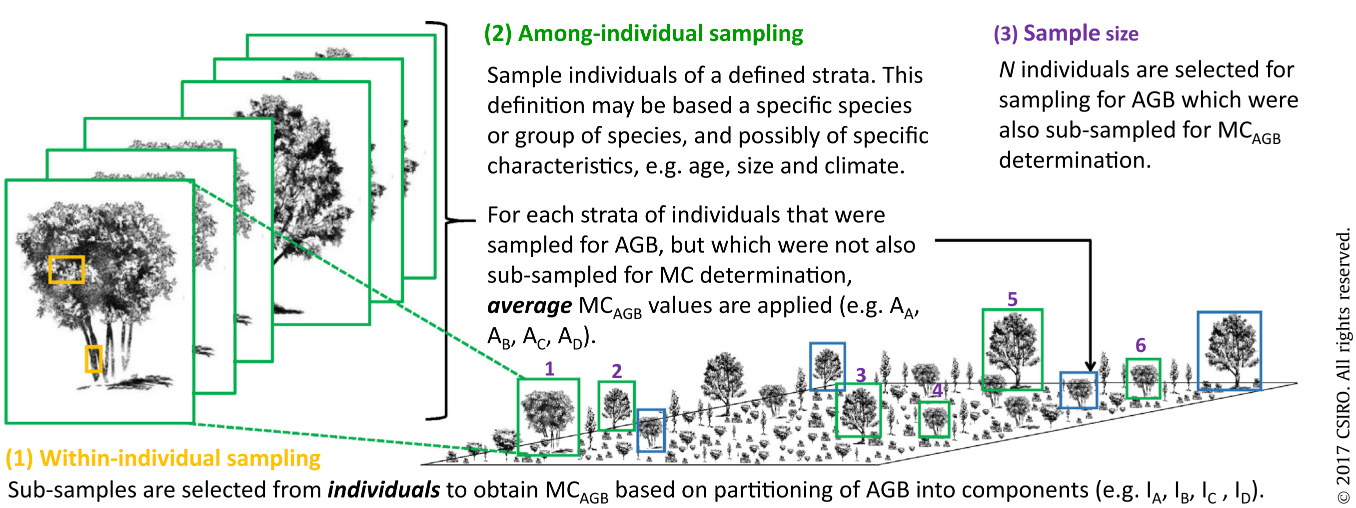

Fig. 1. The three considerations when minimising error in MC_{AGB}; (i) within-individual sampling, (ii) among-individual sampling, and (iii) the number of individuals to sample. The various Methods I_A, I_B, I_C, I_D, A_A, A_B, A_C and A_D, etc. are described in Table 1.