Introduction and Objectives
Forest growth following harvesting is an important terrestrial carbon sink. However, it is difficult to quantify forest ecosystem budgets of C and other elements of interest with confidence, and the uncertainties associated with such budgets are rarely reported. Tree biomass and forest soils present different challenges: Tree biomass is estimated non-destructively using allometric equations, often from older sites, and these equations are difficult to validate; soils are destructively sampled, which results in little measurement error at a point, but large sampling error in heterogeneous soil environments.

In this study, we report nutrient contents of soil and biomass pools in a northern hardwood forest from replicate plots within replicate stands in 3 age classes (14-19 yr, 26-29 yr, and > 100 yr) at the Bartlett Experimental Forest, USA. We compared variation within stands (i.e. variation among the replicate plots or soil pits in a stand) to variation between stands (i.e. spatial variation to the sources of uncertainty derived from allometric equations and measurement error in tissue samples (including destructive and analytical analysis)). We hoped to find that measurement errors would be small compared to natural variation, using common sampling methods, and that our replicate stands would allow for interpretation of nutrient budget changes during forest growth following harvesting.

Sites
We studied nine sites of three stand ages in the Bartlett Experimental Forest, NH (44° 00′-04′ N, 71° 18′-19′ W). Two of the sites in each age class (C1, C2, C4, C6, C8, C9) were intensively studied. Soil and root information comes from these sites, with one pit in each of three plots. Stand inventory data were used from all nine sites, plus additional old-growth and mature stands at Jeffer's Brook and Hubbard Brook Experimental Forest (not shown).

Data Collection
Soils: We excavated quantitative soil pits in 3 plots in each of 6 stands. Soils were collected by depth increment in the mineral soil down to 25 or 50 cm into the C horizon. We used a sequential extraction to define pools in soils (Hartel et al. 2007). Exchangeable C was extracted with NH4Cl (2% w/v). The residue was extracted with cold 1N HNO3 to dissolve amorphous. Silicates were analyzed in a titrator.

Roots: Roots were collected from the same quantitative soil pits (Park et al. 2007). Nutrient concentrations of roots were analyzed in 2007 (Hartel et al., in review).

Tree Inventory: We measured all trees >10 cm DBH within each of four 30 x 30 m plots in each stand. Stems from 2-10 cm DBH were measured on subplots.

Tree Allometry and Tissue Chemistry: In the young stands, 12 trees of six species were husked and used to develop biomass equations (Yanai et al. 2011). The stem, wood, bark, branch, and leaves were subsampled for nutrient analysis. The species studied were Acer rubrum, A. saccharum, Betula alleghaniensis, B. papyrifera, Fagus grandifolia, and Prunus pensylvanica. In the mature stands, bark was collected with a chisel, wood by coring, and leaves with a shugton.

Aboveground Biomass and Nutrient Contents: Aboveground biomass was estimated using allometric equations describing the mass of tree wood, bark, branch, and foliage of trees as a function of DBH. For small trees (<10 cm DBH), we used equations developed at Bartlett (Fatemiet al. 2011). For larger trees, we used equations developed at Hubbard Brook (Vitousek et al. 1974).

Forest Biomass

Monte Carlo Simulation

The uncertainty in biomass and nutrient contents was evaluated with Monte Carlo sampling (Yanai et al. 2012). Nutrient concentrations of biomass by species were randomly sampled from normal distributions defined by the mean and standard error of the reported concentrations. The uncertainty in the allometric equations accounts for the number of trees used to derive the regression equations and the value of each observation (degree of freedom per sample), relative to the sum of squared deviations of the observations used to derive the regression equation (Yanai et al. 2012, Equation 6; Seidner and Cochran 1988, p. 164). Two hundred iterations of total aboveground biomass and nutrient contents were performed for each site and age class. We report the 95% confidence interval (CI) using the 5th and 95th percentile of the simulations. The error of the simulations differ from the nutrient content without error, as reflected in asymmetrical 95% CIs because the biomass equations are non-linear.

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Summary and Recommendations
Uncertainty in allometric equations ranged from 2-7% for aboveground biomass, depending on the stand. Variability in measured nutrient concentrations of tree tissues contributed 1-9% uncertainty (N, Ca, Mg, K). The spatial variation in biomass among pits (S-10%) was always larger than the measurement uncertainties. For soils, variation in soil mass among pits within stands (S-6%) and among stands (S-9%) was similar to the variation in nutrient concentrations (average of 8%, depending on the element and extraction f acidity). Research questions that rely on aboveground measurements will have better power to detect small changes than those that rely on soil pools.

Uncertainty analysis can help direct research effort to areas most in need of improvement. In systems such as the one we studied, more intensive sampling would be the best approach to reducing uncertainty; as natural spatial variation was higher than model or measurement uncertainties.

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Footnotes
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