Nutrient budgets for forested ecosystems have rarely included error analysis, making it difficult to establish the statistical significance of the results. The pursuit of closure in nutrient budgets can provide insight into ecosystem processes and also suggest where more research is needed.

At the Hubbard Brook Experimental Forest, the N budget for the period 1965–1977 showed more N accumulating in living biomass than was deposited from the atmosphere, and the “missing source” of 14.2 kg N ha\(^{-1}\) was attributed to N fixation. More recently (1992–2007), biomass accumulation has been negligible, and streamwater export of N has fallen to ~1 kg N ha\(^{-1}\) year\(^{-1}\) despite chronically elevated atmospheric N deposition, resulting in a “missing sink” of ~6 kg N ha\(^{-1}\) year\(^{-1}\).

The imbalance in the 1965 N budget sparked interest in quantifying N fixation (Roskowski 1980); currently, the N budget closure suggests a missing sink, not a missing source, and researchers are measuring denitrification (Groffman et al. 2009). However, there are large uncertainties in the N budget, some of which have never been quantified.

When estimating forest biomass, researchers commonly report sampling uncertainty but rarely propagate the uncertainty in the allometric equations used to estimate tree biomass. The uncertainty in change over time in biomass at Hubbard Brook is ±6 to ±7 kg N ha\(^{-1}\) year\(^{-1}\), depending on the time interval (Figure 3).

The uncertainty in change in the forest floor is ±21 to ±24 kg N ha\(^{-1}\) year\(^{-1}\) and in the mineral soil ±53 kg N ha\(^{-1}\) year\(^{-1}\). Clearly, the balance of all N sources or sinks to N fixation or denitrification would require more precise estimates of change in soil stores.

Changes in the net hydrologic flux of N (streamflow – precipitation) have less uncertainty than the ecosystem fluxes involving biomass and soils. Gradually, researchers are developing approaches to quantifying uncertainty in ecosystem studies. In this paper, we illustrate current approaches to uncertainty analysis, using the example of the N budget for the Hubbard Brook Experimental Forest in New Hampshire, USA.

Sources of Uncertainty

Sources of uncertainty can be classified into those arising from imperfect knowledge (such as measurement error and model selection error) and those arising from the inherent variability in the system studied (such as spatial and temporal sampling error) (Harmon et al. 2007). For many purposes, the change in a nutrient pool is more important than its size. Figure 3 shows the results of 100 Monte Carlo estimates for the 1997 and 2002 inventory of W6, with the uncertainty in allometry and N concentrations sampled simultaneously for the two sampling dates at each iteration. Because of the consistency of a bias in the calculations, the uncertainty in the change over time (10 kg N ha\(^{-1}\) year\(^{-1}\)) is much less than the uncertainty in the mean at one point in time (108 kg N ha\(^{-1}\) year\(^{-1}\), Figure 1).

Estimating the nutrient contents of forest biomass at Hubbard Brook involves biomass equations and tissue chemistry for 5-6 tree species and 5-7 tissue types applied to thousands of trees. We used a Monte Carlo approach, in which the entire calculation was repeated using random sampling of values for nutrient concentrations and biomass equations defined by the statistical distribution of the sampled trees (Figure 1). The mean for biomass-N content in 1965 is 651 kg N ha\(^{-1}\), and the uncertainty, which has never before been estimated, shows a 95% confidence interval ranging from 562 to 670 kg N ha\(^{-1}\).

Forest soils are notoriously heterogeneous, with both horizontal and vertical spatial variation contributing uncertainty to most sampling approaches. Quantitative soil pits are accurate but not very precise if the number of pits is small, each pit being time-consuming to excavate. More precise estimates can be made by taking a greater number of soil cores, but coring is inaccurate in rocky soils (Levine et al. 2012). Using 60 quantitative soil pits each 0.5 m\(^2\) in area, uncertainty in soil N storage is 730 kg N ha\(^{-1}\) at Hubbard Brook (Huntington et al. 1988). Thus it would require 50 years of observation for a budget error of 14.2 kg N ha\(^{-1}\) year\(^{-1}\) to be distinguishable as a change in the mineral soil. From 1983 to 1998, 15 years post-harvest, there was a non-significant decline of 54 ± 53 kg N ha\(^{-1}\) year\(^{-1}\) (Hamburg et al., in preparation). The total change in soil N storage is thus not significantly different from zero, as assumed in the N budget for Hubbard Brook, but it has an uncertainty of about 70 kg N ha\(^{-1}\) year\(^{-1}\).

Why Use Uncertainty Analysis?

Analyzing the relative contributions of various sources of uncertainty can help identify opportunities to improve allocation of sampling resources. In the case of the N content of forest biomass, individual equations, such as that for bark biomass, may be highly uncertain but not contribute as much to overall uncertainty as an equation with lower uncertainty that describes a more massive ecosystem component, such as wood biomass (Yanai et al. 2010). An optimized sampling design for describing tree allometry might therefore involve greater numbers of trees to describe wood biomass and fewer to describe bark biomass.

Simulating sampling designs of varying sampling intensity (e.g. Figure 2) is another approach to evaluating the efficiency of forest measurements. There are many sampling designs in place that do not optimally allocate resources, and the framework of uncertainty analysis can provide a basis for rational discussion of alternative designs.

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questnetworkandwebsites

We have initiated a research network called QUEST (Quantifying Uncertainty in Ecosystem Studies) to raise consciousness about the value of uncertainty analysis, provide guidance to researchers interested in uncertainty analysis, and support both developers and users of uncertainty analyses. QUEST has a website (http://www.QUESTuncertainty.org) with news feed, relevant papers, and examples of code in SAS, R, stata, and Excel. Please join us if you are feeling at all uncertain.