Steering Committee

Ruth Yanai (Coordinator), SUNY College of Environmental Science and Forestry
John Campbell (Information Management), U.S. Forest Service, Northern Research Station
Mark Green (Statistical Coordinator), Plymouth State University and U.S. Forest Service
Chris Daly (Precipitation), PRISM Climate Group
Rick Hooper (Streamflow), Consortium of Universities for the Advancement of Hydrologic Science Incorporated (CUAHSI)
Jim Clark (Biomass), Nicholas School of the Environment, Duke University
Dan Richter (Soils), Nicholas School of the Environment, Duke University
Mark Harmon (Ecosystem Budgets), Oregon State University

Intellectual Merit

The mission of the proposed Research Coordination Network (RCN) is to facilitate the Quantification of Uncertainty in Ecosystem Studies (QUEST). The calculation of pools and fluxes at ecosystem scales has advanced our understanding of water, carbon, and nutrient cycling. However, uncertainty due to variability or error in observations or representations has rarely been reported. This makes it difficult to determine rates of change over time or compare results across multiple sites with quantitative confidence. Failure to address uncertainties can lead to erroneous conclusions, for example in identifying missing sources and sinks. Uncertainty analyses can also help to improve monitoring efficiency, by allowing sampling designs to optimize information gained relative to the resources required for data collection and analysis.

The QUEST RCN will include the organization of Working Groups addressing five topic areas: atmospheric deposition, stream water export, vegetation, soils, and ecosystem budgets. In consultation with experts on the Statistical Advisory Board, Focus Groups within these areas will address three challenges: (1) clarify the possible approaches to quantifying observation and model uncertainty, (2) demonstrate the use of uncertainty analysis to evaluate the efficiency of monitoring designs, and (3) address the detection of change over time. For all three areas, they will provide examples, make recommendations, and establish wikis for continuing improvement, in addition to publishing articles that can be made freely available on our web site.

To achieve these objectives, we will use multiple approaches to coordination and communication, providing a structure for shared learning and development. Working Groups will communicate through web meetings, conference calls, email, and annual face-to-face meetings. A broader audience will be reached through quarterly webinars and through the QUEST web site, which will have, in addition to the Working Group wikis, pages for Frequently Asked Questions, educational materials, illustrated step-by-step examples, digitial libraries, and a clearinghouse for sharing software, Excel macros, SAS code, R scripts, workflows, and other materials, each tested and documented following QUEST protocols.

The **broader impacts** of the QUEST RCN are potentially transformative. We hope to facilitate a cultural change that makes uncertainty analysis an accepted and expected practice in ecosystem studies. The QUEST network will provide the infrastructure for creating partnerships and advancing discovery within the Working Groups and the web site will promote understanding among a broader audience and contribute to the dissemination of results beyond that possible in the peer-reviewed literature. We will direct outreach to students, early-career scientists, and members of underrepresented groups; the Steering Committee and Working Group participants already represent multiple government agencies, universities, and research organizations. This diversity will enhance our ability to transform the conduct of ecosystem science to include uncertainty analysis as standard practice.

INTRODUCTION

Uncertainty in Ecosystem Studies

In most scientific disciplines, some kind of uncertainty analysis is used to report statistical confidence in results. Clearly, uncertainty is needed for determining the significance of observed differences, for analyzing trends over time or making predictions, and for guiding research investments by identifying which components contribute the most to the overall uncertainty.

In ecosystem studies, however, it is not uncommon for uncertainties to be at least partially ignored. Uncertainty derives from multiple sources, and some reports may focus on natural variation, for example, without addressing uncertainty in underlying models (Figure 1).

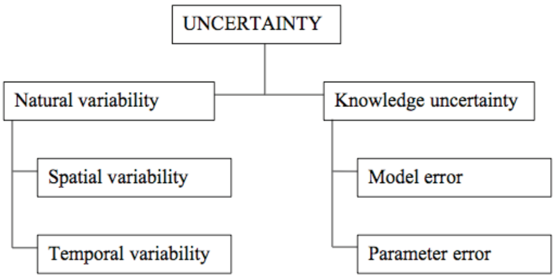


Figure 1. Types of uncertainty commonly encountered in ecosystem studies (Harmon et al. 2007).

The scale and complexity of ecosystem measurements pose special challenges; some issues apply to a variety of ecosystem components and others are unique. In forests, calculating the nutrient content of vegetation depends on multiple non-linear allometric equations, and there is controversy over how to propagate the uncertainty in these equations. Soils are spatially heterogeneous and incompletely sampled. Estimating the uncertainty in components that may not be measured, such as deep soils, dry deposition, groundwater losses, or change over time in tissue concentrations, is essential to attributing uncertainty to ecosystem budgets, but is rarely attempted.

Sources of Uncertainty

Uncertainty derives from multiple sources (Figure 1); in ecosystem measurements, uncertainty in arises both from natural variation in the systems studied and from imperfect knowledge (Harmon et al. 2007). Natural variation cannot be reduced by better measurements, although it can be better described, and understanding the inherent variability in ecosystems is important to interpreting results. For measuring precipitation inputs of nitrogen, spatial variation (including elevation) is the source of greatest uncertainty, and the number and position of precipitation collectors needed to characterize wet deposition of nutrients depends on this natural variation. In contrast, streamwater export of nutrients is commonly measured at a point on a stream that defines the catchment, such that spatial location is not an issue. Instead, uncertainty in estimating stream export derives primarily from the timing of sampling, because many elements have strong relationships between concentration and discharge (with some being diluted and others being concentrated at high flow). Clearly, the effective monitoring of these ecosystem fluxes depends on understanding the natural sources of variation in space and time.

Knowledge uncertainty also has multiple components. Measurement uncertainty is one, which arises from limits of accuracy and precision of field instruments and laboratory analyses. Next, measurements are used in models, such as regression equations, unit conversions, and scaling. Uncertainty in the parameters of these models can be defined statistically and improved through more intensive measurements.

Finally, knowledge uncertainty includes error in model selection. Many different models are possible for calculating nutrient fluxes. For example, to estimate annual stream fluxes, a simple concentration-to-discharge relationship is commonly used along with a continuous discharge time series. However, more sophisticated models are now available, including maximum likelihood estimation (Runkel et al., 2004) and artificial neural networks (Li et al., 2010). These models should make it possible to evaluate bias in simpler models, such as a weekly concentration sample applied to a weekly discharge.

Evaluation of Monitoring Efficiency

Beyond helping to improve the reporting of results in ecosystem studies, uncertainty analysis can be used to evaluate and improve the efficiency of ecosystem monitoring. Ideally, monitoring resources are deployed with the goal of maximizing the information gained per unit effort expended. However, most monitoring designs were not developed based on formal uncertainty analyses. Especially when long-term records are involved, researchers resist scaling back their monitoring efforts, when there is no objective basis for comparing the value of one investment against another. If the intensity of sampling can be shown to be excessive (for example having 25 precipitation collectors at Hubbard Brook, or measuring each of 12,000 trees in one watershed) relative to the information gained, then there is a basis for making difficult decisions about competing demands for labor or other costs.

The Potential for Transformation

Methods and capacity for quantifying uncertainty in ecological systems have advanced dramatically in recent years (Cressie et al. 2009; Luo et al. 2009; Clark 2005). A variety of tools and approaches are now available; the limitation is in the dissemination of these tools and guidance in the selection of various approaches (e.g., Montonari et al. 2009). Uncertainty analyses in ecosystem studies can benefit from expertise in other disciplines that have already established approaches, such as restoration (Moilanen et al. 2009), resource management (Malca and Freire 2010), and aquatic fisheries and conservation (Sipkay et al. 2009; Moore and Reade 2008; Chaloupka and Balazs 2007), as well as in many industrial and socio-economic disciplines. Closer to home, in hydrology and water resources science, there has been heightened interest in promoting uncertainty analysis and in developing new methods for such analyses, particularly in the rainfall-runoff modeling community (Beven 1993, 2006; Alvisi and Franchini, 2011). A special section of Water Resources Research (Montonari et al., 2009) was devoted to a series of papers on uncertainty analysis in hydrology. The propagation of errors in model-based carbon and water analyses is an area of active research (Rauchpach et al. 2005; Pappenberger and Beven 2006; Larocque et al. 2008; Verstraeten et al. 2008). However, these approaches have not yet been applied to nutrient budgets, and there are many unsolved problems, such as when groundwater fluxes are not measured and evapotranspiration is calculated by difference.

GOALS, OBJECTIVES, AND SUPPORTING ACTIVITIES

The mission of QUEST (Quantifying Uncertainty in Ecosystem Studies) is to improve the quality and quantity of uncertainty analyses in ecosystem studies. Our goals are to raise consciousness about the value of uncertainty analysis, provide guidance to researchers interested in uncertainty analysis, and provide support to both developers and users of uncertainty analyses.

Objective 1: Reach out to form a QUEST community.

We will reach out to a broad audience interested in improving the practice of uncertainty analysis in ecosystem studies, ranging from experts in uncertainty techniques to novices who would like to learn to conduct uncertainty analyses. We will recruit participants into five broad Working Groups organized to address critical ecosystem components: Atmospheric deposition, Stream water export, Vegetation, Soils, and Ecosystem budgets. We will also recruit a Statistical Advice Bureau of experts in various analytical approaches and areas of applications.

Objective 2: Develop recommendations on the conduct and application of uncertainty analyses in multiple components of ecosystem studies.

Within each of the broad Working Groups, smaller Focus Groups will tackle three Challenge Areas: (1) Clarify the possible approaches to quantifying uncertainty, (2) Demonstrate the use of uncertainty analysis to evaluate the efficiency of monitoring designs, and (3) Address the detection of change over time. The Focus Groups will develop examples, provide recommendations, and establish wikis for continuing improvement, in addition to making presentations at meetings and publishing articles that can be made freely available on our web site.

Objective 3: Support continuous improvement and sharing of these efforts.

QUEST provides the structure for researchers to learn from one another and solve new problems together. Working Groups will communicate through web meetings, conference calls, email, and annual face-to-face meetings. A broader audience will be reached through quarterly webinars and through the

QUEST website, which will have, in addition to the wikis, pages for Frequently Asked Questions, educational materials, illustrated step-by-step examples, digital libraries, and a clearinghouse for sharing software, excel macros, SAS code, R scripts, workflows, and other materials, each tested and documented following QUEST protocols.

ISSUES TO BE ADDRESSED

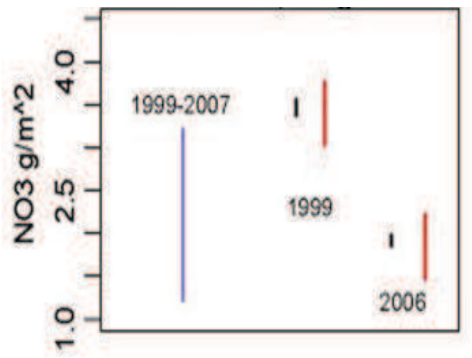
The QUEST RCN will be organized into Working Groups, each addressing issues in uncertainty analysis relevant to different components of ecosystems, such as vegetation, soils, and hydrologic inputs and outputs. Some issues are relevant to multiple areas, but many are discipline-specific, and we expect to reach different but overlapping audiences through the different Working Groups.

Within the Working Groups, smaller Focus Groups will tackle the three challenge areas: approaches to uncertainty, application to evaluation of monitoring, and change over time. Some of the ideas we expect them to address are outlined below. Before assembling the QUEST investigators and undertaking the work, it is difficult for us to specify all the needs they will identify. Other Focus Groups will likely emerge to address additional limitations to application and adoption of uncertainty analysis in ecosystem studies. Although we highlight below some of our own preliminary analyses from Hubbard Brook and other sites, the QUEST Working Groups and Focus Groups will bring their own experience and data sets to the RCN.

Atmospheric Deposition

Uncertainty

Quantifying the influx of water and elements to ecosystems via atmospheric deposition is uncertain mainly because of spatial variability; interpolation between precipitation stations is a major source of uncertainty at the ecosystem scale. Various methods of interpolation are used in precipitation and atmospheric deposition studies (Garcia et al. 2008, Weathers et al. 2006), but the uncertainty in the interpolation is rarely reported. Temporal dynamics generally contribute less uncertainty to estimates of deposition, because precipitation amounts are measured at short intervals (15 minute steps or shorter) or are cumulative, giving good estimates of rainfall amounts at a point. The chemistry of precipitation is also commonly measured on an accumulated sample and is thus representative of the time interval sampled. The uncertainty in a point estimate of elemental deposition may thus be quite low, reflecting the instrumental and analytical uncertainty rather than sampling uncertainty.



Black: Uncertainty (SD) due to missing precipitation volumes modeled as a function of elevation, slope, and aspect, fit to other gages for each sample period.
Red: Also includes variation in concentration estimated as a Gaussian distribution at each sample period with SD set to analytical measurement error.
Blue: Full model (on left) shows uncertainty in annual flux, including precip model, chemistry samples and interannual variability.

Figure 2. Uncertainty in annual wet deposition of nitrate at Hubbard Brook Gage 11 (W6) for 1999 (the wettest year), 2006 (the driest year), and the period 1999-2007.

Shannon LaDeau is applying Markov Chain Monte Carlo in a uncertainty analysis of nitrate deposition, using data from the Hubbard Brook Experimental Forest in New Hampshire. The natural interannual variation contributes uncertainty in annual nitrate loads, as does variation in nitrate concentration across gages and filling missing volume data by regression (Figure 2). Future work will include the spatial uncertainty in various interpolation methods, including regression, kriging, and inverse-distance weighting.

Additional challenges to be addressed by the Atmospheric Deposition Working Group are associated with the difficulty of monitoring dry deposition and cloud deposition and their interaction with vegetation structure. As in other areas, it is important for an estimate of ecosystem inputs to include components that were not measured and thus cannot be described with analytical or sampling uncertainty.

Efficiency of Monitoring

Uncertainty analysis of atmospheric deposition can be applied to evaluate monitoring efficiency. For example, at Hubbard Brook, eleven rain gages are used to estimate anual precipitation for six adjacent experimental watersheds. Thiessen polygons (Viessman and Lewis 1996) are used to define the area characterized by each gage, and precipitation to a watershed is calculated as the average of the surrounding gages weighted by the area contributed by each polygon. To test the effect of sampling intensity on our confidence in the annual precipitation estimates, we sequentially omitted individual precipitation gauges from this analysis. We found that the annual precipitation estimates varied little until five of the eleven precipitation gauges were ignored (Figure 3). This type of analysis can provide a rational basis for deciding, for example, to reduce the intensity of precipitation monitoring in favor of increasing effort in a another aspect of the ecosystem where uncertainty is higher.

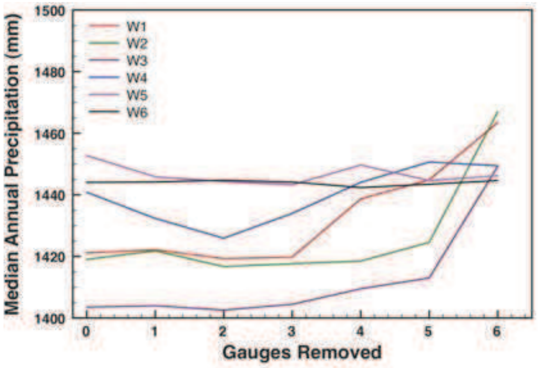


Figure 3. Annual precipitation estimates for six experimental watersheds at Hubbard Brook as precipitation gauges are removed.

Change over Time

Similarly, uncertainty analysis can be used to describe the confidence in change over time in atmospheric deposition as a function of monitoring intensity. Carrie Rose Levine has conducted an uncertainty analysis of air pollutants in precipitation for the New York State Energy Research and Development Authority (NYSERDA). The standard error of the slope of a regression of sulfate deposition from 1987 to 2010 decreased as the number of stations increased (100% represents the 22 collectors in operation during that time period) (Figure 4). The optimal sampling intensity depends on other factors such as the cost and the science and policy needs.

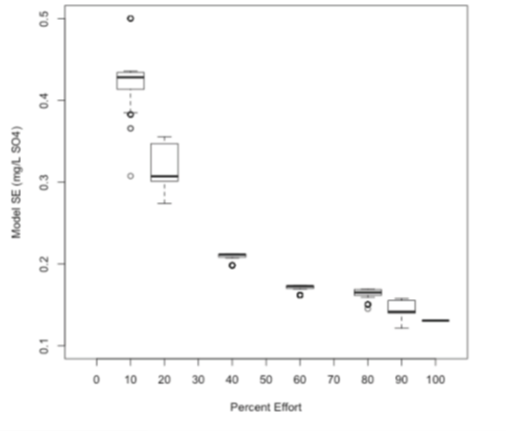


Figure 4. Uncertainty in change over time in sulfate in atmospheric deposition in NY as a function of sampling intensity (22 stations = 100%)

Streamflow and Nutrient Export

Uncertainty

In contrast to atmospheric deposition, which is problematic because of spatial interpolation, stream water export is difficult to characterize primarily because of high variability over time in both discharge and concentration. Methods for calculating solute fluxes include assuming constant concentrations between measurements, interpolating linearly between measurements, and using correlations such as that between discharge and concentration. The model selected is known to affect flux estimates (Johnes 2007, Birgand et al. 2010, Wang et al. 2011), but many of the comparisons of methods compare only the flux estimates, not the uncertainty in the flux estimates.

Mark Green has estimated fluxes of dissolved inorganic nitrogen (DIN) via a bootstrapping methodology. This approach produced a daily series of DIN concentrations by using daily flow values and resampling existing DIN samples from similar flow rates. This approach was repeated 1000 times to determine the uncertainty in material fluxes. An example distribution for annual DIN flux for the 1997 to 2002 period is shown in Figure 5.

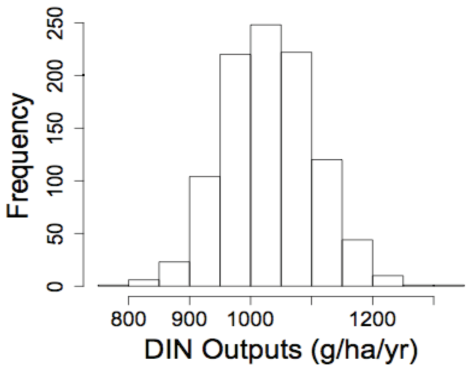


Figure 5. Distribution of 1000 bootstrap estimates of annual DIN flux from HBEF Watershed 6 during the 1997 to 2002 period.

There are many other possible ways to calculate stream export of solutes, even from the same sampled data, such as using various regressing models to predict concentration from discharge and other factors. A Stream Loads Focus Group has already formed to address uncertainty in model selection, following a workshop on ecosystem uncertainty organized by John Campbell in 2011. This Focus Group, led by Doug Burns, is analyzing export of four solutes from five long-term experimental watersheds, comparing simple linear interpolation with a composite method (Aulenbach and Hooper 2006) that uses regression models to interpolate stream chemistry between sampling dates. The uncertainty in the composite method remains to be addressed, as it depends on the serial autocorrelation in stream concentration; this topic could be addressed by a future Focus Group using high-frequency data, such as that described below.

Efficiency of Monitoring

Although stream discharge has been measured continuously, ever since the advent of chart recorders, stream concentrations have traditionally been sampled at frequencies of weekly or less. Recently, hydrologic flux monitoring has begun to use higher-frequency instruments (15-minute) to provide more refined estimates of fluxes (e.g., Pellerin et al., 2009). High-frequency concentration data can be subsampled to generate lower frequency data to identify the relationship of uncertainty and sampling effort (e.g., Stelzer and Likens 2006, Birgand et al. 2010). For sites at which streams have been sampled for many decades, this approach can be used to quantify the value of sampling more streams as opposed to sampling them more often. Would it be better, for example, to sample a few streams continuously or more streams on an intermittent schedule? The answer may differ depending on the site and solute in question and even on what questions are being asked. The Streamwater Working Group will have access to a large number of sites, some with long data records, which will allow them to make recommendations about approaches to evaluating monitoring decisions.

Change over Time

One of the goals of streamwater monitoring is to detect change over time. Commonly, trend detection is conducted on calculated flux measurements without considering the uncertainty in the flux values themselves. Mark Green used bootstrap resampling as described above (Figure 5) to DIN export, to give the first estimate of uncertainty in DIN export over the 50-year Hubbard Brook record (Figure 6). Multiple methods of flux estimation, as described above for the uncertainty of hydrologic fluxes, will be used by the Streamwater Working Group to explore the consequences for detecting change over time.

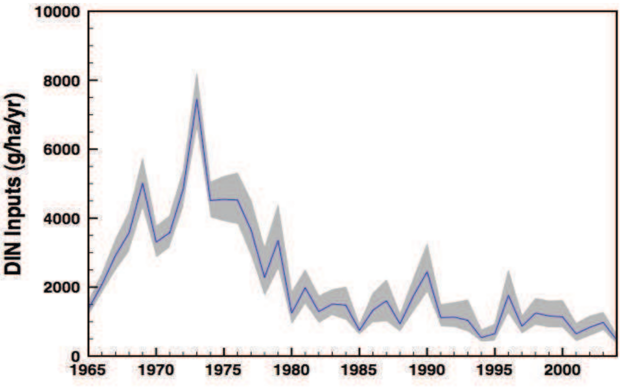


Figure 6. Annual export of DIN at Hubbard Book W6 (median of 1000 bootstrapped samples and 95% confidence interval).

Vegetation

Uncertainty in Forest Biomass

For systems of small stature, such as grasslands or tundra, the carbon and nutrient content of vegetation can be assessed independently on multiple plots, and reporting the variation across plots is sufficient to describe the uncertainty in the estimates. Forest ecosystem budgets, however, generally use allometric equations to estimate the biomass of tree components. The uncertainty in these equations should be included in estimates of uncertainty in nutrient budgets, along with the uncertainty in nutrient concentrations of tissues and the measurement and sampling error. Traditionally, this was not done, perhaps because the earlier researchers did not know how to do it. Whittaker et al. (1974, p. 241) reported that "the problem of confidence limits for treatment of forest samples by logarithmic regression is unsolved." It is certainly also the case that uncertainty calculations are easier to make now than they were a few decades ago.

Yanai et al. (2010) published the first example of uncertainty in the nutrient content of forest biomass, using a Monte Carlo approach. Earlier studies had used this approach to evaluating uncertainty in biomass, but not nutrient contents. Specifically, biomass with uncertainty had been reported for tropical forests (Chave et al. 2004), temperate hardwood forests (Fahey et al. 2005), temperate conifer plantations (Sicard et al. 2006), and oak woodlands (Harmon et al. 2007). The majority of ecosystem nutrient budgets, however, still do not account for uncertainty in allometric equations. At best, they report the variation across multiple sample plots (e.g., Richter et al. 2000). Some have incorrectly described uncertainty in the regressions (e.g., Fahey et al. 2005, Harmon et al. 2007); the information required to accurately describe uncertainty is not commonly reported. The approach used by Yanai et al. (2010) required unpublished data from Whittaker et al. (1974) to represent uncertainty in the allometric equations (Figure 7). Other approaches use the variance and covariance matrix of the parameters (e.g., Sicard et al. 2006) or resampling with replacement from the original allometric data (Chernick 2008).

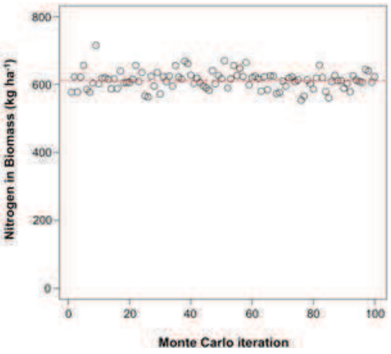


Figure 7. 100 Monte Carlo estimates.of nitrogen in aboveground biomass in W6 at Hubbard Brook.

An important issue in the use of uncertainty in estimation of biomass is the uncertainties introduced at each level of scaling, which have never been addressed simultaneously. For example, when calculating nutrient contents, allometric equations must be applied for tissues of contrasting concentration (e.g. bark, wood, foliage) within a tree. Summation of components provides the tree-level estimate of biomass or nutrient contents, and summation of trees in a plot provides plot-level estimates. However, the fitting procedure of these allometric equations usually provides information only on the error distribution among trees, and, in the best of circumstances, on the relationship of error terms among components within trees. Errors due to differences among plots or regions are usually unknown, making it difficult to estimate the uncertainty associated with the application of equations not developed locally. The Vegetation Working Group will make the research community aware of these limitations, provide recommendations, and actively promote the development of studies to address these issues, such as comparing allometric data obtained from different locations.

Evaluation of Monitoring Designs

Uncertainty analysis can identify opportunities for reducing uncertainty by better allocation of sampling resources. For example, a Monte Carlo analysis of the N content of forest biomass (Yanai et al. 2010) can provide information about which of the allometric equations are most important to improve, based on their effect on overall uncertainty. This is not the same as the uncertainty in the individual equations, because some equations are more important than others to the final result. For example, although the uncertainty in the equation for bark biomass is higher than for wood biomass (Whittaker et al.

1974), this uncertainty contributes less to the uncertainty in total biomass N, because the wood contains so much more N than the bark. In this data set, branches have both high uncertainty in the biomass equation and high N content, and thus contribute the greatest uncertainty (34 kg N/ha) to the overall estimate of N in biomass at Hubbard Brook (which had an uncertainty of 66 kg/N/ha) (Yanai et al. 2010).

This case study also illustrates the use of uncertainty analysis to evaluate the optimal intensity of sampling. There are a large number of vegetation plots arrayed across the Hubbard Brook Valley, from which we selected different numbers of plots to investigate the effect of sampling intensity on uncertainty. With only 5 plots, the uncertainty in N contents of the ecosystem was 15%. With 30 to 60 plots, it was 7%. Adding more plots does not reduce the uncertainty below that contributed by the other sources, which was 7% (Yanai et al. 2010). There are many sampling designs in place that do not optimally allocate resources, and the framework of uncertainty analysis can provide a basis for objective evaluation of alternative designs.

Change over Time

Very often, ecologists and managers want to know the extent to which an ecosystem property such as biomass has changed over time, or is expected to change in the future. For projections, knowing the uncertainty associated with the model used to estimate future properties bounds the limit of detectability of future changes. For example, Coulombe et al. (2010) found that the uncertainty in growth and yield equations was greater than the change expected due to climate change. In change detection, expected changes are usually far less than the actual state variable. Determining differences usually means comparing two relatively large and uncertain numbers. The difference may end up being much smaller than the uncertainty associated with the operation. Knowing how much uncertainty is carried forward in such operations enables us to put the result in its proper perspective, and to understand how to improve the detectability of change.

There are many possible approaches to quantifying uncertainty in vegetation change over time, and the selection of the correct approach may not be immediately obvious. For example, although the uncertainty in N in biomass at Hubbard Brook at one point in time was ±54 kg N ha^{-1} (Figure 7), our ability to detect change over time is much better, ±5 kg N ha^{-1} (Figure 8). It is important to recognize that uncertainty in the allometric equations and tissue concentrations pertains equally to any point in time, and to apply any sampled error terms simultaneously for all observations at each iteration of the Monte Carlo (Yanai et al. 2010). In this case, if Whittaker's equations (Whittaker 1974) are in error about, for example, the mass of the branches of sugar maple trees, they are equally in error at both time steps. This source of error does not contribute as much to the uncertainty in detecting differences between plots or sites or repeated sampling dates as it does to the uncertainty in the mean (Figure 8). Note, however, that applying uncertainty independently for each tree will greatly underestimate the uncertainty in the ecosystem biomass, as the errors will tend to cancel out (becoming zero in the case of infinite numbers of trees). QUEST will address these issues, providing examples developed by the Vegetation Working Group.

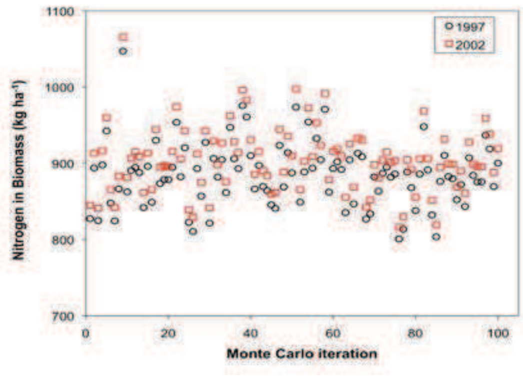


Figure 8. Nitrogen content in aboveground biomass at Watershed 6 at Hubbard Brook in 1997 and 2005, 100 iterations of a Monte Carlo. The uncertainty in the difference between years is much smaller than the uncertainty of either biomass estimate.

Soils

Uncertainty in Soil Properties

Soils are notoriously difficult to sample. They can be indurated in dry seasons or liquid in wet seasons. They commonly have rocks or roots that obstruct easy excavation. Soil heterogeneity can be extreme even at the sub-meter scale. Recent studies by Fraterrigo et al. (2005) and Li and Richter (2010) quantify soil heterogeneity within the scale of individual management units (farm fields or forest stands) as a function of land-use history, showing that precision can sometimes be obtained only at the cost of very high sampling intensity (Li and Richter 2010).

Most soil sampling schemes involve depth profiles, because of the pronounced vertical gradients of many soil properties (Robertson et al. 1999). Samples from known depths or horizons can be collected from the sides of soil pits or with a corer or sampling box of known volume inserted into the soil with a punch tube or slide hammer. To scale up from point samples to the whole profile requires knowing the mass or volume of soil with depth, which is especially difficult in rocky soils. Quantitative soil pits provide a better measure of rock volume than cores, in rocky soils, but they are time-consuming to excavate (Hamburg 1984, Vadeboncoeur et al. in press). Finally, there are uncertainties in the laboratory analyses required to estimate soil properties, often with many steps in the process (drying, seiving, grinding, digestion, and analysis).

Evaluating uncertainty at depth in soils is especially problematic. Most soils information is drawn from superficial horizons, despite the fact that plants can root deeply and that the full unconsolidated soil system is often much deeper than is appreciated. At the Calhoun Experimental Forest, nearly half of the soil nitrogen depleted by tree uptake to support the first 40 years of forest growth originated from the 35 to 60-cm layer of the soil (Richter et al. 2000), a depth rarely sampled in ecosystem studies. In recent reviews of land-use affected changes in soil carbon, about 90% of >300 studies reviewed sampled soil to no more than 30-cm depth (Post and Kwon 2000, West and Post 2002, Richter and Mobley 2009). Because many important ecosystem processes take place at >30-cm depth (Richter and Markewitz 1995, Harrison et al. 2011), surficial soil sampling presents special challenges for linking soils and ecosystems. In cases where budgets depend on estimating total soil pools, uncertainty in pools deeper than those measured needs to be addressed.

The Soils Working Group will address these sources of uncertainty. We expect that the uncertainty introduced by post-collection processing is small compared to the natural variation in soil properties, and that spatial variation is greater than temporal variation, but the answers will depend on the nature of the ecosystem and the soil properties being measured. Developing protocols that are well suited for specific sites is critical to estimating soil properties and for monitoring change over time. It is more often of interest to estimate change in storage than soil pools, whether balancing nutrient budgets or evaluating carbon sequestration potential for climate change mitigation.

Because of the heterogeneity of soil systems, soils are often inadequately sampled for characterizing change over time (Stone 1975). Many examples can be found in the literature of estimates of carbon sequestration or inventories in which soils at particular sites are sampled with but one or a few point samples. Compounding the soil sampling problem is that sites are frequently characterized with few reports of sampling errors or spatial heterogeneity. At the Calhoun Experimental Forest in South Carolina, soils have been sampled repeatedly on multiple 0.1-ha plots, ever since the site was planted with loblolly pine in 1957. Changes in soil N are dramatic in both surface and deep soils (Figure 9). In this case, the sampling design allows natural variation to be characterized (plot to plot). Long-term soil experiments like this one, especially if they are intensively sampled, allow for many sources of uncertainty to be characterized.

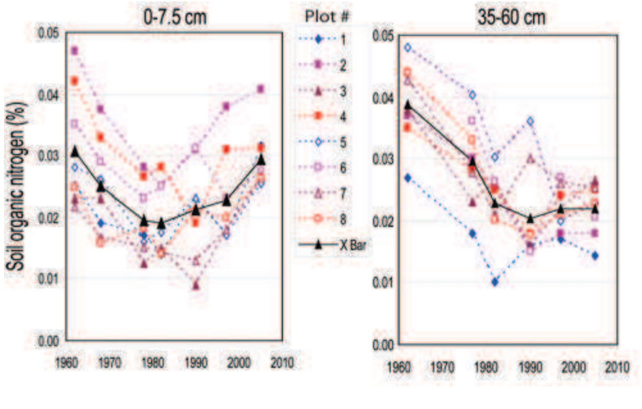


Figure 9. Total soil N in samples from two depths in eight 0.1-ha plots at Calhoun Experimental Forest in South Carolina. The patterns illustrate that within-plot sampling protocols (composites made from twenty individual 2-cm diameter samples) obtain high quality, representative samples from each plot.

Soil science is long overdue for a critical review of field sampling and sampling designs for monitoring change over time. The Soils Working Group will review contemporary methods used at a number of long-term ecological studies. Members of the Northeastern Soil Monitoring Cooperative are already working on papers describing the challenges involved in resampling soils and the uncertainty due to lab-to-lab differences in analytical procedures; these efforts could be supported as a Focus Group by the QUEST RCN.

Changes in the Forest Floor

The forest floor, which is the accumulation of organic horizons above the mineral soil, is a critical component of some ecosystems. The forest floor is attractive to monitor because it is easier than the mineral soil to sample repeatedly. In the case of soil carbon change, forest floor dynamics have been extrapolated to estimate change in the mineral soil (e.g. Houghton et al. 1983, Harmon et al. 1990), an interpretation not justified by any uncertainty analysis (Yanai et al. 2003). The forest floor must be distinguished from the mineral soil in ecosystem budgets, as forest floor dynamics may depend more on patterns in aboveground cycling of organic matter and nutrients (Yanai et al. 1999) and even show changes in opposite directions from those in the mineral soil (Bohlen et al. 2004a, Bohlen et al. 2004b).

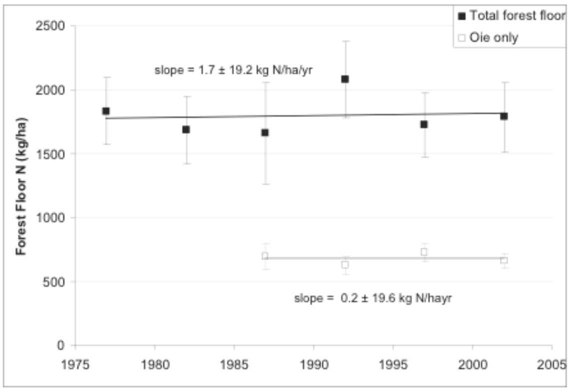


Figure 10. Nitrogen content of the whole forest floor and the Oie horizon alone (when sampled separately), at Hubbard Brook W6. Error bars show 95% confidence intervals for the mean.

Uncertainty in changes in the forest floor can contribute to uncertainty in ecosystem budgets. At Hubbard Brook, forest floors were sampled consistently at a 5-yr interval from 1977 to 2002, allowing the rate of change over time to be described by linear regression, with associated uncertainty. Even with 60-80 samples at each collection date, the 95% confidence interval on the slope for the rate of change in N content ranged from -21 to +24 kg N ha^{-1} y^{-1} (with an insignificant mean accumulation rate of 2 kg N ha^{-1} y^{-1}) (Figure 10). Although the estimated rate of change is negligible, the uncertainty is important to our confidence in ecosystem budgets, as will be seen below.

In addition to the mineral soil and the forest floor, Focus Groups within the Soils Working Group may take on topics relevant to the quantification of uncertainty in related ecosystem pools and fluxes, such as coarse woody debris, soil respiration, denitrification and other gas fluxes from soil, or belowground carbon allocation. Alternatively, if there is enough interest, these topics may become the purview of new QUEST Working Groups.

Ecosystem Budgets

The function of the Ecosystem Budgets Working Group is to address the issues that arise when combining information from multiple ecosystem components, such as, but not limited to, those addressed by the other Working Groups. Some of the questions that arise also pertain to some operations within components, such as the need to address whether the error structures of the parts being combined are independent.

Combining components in a budgetary framework can provide the possibility of cross validation, as when an estimate can be arrived at by two independent sets of measurements. For example, nutrient uptake can be measured at the root surface and scaled up to the ecosystem using the root surface area of the ecosystem, and then compared to nutrient uptake budgeted as the sum of the nutrient fluxes in aboveground litter production, root turnover, and nutrient accumulation in perennial tissues (Yanai et al. 2009). Obviously, testing whether the two estimates are in agreement requires quantifying the uncertainty in each.

Another important example of such an ecosystem budgetary calculation is the comparison of hydrologic inputs and outputs, which can be compared to changes in storage in vegetation and soil pools.

To take Hubbard Brook as an example, atmospheric inputs of N currently exceed streamflow outputs by ~7 kg N/ha/yr, with an inter-quartile range of ~2 kg N/ha/yr around that estimate, using our approach to uncertainty estimation. Much attention has focused on the nature of this "missing sink" for N, with some arguing that denitrification has increased over time (Hamburg et al., in review). However, as described above, the uncertainty in change in N storage in the forest floor alone is 45 kg N/ha/yr. The uncertainty in the change in soil storage has yet to be estimated. Similarly, the first N budget for the Hubbard Brook Experimental Forest in New Hampshire (Bormann et al. 1977) described a "missing source" of 14.2 kg N/ha/yr, which was attributed to N fixation, based on the assumption that the change in soil N storage was zero. Needless to say, there was no uncertainty analysis presented with that budget. To our knowledge, there has yet to be a complete uncertainty analysis published for any forest nutrient budget. A comprehensive uncertainty analysis for a marsh ecosystem found the uncertainty in the inputs and outputs to be larger than the means (Lehrter and Cebrian 2009).

To guide the development of uncertainty analysis for ecosystem budgetary calculations, this QUEST Working Group will select ecosystem sites with which to develop case studies of uncertainty budgets. They will assess uncertainties due to natural variation, the uncertainty in which depends on sampling intensity; measurement error, which will likely be small relative to other sources of uncertainty; parameter uncertainty, which will differ according to the models used; and model selection. Competing models could be compared within and across sites to evaluate their estimation of fluxes and associated uncertainty.

In the Ecosystem Budgets Working Group, the Focus topics may not follow the Challenge Areas addressed by the other Working Groups, but will likely be organized around various types of problems involving multiple ecosystem components. Carbon budgeting is among the hot topics, with uncertainty in soil storage playing a key role. The Ecosystem Budgets Working Group will benefit very directly from the materials and recommendations developed by the other Working Groups and will likely provide a lead role in developing standards for their products.

RESEARCH COORDINATION PLAN

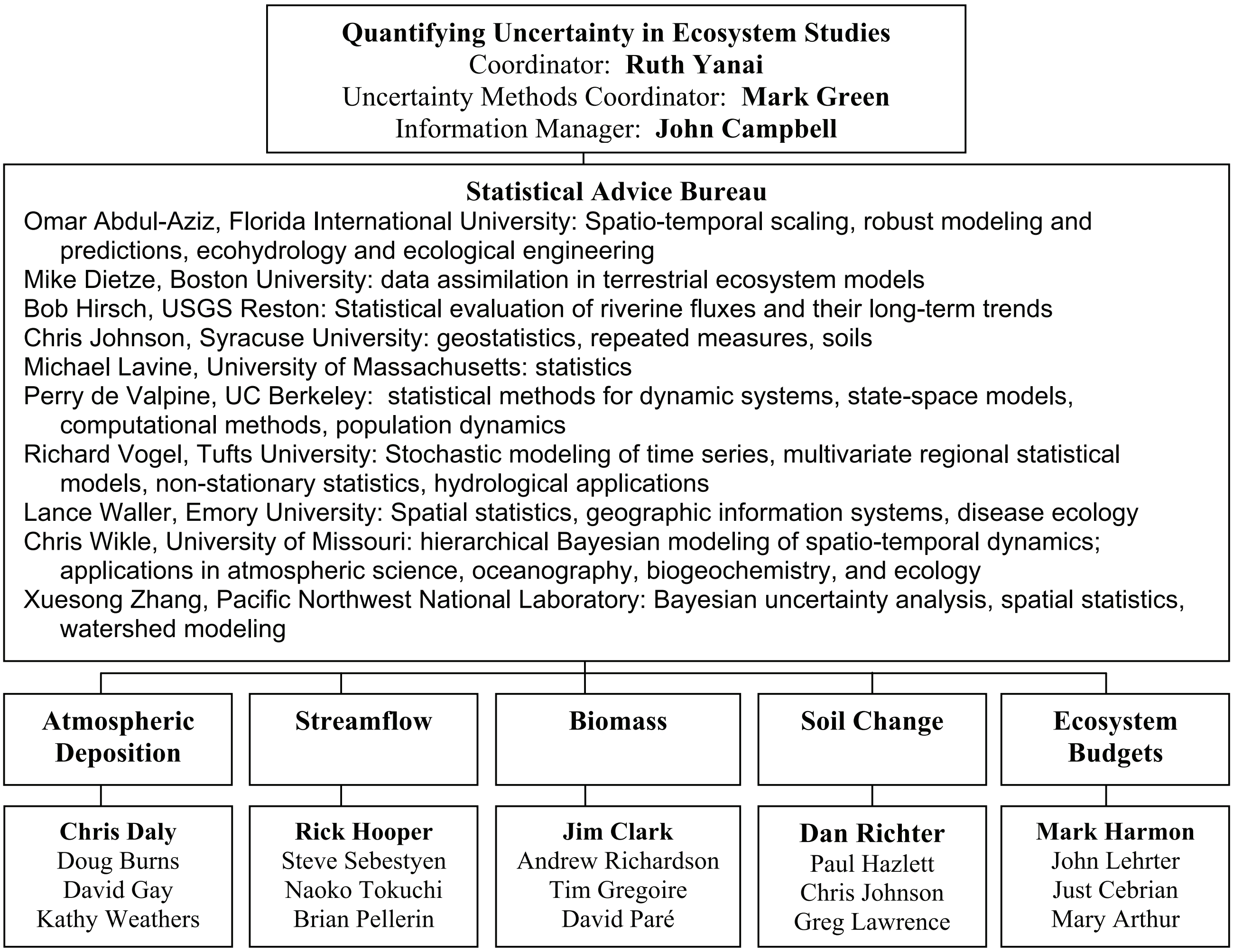
Working Groups

The QUEST RCN will be organized into Working Groups defined by major ecosystem components (Figure 11). Within each Working Group, we expect smaller Focus Groups to take on the three Challenge Areas (uncertainty, monitoring, change). The presentations at QUEST Symposia (described below) in years 2, 3, and 4, should help crystallize the identity of these Focus Groups and give them a deadline for presenting first drafts. Quite likely, additional Focus Groups will emerge to tackle problems even more important than those we have so far identified.

The Steering Committee consists of the leaders of the five Working Groups together with the Leadership Team of Yanai, Campbell, and Green. The Steering Committee will coordinate efforts across Working Groups, helping to define the projects and identify participants in Focus Groups, including those from the Statistical Advice Bureau (described below). A large number of people have expressed interest in QUEST--177 people are on the QUEST mailing list. Contact us at quantifyinguncertainty@gmail.com if you would like to be added to our list!

Statistical Advice Bureau

The greatest criticism of a previous QUEST RCN proposal, submitted in 2011, was that there was a lack of identified statisticians. We will assemble a Statistical Advice Bureau, whose members may be approached by scientists faced with challenging problems in uncertainty analysis, and who will share their expertise via workshops, tutorials, discussion groups, wikis, and the journal articles produced by QUEST Focus Groups. A number of experts have already agreed to serve on the QUEST Statistical Advice Bureau (Figure 11) representing a variety of approaches and applications. We will continue to recruit members of the Statistical Advice Bureau as well as members of the Working and Focus Groups.



Quantifying Uncertainty in Ecosystem Studies
Coordinator: **Ruth Yanai**
Uncertainty Methods Coordinator: **Mark Green**
Information Manager: **John Campbell**

Statistical Advice Bureau

Omar Abdul-Aziz, Florida International University: Spatio-temporal scaling, robust modeling and predictions, ecohydrology and ecological engineering
Mike Dietze, Boston University: data assimilation in terrestrial ecosystem models
Bob Hirsch, USGS Reston: Statistical evaluation of riverine fluxes and their long-term trends
Chris Johnson, Syracuse University: geostatistics, repeated measures, soils
Michael Lavine, University of Massachusetts: statistics
Perry de Valpine, UC Berkeley: statistical methods for dynamic systems, state-space models, computational methods, population dynamics
Richard Vogel, Tufts University: Stochastic modeling of time series, multivariate regional statistical models, non-stationary statistics, hydrological applications
Lance Waller, Emory University: Spatial statistics, geographic information systems, disease ecology
Chris Wikle, University of Missouri: hierarchical Bayesian modeling of spatio-temporal dynamics; applications in atmospheric science, oceanography, biogeochemistry, and ecology
Xuesong Zhang, Pacific Northwest National Laboratory: Bayesian uncertainty analysis, spatial statistics, watershed modeling

Atmospheric Deposition	**Streamflow**	**Biomass**	**Soil Change**	**Ecosystem Budgets**
Chris Daly Doug Burns David Gay Kathy Weathers	**Rick Hooper** Steve Sebestyen Naoko Tokuchi Brian Pellerin	**Jim Clark** Andrew Richardson Tim Gregoire David Paré	**Dan Richter** Paul Hazlett Chris Johnson Greg Lawrence	**Mark Harmon** John Lehrter Just Cebrian Mary Arthur

Figure 11: Organization of QUEST, showing the Leadership Team, the Statistical Advice Bureau, and the five Working Groups. The Working Group Leaders are also on the Steering Committee. Just a few names of participants are listed with each Group; additional members will be recruited continuously. Focus Groups are not shown.

Research Communications

Quarterly Webinar

QUEST will host quarterly webinars throughout the 5-year project to educate the broader ecosystem science community, promote our activities, recruit QUEST participants, and bring in new ideas. The webinars will be broadcast via services such as WebEx or AdobeConnect and will be archived on our web site for viewing at any time.

Topics for webinars will be developed with input from Working Groups and from the QUEST web site audience. Initially, webinars will focus on teaching simple approaches to uncertainty analysis given by members of the Statistical Advice Bureau. Later, webinars will highlight findings of QUEST researchers and Working Groups. Speakers from outside the field of ecosystem science will provide fresh perspectives.

Opportunities to engage in QUEST activities will be advertised at the beginning and end of each webinar. Recruiting of new members will be a perennial goal of the QUEST RCN.

Website

The mission of the proposed RCN is to make uncertainty analysis more accessible to the ecosystem science community. To that end, we have begun to develop a publicly accessible website http://www.quantifyinguncertainty.org, which will provide general information on uncertainty analysis, opportunities to get involved in the RCN, and guidance for users implementing uncertainty analyses with their own data.

To date, we have conducted uncertainty analyses in Excel, R, WinBUGS, SAS, and Stata, and we expect that other software and tools will follow, thereby making these analyses broadly accessible to a wide variety of users. All programs and macros used in QUEST projects will be made freely available over the internet. Before posting them, they will undergo testing and meet standards for documentation and review that will be developed in the QUEST Working Groups.

The website will include a wiki section. A wiki is a website that provides a resource for the creation and editing of several interlinked pages by any user. These pages will provide a resource for FAQs, tips and advice, and conversations about uncertainty methods that anyone can edit. This is a useful forum in which people can connect with others doing similar work and find answers to questions about their own methods and approaches. Additionally, the interlinked pages allow users to easily navigate between related subjects. We have had several requests to post libraries of relevant publications, and these could be organized through wiki pages.

Publications

The articles produced by the QUEST Focus Groups will be published in peer-reviewed journals using open-access options. Open-access options allow articles to be distributed free of charge, which means that we can post them on our web site and also that anyone who finds QUEST articles by other means will not pay to get them from the publishers. Open Access publication will allow unrestricted access to the results and recommendations from the Focus Groups, and will increase the availability of this information to interested researchers, educators, and students.

Annual meetings

The five Working Groups will meet simultaneously once per year in a physical location, as well as meeting more frequently via video conferencing, etc. We propose holding this meeting in the two days prior to the ESA or AGU meeting, and at the same location, to save on travel expenses and to provide for continued interactions for those people participating in the larger meeting.

Symposia and Workshops

Symposia and Workshops are an important mechanism of outreach for Quest. We will hold a QUEST Symposium in years 2, 3, and 4, one at each of AGU, ESA, and ASA, focused sequentially on Uncertainty, Monitoring, and Change. Planning for these events will help develop Focus Groups, and the results and recommendations presented at the Symposia will form the basis for wikis and published papers. Workshops can be offered at these meetings and at any meetings attended by QUEST members. Several of the QUEST Steering Committee members have already offered such workshops at the annual meetings of their respective professional societies.

Video conferences

Video conferencing within Working Groups will be conducted using software such as WebEx or AdobeConnect subscription. One advantage of these services over free access to Skype is that the conferences can be recorded and made available for later viewing on the QUEST web site.

Timeline and Products

2013: Outreach: recruit Interested Parties and members of Working Groups. Launch the QUEST web site, and solicit suggestions via a questionnaire. Begin quarterly Webinars. Convene Working Groups, meeting virtually.

2014: Identify Focus Groups within each Working Group to prepare papers on Approaches to Uncertainty, developed via wiki, and present them in a QUEST Symposium prior to submitting them to journals. Continue development of virtual QUEST community.
2014-15: Focus Groups within Working Groups address issues related to Monitoring Efficiency, developed via wiki, present them at a QUEST Symposium, and prepare papers for publication. Continue other QUEST activities.
2015-16: Focus Groups within Working Groups prepare papers on Detecting Change over time (unless they have developed different ideas for products) and present them at a final QUEST Symposium.
2016-17: Final sets of papers completed by Focus Groups. Wikis continue to collect examples and improve recommendations in all topic areas.
Continually: Support Working Groups, Focus Groups, outreach to the broader community, and self evaluation.
Annually: Meetings of the Working Group participants at a common location.
Quarterly: Webinars open to all interested parties. Working Groups report to each other.
Monthly: Meetings (virtual) of the Steering Committee, review of requests for support.
Weekly: Updates to the web site, responses to questions.

MANAGEMENT PLAN

Organizational structure

The QUEST RCN has a Steering Committee of eight members (Figure 11). The leaders of the Working Groups are members of the Steering Committee, which helps assure coordination across Working Groups. The Steering Committee also includes an overall Coordinator (Ruth Yanai), a coordinator for Uncertainty Methods (Mark Green), and a Network Manager (John Campbell).

There will be five Working Groups at the outset of the RCN. However, a new Working Group can be established at any time by petition to the Steering Committee. The chair of the new group will then be added to the Steering Committee. Within the Working Groups, smaller Focus Groups will make commitments to tackle Challenge Areas, present and publish papers, and initiate wikis. There may be overlap in the membership of Focus Groups within a Working Group and also across Working Groups.

Membership in QUEST will be very broad, not limited to those people involved in the Working Groups or Focus Groups. Anyone with interest in quantifying uncertainty in ecosystem studies can search the website, contribute to the wikis, contribute reviews or examples of tools and software, or join QUEST listserve. Our outreach efforts are intended to maximize awareness of these opportunities and recruit members at all levels of expertise and possible involvement.

Scope

The scope of the QUEST RCN is meant to be broad and we hope to attract more researchers in additional subject areas as time goes on. Examples of topic areas for new Working Groups are groundwater and gas fluxes. Alternatively, these topic areas may be taken up within the current Working Group structure.

It is important for us to have participation from watershed studies, so that the Ecosystem Budgets Working Group can work with data sets that include hydrologic inputs and outputs as well as vegetation and soils. We do not restrict the activities of the other Working Groups to data from these sites, because participants with expertise outside of small watershed settings are important to the success of those working groups. For example, in the Soils and Vegetation Working Groups, the majority of the participants who have expressed interest to date are not associated with small watershed sites.

In the QUEST RCN, we will explore a broad range of statistical approaches for estimating and partitioning sources of uncertainty in ecosystem calculations, including likelihood and Bayesian methods when appropriate. Each working group, with help from the Statistical Advice Bureau and wiki site audiences, will populate a list of relevant methods, beginning with nonparametric Monte Carlo approaches using sampling algorithms to randomly sample reported distributions or raw data to generate uncertainty estimates. We intend for each of the Working Groups, using experts from the Statistical Advice Bureau, to consider, contrast, and compare multiple options for approaching uncertainty analysis.

Allocation of resources

The resources to be allocated through QUEST are modest; the primary resource is the intellectual capacity and uncompensated time and energy of the participants.

The paid staff of QUEST will consists of one part-time webmaster/administrative assistant. The Webmaster will fill requests for minor tasks (e.g. adding material to the web site) on a first-come, first-served basis, presuming that these can be accomplished in the time available. For more time-consuming activities, if a backlog develops, the list of requests will be posted in priority order and reviewed monthly by the Steering Committee.

Programming support will be provided to Working Groups ($30,000 per year is budgeted in years 2-5). Requests for support will be presented to the Steering Committee. These requests will be reviewed monthly and prioritized. We will likely have experienced programmers available, but we expect that in most cases groups will recruit their own programmers to provide this support.

Support for travel to our annual meeting will be allocated by the Working Groups with oversight by the Steering Committee. Groups may choose to provide full support to a small number of participants or partial support to a larger number. A sum will be set aside to support the attendance of graduate students and early career scientists.

Finally, QUEST will provide for Open Access publication of the papers developed by the Focus Groups. We have budgeted for three papers from each of the five Working Groups, addressing each of the Challenge Areas (Uncertainty, Monitoring, Change). There will be fewer of these papers if multiple Challenge Areas are combined, or if not all of the five groups completes all of the challenges on schedule. We also expect Focus Groups to emerge outside of our Challenge framework. Resources will be allocated to additional papers produced through QUEST by application to the Steering Committee.

Assessment plan

The Steering Committee will be responsible for evaluating the QUEST RCN. A list of major stakeholders and other beneficiaries will be established at the onset of the program and will be updated throughout the program by reaching out to various individuals and groups through avenues such as email, the QUEST website, and meetings and conferences. The stakeholders contacted will include federal and state agencies (e.g., US Forest Service, US Geological Survey, New York State Energy Research and Development Authority), environmental monitoring networks (e.g., National Atmospheric Deposition Program, Clean Air Status and Trends Network, Soil Climate and Analysis Network), and individual research scientists and students. The Steering Committee will also contact international partners and organizations. Stakeholders will be polled annually using an on-line survey to determine what aspects of the RCN are most useful, how the information is being used, and what needs improvement.

QUEST website usage will be tracked with Google Analytics to determine general information about who is accessing the website and what areas of the website are most in demand. The website will also have a registration page that will be used to track individuals downloading programs and code and further develop the list of contacts. Information obtained from the website statistics and on-line surveys will serve as basis for decisions about how best to allocate time and resources.

COORDINATION PLAN

Members of the leadership team have been involved in several QUEST efforts since the QUEST RCN was first proposed in 2011. Two Synthesis Working Groups have been funded by the LTER Network Office. After the first workshop, in 2011, a prototype Focus Group formed to compare models for interpolating stream chemistry, using five long-term research sites, led by Doug Burns. The second SWG, in 2012, addressed uncertainty in precipitation; this work continues and will result in a paper in Frontiers, led by Campbell. Shannon LaDeau, supported by an NSF EAGER grant to Yanai, is conducting a hierarchical uncertainty analysis of precipitation at Hubbard Brook. Craig See, a Yanai student, is leading an analysis of uncertainty due to gaps in monitoring preciptation and stream fluxes; we will solicit the participation of additional sites at the LTER All Scientists Meeting in September 2012, where there will be a QUEST workshop. Also, in 2011-2012, the New York State Energy Research and Development Authority funded an analysis of long-term monitoring programs for sulfur, nitrogen and mercury in New York State, as a Fellowship supporting Carrie Rose Levine, a former Yanai student. She will lead a paper using the NYSERDA examples, along with others, to illustrate the use of uncertainty analysis to guide the improvement of monitoring designs.

Individuals from the following sites have been involved so far in proposals to conduct ecosystem uncertainty analyses: Bear Brook Watershed (Maine), Biscuit Brook (New York), Calhoun Experimental Forest (South Carolina), Duke Forest (North Carolina), Coweeta Hydrologic Laboratory (North Carolina), Fernow Experimental Forest (West Virginia), H.J. Andrews Experimental Forest (Oregon), Hubbard Brook Experimental Forest (New Hampshire), Huntington Forest (New York), Kiryu Experiment Watershed (Japan), Luquillo Experimental Forest (Puerto Rico), Marcell Experimental Forest (Minnesota), Niwot Ridge (Colorado), Sleepers River (Vermont), and Turkey Lakes (Ontario).

Other groups are relevant to the QUEST RCN. The Northeastern Soil Monitoring Cooperative was started by Greg Lawrence and Scott Bailey in 2007 (http://www.uvm.edu/~nesmc/). Activities include evaluating the effectiveness of soil resampling in detecting change over varying time periods, developing a publicly accessible database linked to available archived soil samples, and establishing a quality assurance soil reference sample exchange (round-robin) to evaluate inter-laboratory consistency. The QUEST RCN could support some of these efforts as Focus Groups within the Soils Working Group.

Dan Richter, Leader of the Soils Working Group, brings to QUEST the benefits of an earlier RCN, which produced a new global inventory of long-term soil experiments on all continents (http://ltse.env.duke.edu/), accumulating metadata of experimental objectives, methods, ecosystem characteristics, and literature for about 300 such experiments (Richter et al. 2007). The existence of 20 long-term soil experiments with sample archives going back at least 50 years is a resource for QUEST, along with database of investigators at these experiments.

DIVERSITY AND BROADER IMPACTS

The broader impacts of the QUEST RCN will be transformative. We hope to facilitate a cultural change that makes uncertainty analysis an accepted and expected practice in ecosystem studies. The QUEST network will provide the infrastructure for creating partnerships and advancing discovery within the Working Groups and the web site will promote understanding among a broader audience and contribute to the dissemination of results beyond that possible in the peer-reviewed literature.

The Steering Committee and the proposed lists of Working Group participants represent multiple government agencies, universities, and research organizations. The year devoted to outreach will allow us to recruit from additional sectors of the research community, and we will direct targeted solicitations to students, early-career scientists, and members of underrepresented groups. The diversity in the backgrounds, experiences, and professional cultures of the QUEST participants will enrich the collaborative relationships and make the results more broadly useful to society.

The benefits of QUEST to society include improvements to the conduct of basic science in ecosystem studies. The applications of uncertainty analysis to the evaluation of monitoring strategies will be relevant to many agencies involved in environmental monitoring, such as the US Forest Service, US Geological Survey, National Acid Deposition Program, and NSF's Long-Term Ecological Research network and National Ecological Observatory Network. In Canada, similarly, there are management agencies interested in advancing their understanding of uncertainty, for example in estimates of woody biomass, that will directly benefit from a coordinated approach to uncertainty assessment. The outcomes from QUEST will provide a rational basis for local sites, State and Provincial governments, and national level monitoring efforts to evaluate the allocation of monitoring efforts essential to managing environmental quality. The evaluation of change over time in carbon storage is essential to land-use based mitigation of greenhouse gas emissions. QUEST will increase the use of uncertainty analysis in the conduct of basic and applied ecosystem science and improve the basis for sound environmental policy and management decisions.

References Cited

Alvisi, S. and M. Franchini. 2010. Pipe roughness calibration in water distribution systems using grey numbers. Journal of Hydroinformatics 12(4):424–445.

Beven, K. 1993. Prophecy, reality and uncertainty in distributed hydrological modelling. Advances in Water Resources 16(1):41-51.

Beven, K. 2006. A manifesto for the equifinality thesis. Journal of Hydrology 320(1-2):18-36.

Birgand, F., C. Faucheux, G. Gruau, B. Augeard, F. Moatar, and P. Bordenave. 2010. Uncertainties in assessing annual nitrate loads and concentration indicators: Part 1 Impact of sampling frequency and load estimation algorithms. Transactions of the ASABE 53:437-446.

Bohlen, P.J, D.M. Pelletier, P.M. Groffman, T.J. Fahey, and M.C. Fisk. 2004. Influence of earthworm invasion on redistribution and retention of soil carbon and nitrogen in northern temperate forests. Ecosystems 7:13-27.

Bohlen, P.J, P.M. Groffman, T.J. Fahey, M.C. Fisk, E. Saurez, D.M. Pelletier, and R.T. Fahey. 2004. Ecosystem consequences of exotic earthworm invasion of north temperate forests. Ecosystems 7:1-12.

Bormann, F.H., G.E. Likens, and J.M. Melillo. 1977. Nitrogen budget for an aggrading northern hardwood forest ecosystem. Science 196 (4293) 981-983.

Chaloupka, M. and G. Balazs. 2007. Using Bayesian state-space modelling to assess the recovery and harvest potential of the Hawaiian green sea turtle stock. Ecological Modelling, 205**,** 93-109.

Chave J., R. Condit, S. Aguilar, A. Hernandez, S. Lao, and R. Perez. 2004. Error propagation and scaling for tropical forest biomass estimates. Philosophical Transactions of the Royal Society B: Biological Sciences 359:409–20.

Chernick M.R. 2008. Bootstrap methods: a guide for practitioners and researchers. 2nd edn. Hoboken, NJ: John Wiley and Sons Inc. 369 p.

Clark, J. S. (2005) Why environmental scientists are becoming Bayesians. Ecology Letters, 8**,** 2-14.

Clark,J.S., G. Ferraz, N. Oguge, H. Hays, and J. DiCostanzo. 2005. Hierarchical Bayes for structured and variable populations: From capture-recapture data to life history prediction. Ecology 86(8):2232–2244.

Coulombe , S., P.Y. Bernier, and F. Raulier. 2010. Uncertainty in detecting climate change impact on the projected yield of black spruce (Picea mariana). Forest Ecology and Management 259(4):730-738.

Cressie, N., C. A. Calder, J. S. Clark, J. M. V. Hoef & C. K. Wikle. 2009. Accounting for uncertainty in ecological analysis: the strengths and limitations of hierarchical statistical modeling. Ecological Applications, 19**,** 553-570.

Fahey T.J., T.G. Siccama, C.T. Driscoll, G.E. Likens, J. Campbell, C.E. Johnson, J.J. Battles, J.D. Aber, J.J. Cole, M.C. Fisk, P.M. Groffman, R.T. Holmes, P.A. Schwarz, and R.D. Yanai. 2005. The biogeochemistry of carbon at Hubbard Brook. Biogeochemistry 75:109–76.

Fraterrigo, J.M., M.G. Turner, S.M. Pearson, and P. Dixon. 2005. Effects of past land use on spatial heterogeneity of soil nutrients in southern Appalachian forests. Ecological Monographs 75:215–230.

Garcia, M., C.D. Peters-Lidard, and D.C. Goodrich. 2008. Spatial interpolation of precipitation in a dense gauge network for monsoon storm events in the southwestern United States. Water Resources Research 44:14 pp.

Hamburg, S.P. 1984. Effects of forest growth on soil nitrogen and organic matter pools following release from subsistence agriculture. p. 145-148. In E.L. Stone (ed). Forest Soils and Treatment Impacts. University of Tennessee, Knoxville.

Hamburg, S.P., R.D. Yanai, M.A. Vadeboncoeur, M.A. Arthur, C.B. Fuss, C.L. Goodale, P.M. Groffman and T.G. Siccama. Sources and sinks of nitrogen in a northern hardwood forest. Proc. Nat. Ac. Sci. In review.

Harmon M.E., W.K. Ferrell, J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247: 699-702.

Harmon, M.E., D.L. Phillips, J.J. Battles, A. Rassweiler, R.O. Hall, and W.K. Lauenroth. 2007. Quantifying uncertainty in net primary production measurements. In: Fahey TJ, Knapp AK (eds.) Principles and standards for measuring primary production. New York: Oxford University. p 238–60.

Harrison, R., D. Richter, and T. Fox. 2011. Deep soils. Forest Science 57: (in press).

Houghton R.A., J.E. Hobbie, and J.M. Melillo. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO2 to the atmosphere. Ecological Monographs 53: 235-262.

Johnes, P. 2007. Uncertainties in annual riverine phosphorus load estimation: Impact of load estimation methodology, sampling frequency, baseflow index and catchment population density. Journal of Hydrology 332:241-258.

Larocque, G.R., J.S. Bhatti, R. Boutin, and O. Chertov. 2008. Uncertainty analysis in carbon cycle models of forest ecosystems: Research needs and development of a theoretical framework to estimate error propagation. Ecological Modeling 219:400-412.

Lehrter, J.C. and C. Just. 2010. Uncertainty propagation in an ecosystem nutrient budget. Ecological Applications 20:508-524.

Li, X., M.H. Nour, D.W. Smith, and E.E. Prepas. 2010. Neural networks modeling of nitrogen export: model development and application to unmonitored boreal forest watersheds. Environmental Technology 31:495.

Li, J.W. and D.D. Richter. 2010. Effects of land-use history on soil spatial heterogeneity of macro- and trace elements in the Southern Piedmont USA. Geoderma 156: 60-73.

Luo, Y., E. Weng, X. Wu, C. Gao, X. Zhou, and L. Zhang. 2009. Parameter identifiability, constraint, and equifinality in data assimilation with ecosystem models. Ecological Applications 19:571-574.

Malca, J. & F. Freire (2010) Uncertainty analysis in biofuel systems. Journal of Industrial Ecology, 14**,** 322-334.

Moilanen, A., A. J. A. van Teeffelen, Y. Ben-Haim & S. Ferrier. 2009. How much compensation is enough? A framework for incorporating uncertainty and time discounting when calculating offset ratios for impacted habitat. Restoration Ecology, 17**,** 470-478.

Montonari, A., C.A. Shoemaker, and N. van de Giesen. 2009. Introduction to Special Section on uncertainty assessment in surface and subsurface hydrology: An overview of issues and challenges. Water Resources Research 45.

Moore, J. E. & A. J. Read. 2008. A Bayesian uncertainty analysis of cetacean demography and bycatch mortality using age-at-death data. Ecological Applications, 18**,** 1914-1931.

Pappenberger, F. and K.J. Beven. 2006. Ignorance is bliss: Or seven reasons not to use uncertainty analysis. Water Resources Research 42:W05302.

Pellerin, B.A., B.D. Downing, C. Kendall, R.A. Dahlgren, T. Kraus, J. Saracenco, R. Spencer, and B.A. Bergamaschi. 2009. Assessing the sources and magnitude of diurnal nitrate variability in the San Joaquin River (California) with an in situ optical nitrate sensor and dual nitrate isotopes. Freshwater Biology 54:376-387.

Post, W.M., K.C. Kwon. 2000. Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6: 317-327.

Raupach, M.R., P.J. Rayner, D.J. Barrett, R.S. DeFries, M. Heimann, D.S. Ojima, S. Quegan, and C.C. Schmullius. 2005. Model-data synthesis in terrestrial carbon observation: methods, data requirements and data uncertainty specifications. Global Change Biology 11:378-397.

Richter, D.D., and D. Markewitz 1995. How deep is soil? BioScience 45:600-609.

Richter, D.D., D. Markewitz, P.R. Heine, V. Jin, J. Raikes, K. Tian, and C.G. Wells. 2000. Legacies of agriculture and forest regrowth in the nitrogen of old-field soils. Forest Ecology and Management 138: 233-248.

Richter, D.D., M. Hofmockel, M.A. Callaham, D.S. Powlson, and P. Smith. 2007. Long-term soil experiments: Keys to managing earth's rapidly changing ecosystems. Soil Science Society of America Journal 71:266–279.

Richter, D.D. and M.L. Mobley. 2009. Monitoring the Earth's critical zone. Science 326:1067-1068.

Robertson, G.P., C.S. Bledsoe, D.C. Coleman, and P. Sollins, eds. 1999. Standard Soil Methods for Long-Term Ecological Research. Oxford University Press, New York.

Runkel, R.L., Crawford, C.G., and Cohn, T.A. 2004. Load Estimator (LOADEST): A FORTRAN Program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques and Methods Book 4, Chapter A5, 69 p.

Sicard C., L. Saint-Andre, D. Gelhaye, J. Ranger. 2006. Effect of initial fertilization on biomass and nutrient content of Norway spruce and Douglas fir plantations at the same site. Trees - Structure and Function 20:229–46.

Sipkay, C., K. T. Kiss, C. Vadadi-Fulop & L. Hufnagel. 2009. Trends in research on the possible effects of climate change concerning aquatic ecosystems with special emphasis on the modelling approach. Applied Ecology and Environmental Research, 7**,** 171-198.

Stelzer, R.S., and G.E. Likens. 2006. Effects of sampling frequency on estimates of dissolved silica export by streams: The role of hydrological variability and concentration-discharge relationships. Water Resources Research 42:10 pp.

Stone, E.L. 1975. Species effects on nutrient cycles and soil change. Philosophical Transactions of the Royal Society B: Biological Sciences 371:149-162.

Vadeboncoeur MA, Hamburg SP, Blum JD, Pennino MJ, Yanai RD, Johnson CE. The quantitative soil pit method for measuring belowground carbon and nitrogen stocks. Soil Sci. Soc. Am. J, in press.

Verstraeten, W.W., F. Veroustraete, W. Heyns, T. Van Roey, and J. Feyen. 2008. On uncertainties in carbon flux modeling and remotely sensed data assimilation: The Brasschaat pixel case. Advances in Space Research 41:20-35.

Viessman, W., and G.L. Lewis. 1996. Introduction to Hydrology. 4th ed. Harper Collins. 760 pp.

Wang, Y., P. Kuhnert, and B. Henderson. 2011. Load estimation with uncertainties from opportunistic sampling data - A semi-parametric approach. Journal of Hydrology 396:148-157.

Weathers, K.C., S.M. Simkin, G.M. Lovett, and S.E. Lindberg. 2006. Empirical modeling of atmospheric deposition in mountainous landscapes. Ecological Applications 16(4):1590–1607.

West, T.O. and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and c rop rotation: a global data analysis. Soil Science Society of America Journal 66:1930-1946.

Whittaker, R.H., F.H. Bormann, G.E. Likens, and T.G. Siccama. 1974. The Hubbard Brook Ecosystem study: forest biomass and production. Ecological Monographs 44:233-252.

Yanai, R.D., T.G Siccama, M.A. Arthur, C.A. Federer, and A.J. Friedland. 1999. Accumulation and depletion of base cations in forest floors in the northeastern US. Ecology 80:2774-2787.

Yanai, R.D., S.V. Stehman, M.A. Arthur, C.E. Prescott, A.J. Friedland, T.G. Siccama, and D. Binkley. 2003. Detecting change in forest floor carbon. Soil Science Society of America Journal 67:1583-1593.

Yanai, R.D, K.J. McFarlane, M.S. Lucash, J.D. Joslin, and S.E. Kulpa. 2009. Nutrient uptake by Engelmann spruce and subalpine fir at two Colorado subalpine forests. Forest Ecology and Management 258(10):2233-2241.

Yanai, R.D., J.J. Battles, A.D. Richardson, C.A. Blodgett, D.M. Wood, and E.B. Rastetter. 2010. Estimating uncertainty in ecosystem budget calculations. Ecosystems (2010) 13: 239–248.

QUEST RCN Data Management Plan

The scientists and cooperators involved in the proposed QUEST Research Coordination Network are committed to providing high quality analyses, programs and information for use in this project and for future use by others. The organization, storage, management, backup, and retrieval of data, programs, and associated data products are critical to the success of the project. One of the primary goals of this RCN is to make uncertainty analysis an accepted and expected practice in the ecological community. To that end, we want to be as transparent as possible in showing how methods were developed and applied. All procedures will be described in sufficient detail to allow reproducibility, which will ensure the reliability of the methods and results.

Products - Primary data will not be collected in the QUEST RCN. Focus Groups will rely on existing data to conduct uncertainty analyses and illustrate their approaches. In many cases, these data are publicly available via the internet; in other cases the data will be provided by the principal investigators. Data used in this proposed work will consist of a variety of different types, including field measurements, sensor data, physical samples, chemical analyses, and model output. Additionally, there are programs and scripts that will be developed and used in the uncertainty calculations, which will be shared through QUEST.

Metadata - One reason that sources of uncertainty are rarely comprehensively considered is that the sequence of operations involved in many ecosystem calculations is complex and typically not completely documented. The detail necessary to reproduce the results far exceeds the amount of information that can be published in journal articles. To resolve this issue, we are planning to use scientific workflows using software such as Kepler to record and execute uncertainty analyses so that the steps involved and code used can be followed and repeated. We will post examples with real data to ensure that the procedures can be easily implemented by individuals unfamiliar with uncertainty analysis. By making these programs readily available, we hope to increase use of uncertainty analysis in the ecological community.

The format of programs and data generated as part of this RCN will vary depending on the type of analyses done and data used. Emphasis will be placed on selecting formats that are non-proprietary and can be applied across computing platforms. To facilitate current and continued future use of the data used in uncertainty analysis examples, we will use Ecological Metadata Language (EML) as the content standard for data used in this project. We anticipate that EML has already been developed for some of the data sets that will be used. Where this is not the case, we will work with the principal investigator to develop EML for the data. EML is machine readable, making it compatible with scientific workflows systems. Thus, the provision of well-developed metadata will enhance the utility of the data and will facilitate the application and enhancement of uncertainty analyses.

Access and sharing - Data will be used only with the expressed consent of the principal investigator, and all who provide data will be given the opportunity to be involved in analyzing the data, interpreting the results, and writing manuscripts. Opportunities for coauthorship on all QUEST publications will be extended to Working Group members and others who make intellectual contributions. Care will be taken to ensure that all those involved are satisfied with their role, the work of other scientists is properly cited, and support or specific funding awards are properly acknowledged.

The investigators in this project consist of a geographically dispersed group of cooperators from different institutions (e.g., universities, research institutes, government agencies). To assist the Focus Groups in their investigations, we will provide an intranet site for willing participants to share data, results, and manuscript drafts. There will be strict computer access control, enforced through password protection and user rights. Beyond this internal collaborative realm, original data sets will not be redistributed without the expressed consent of the principal investigator. The data and programs used in this RCN will be uploaded by these researchers to a central data repository on a server at the State University of New York – College of Environmental Science and Forestry (SUNY-ESF) under the guidance of the information manager. Each investigator will be responsible for quality assurance and quality control (QA/QC) for the data that they submit. However, additional QA/QC procedures will be performed by the information manager as the data are ingested into the relational database management system. Any potential QA/QC issues will be communicated to the principal investigator responsible for collecting the data before changes are made. A relational database schema will be developed and the organization, contents, and conventions of the database will be documented.

All programs, workflows, data, metadata and related project information will be stored on a secure computer server at SUNY-ESF. Computer servers and networked computers are backed up as part of a standardized University procedure. This backup system is automated and includes replicate off-site storage. Periodic test restorations are performed to verify that the backup and recovery system is working properly. We plan to use the QUEST website as a mechanism to inform and communicate progress on the project among co-investigators, cooperators, stakeholders, and the interested public. A password protected section of the website will be dedicated to sharing data, documents and other information. This forum will be used to exchange preliminary data and ideas and will promote interactions among those involved with the study.

Distribution and re-use - The QUEST web page will be the primary means by which data and information are made publically available. The website will also provide information and results to the general scientific community and others who may be interested in uncertainty analysis. Scientific workflows, source code, and detailed instructions for running analyses will be made freely available on the QUEST website. Example input data and the output generated by the programs and scripts will also be posted on the QUEST website along with accompanying metadata for complementary studies and analyses. In addition to the distribution of data and programs via the web page, we will also disseminate results in the form of peer reviewed journal articles and reports. The results of this project will be presented at professional meetings and conferences, which we will use as a venue for advertising the availability and use of data and programs.

Archiving - Digital data collected for this study will be archived in its raw unmanipulated form on the server at SUNY-ESF. Data provenance will be thoroughly documented so that any subsequent data manipulations (e.g., quality control, gap filling) can be reproduced. It is expected that the data, programs, workflows and records will be retained on the server and backup media in perpetuity for future use by others.