20. Quantification of uncertainties in the inventory (WP 3)

M. van Oijen
Centre for Ecology and Hydrology, Bush Estate, Penicuik

20.1 Introduction

WP3 aims to comprehensively quantify the uncertainties in the inventory. This includes quantifying uncertainties in empirical information and uncertainties associated with calculations and process-based modelling. The ultimate aim is to provide a rigorously determined measure of reliability to all parts of the inventory produced in WP1. Uncertainty quantification (UQ) in the inventory project is complicated because different parts of the inventory are calculated in different ways, depending on the output variable of interest. Figure 20-1 shows schematically the flows of information in the project.

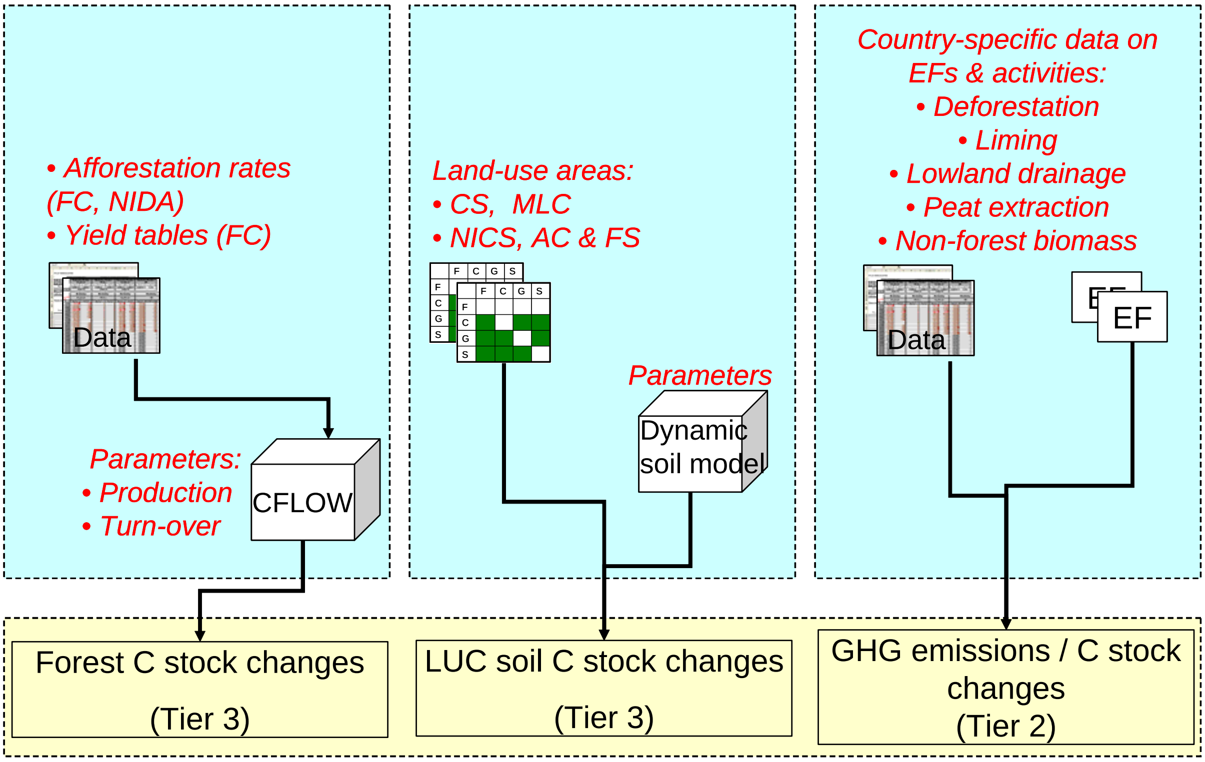

Figure 20-1: Information flows in the calculation of the UK GHG Inventory associated with LULUCF. In red italics: input factors. In yellow boxes: the three major types of output.

As the Figure shows, there are three major flows of information. First, changes in forest carbon stocks are calculated for areas afforested after 1920, using data provided by the Forestry Commission and NIDA, followed by data-processing using the CFLOW model. The second flow of information is to calculate soil carbon stock changes associated with land use change, using land-use change matrices derived from various sources (see Figure), followed by data-processing by means of simple dynamic soil models that quantify the progression over time from one soil-C equilibrium towards another. The third flow of information uses the IPCC Tier 2 activity data and emission factor approach to calculate GHG emissions and C stock changes associated with a range of specific activities including deforestation, liming, lowland drainage and peat extraction. Associated with all three flows of information are uncertainties, first of all in the numerous input factors used in the calculations (indicated in red italics in the Figure), but also in the choice of calculation tools (the CFLOW model, soil models, Tier 2 emission calculations). It is the task of WP3 to quantify these uncertainties and determine how they propagate to the output variables indicated at the bottom of the Figure.

Note that the scheme only shows the information flows for the methods currently applied in the inventory. As described in various work packages in group 2, we are working towards the use of extra information (regional differences in climate, soil nitrogen content etc.) and more tools (in particular more detailed process-based ecosystem models) in the inventory. This will inevitably lead to more demands on UQ.

UQ was already applied in previous instalments of the inventory. However, this was restricted to preliminary simulations of carbon sequestration in forests by means of the model BASFOR, and estimation of land-use changes between non-forest land use categories, where sensitivity of calculated stock changes to input uncertainty was examined by means of Monte Carlo simulations. Both of these activities are carried out more rigorously in the current project (WP's 2.11 and 2.13) and WP3 builds on their results.

In the following two sections of this annual progress report, we describe the methodology and the progress to date.

20.2 Methodology

The basis of our method for UQ is IPCC Good Practice Guidance methodological Tier 2. We first quantify the uncertainties associated with the many input factors used in the inventory calculation, by expressing them as probability distribution functions (pdf's). Then representative samples are taken from the pdf's to propagate input uncertainty forward through the calculations. This results in representative samples of the desired output variables. Although this method is relatively straightforward, it needs to be applied with caution. If the only source of information for the input factor pdf's is direct measurement or expert opinion, the resulting output uncertainty may be overly high, because knowledge about inputs is generally incomplete, input factors interact and uncertainty may propagate nonlinearly in the calculations. To prevent generating inventory uncertainty estimates that are unrealistically high, or even unusable in practice, we need to reduce input uncertainties where possible, but we also need to combine direct and indirect information when estimating uncertainties. We apply Bayesian techniques to incorporate as much information in our pdf's as possible (Patenaude *et al*., 2005). The techniques make extensive use of Bayes' Theorem:

$$p(\theta|D) = c\ p(D|\theta)\ p(\theta)$$

where $p(\theta|D)$ is the so-called posterior pdf for our input factors θ after incorporating new direct or indirect information D, $p(\theta)$ is the prior pdf for θ that we had before arrival of the new information D, $p(D|\theta)$ is the likelihood of D for given values of θ, and c is a proportionality constant. Bayes' Theorem is valuable for the inventory because it is often relatively easy to quantify the likelihood of new information in which case the theorem tells us immediately how our uncertainty about the input factors θ decreases because of that information. Useful information D could be measurements of carbon stock changes or emissions, i.e. the key output variables of interest in the inventory, but equally well measurements of any other variables that play a role in the inventory calculation such as litter fall rates or SOM-decomposition rates that are intermediate variables in the calculations of the CFLOW model.

Bayes' Theorem is valid without limitation and we shall apply it to all three flows of information in the inventory. This includes the calculations of both past GHG and C-stock dynamics as well as the projections of future CO_2 emissions and removals in WP 1.4. Obviously no measurements of future emissions are available to feed into Bayes' Theorem, but the parameter uncertainty of the models used for future projections can be reduced by

Bayesian calibration using existing data. The long-term perspective of the approach is that the annual generation of the GHG inventory becomes a self-learning system where new information, even including observed mismatches between past projections and current observations, automatically leads to improvement of the calculations.

20.3 Progress to date

The focus of the work in WP3, in the current reporting period, has been on putting the methodology in place. This included comparing the approach extensively with methods proposed by other parties and collecting preliminary information on uncertainty in input factors.

20.3.1 Review of existing guidelines for uncertainty quantification

A comprehensive literature review was carried out to assess how various international organisations related to the environmental and natural sciences have drafted guidelines, protocols or standards for UQ. Table 20-1 lists those that were found to be relevant to the inventory work.

Table 20-1: Internationally used guidelines, protocols and standards relevant to uncertainty quantification in the UK GHG Inventory associated with LULUCF.

Guidelines, protocols, standards	***Long name***	***Organisation***	***Year***	***URL***
ISO-14064		ISO	2006	www.ecologia.org/ems/ghg
GHG-Protocol	Greenhouse Gas Protocol Initiative	WBCSD/ WRI	2004-2005	www.ghgprotocol.org
2006 IPCC Guidelines	2006 IPCC Guidelines for National Greenhouse Gas Inventories	IPCC		www.ipcc-nggip.iges.or.jp/public/2006gl
GPG-LULUCF	Good Practice Guidance for Land Use, Land-Use Change and Forestry	IPCC	2003	www.ipcc-nggip.iges.or.jp/public/gpglulucf
GPG2000	Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories	IPCC	2000	www.ipcc-nggip.iges.or.jp/public/gp
GMP-Handbook	Good Modelling Practice Handbook	STOWA *et al*	1999	www.estuary-guide.net/pdfs/STOWA-RIZA%20guide.pdf
NIST-TN1297	Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technical Note 1297. 1994 Edition.	NIST	1994	physics.nist.gov/Document/tn1297.pdf physics.nist.gov/cuu/Uncertainty
AEAT-2688	Treatment of Uncertainties for National Estimates of Greenhouse Gas Emissions	NAEI		www.aeat.co.uk/netcen/airqual/naei/ipcc/uncertainty/contents.html
AEAT/ENV/R/1039	Estimation of Uncertainties in the National Atmospheric Emissions Inventory	NAEI	2003	www.airquality.co.uk/archive/reports/cat07/AEAT1039_finaldraft_v2.pdf
GUM	Guide to the Expression of Uncertainty in Measurement	ISO *et al*	1993, 1995	
UK-GHG-1990-1999-A8	UK Greenhouse Gas Inventory, 1990 to 1999, Appendix 8, Uncertainties	NETCEN	2001	www.aeat.co.uk/netcen/airqual/reports/ghg/ukghgi_90-99_append_7-9.pdf
Protocol-UQ/UA	Protocol for Uncertainty Quantification and Analysis	NitroEurope	2006	www.nitroeurope.eu

The published guidelines listed in Table 20-1 demonstrate the recognised importance of UQ. However, most of these guidelines only provide general advice, not going into detail except where uncertainty associated with small and random linear-scale measurement error is addressed (NIST-TN1297).

ISO-14064 provides general advice on GHG accounting and data quality assurance, but sees uncertainty primarily as something to be minimised rather than as something requiring extensive quantification or analysis: "The organization shall select and use quantification methodologies that will reasonably minimize uncertainty and yield accurate, consistent and reproducible results". It stresses that two main sources of uncertainty in GHG estimates are normally baseline uncertainty and data uncertainty. ISO-14064 recommends a very conservative quantification in case of a highly uncertain baseline. This recommendation is possibly at odds with the goal of scientific objectivity. In WP3, we aim for objective UQ. ISO-14064 is focused on use by businesses as is the document on which it is partly based, i.e. the Greenhouse Gas Protocol Initiative (GHG-Protocol), issued by WBCSD/WRI. For details of UQ, the ISO guidelines refer to the Guide to the Expression of Uncertainty in Measurement (GUM).

GUM has in practice already been superseded by the Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results (NIST-TN1297). NIST-TN1297 has a heavy focus on standardisation of how to report uncertainty, recommending the use of standard deviations in general, and the methods for UQ are mostly analytical, rather than Monte Carlo based. This does pose limitations on the applicability of their techniques.

Of central importance for the UK GHG Inventory are of course the guidelines published by the IPCC (GPG2000, GPG-LULUCF, 2006 IPCC Guidelines), NETCEN (UK-GHG-1990-1999, in particular Appendix 8) and NAEI (AEAT-2688, AEAT/ENV/R/1039). GPG2000 does not cover LULUCF but is consistent with GPG-LULUCF which does. GPG2000 stresses objectivity: inventories consistent with good practice are those that "contain neither over- nor underestimates so far as can be judged, and in which uncertainties are reduced as far as practicable". Chapter 6 of GPG2000 discusses how to quantify uncertainties in practice. The central role of pdf's in UQ is emphasised, both when dealing with data and when summarising expert opinion. Both analytical (Tier 1) and numerical (Tier 2, Monte Carlo) methods for uncertainty propagation are discussed, and the use of Monte Carlo methods in estimating uncertainties by source categories is explained.

Chapter 6.5 of GPG2000 provides a very useful overview of practical considerations in the use of Monte Carlo methods. This includes advice on specifying pdf's both for data and for the prior of model parameters. It is stressed that the effort required in UQ of individual parts of the inventory should stand in proper relation to their contribution to overall uncertainty: the inventory does not have unlimited resources, so good practice entails that effort is balanced against the need for timeliness and cost effectiveness. Monte Carlo operates by sampling from the pdf's and the higher efficiency of Latin Hypercube Sampling compared to fully random sampling is explained. The chapter concludes by discussing how correlations among variables can be treated. Much of this discussion is clearly relevant to WP3.

Other information in GPG2000 useful for the work in WP3 is found in the Annexes. Annex 1 discusses the "Conceptual Basis for Uncertainty Analysis". It discusses specification of pdf's in A1.2.4-6 and suggests that good practice implies choosing full or truncated normal or lognormal distributions or – to represent absence of information – uniform or triangular distributions. This advice is debatable in the context of WP3, as the primary purpose of quantifying the pdf's is properly representing the available information about a quantity, and the best representation may be a different pdf. In preliminary work in WP3 we found beta-distributions to be appropriate in many circumstances. Moreover, when new pdf's are formed by forward propagation of input uncertainties or by applying Bayes' Theorem to calibrate model parameters, the resulting output samples need not match any of the standard distributions. Annex A1.3 provides a useful checklist of the different sources of uncertainty in GHG inventories, including those associated with measurement, sampling, lack of representativeness of data, and expert judgment. Similarly, A1.4.1 has an excellent list of 15 descriptors that – ideally – should accompany all data to allow UQ. However, experiences in projects where data providers collaborate with data users do not suggest that completion of that list will be achieved very often. A1.4.2 deals with the standard problem in any national inventory of UQ associated with sampling and upscaling in time and/or space.

Whereas GPG2000 provides valuable general methodological advice, GPG-LULUCF adds concrete advice and information for UQ in the LULUCF inventory. Chapters 2 discusses quantification of land area, land use and land use change and lists sources of uncertainty. This area will be developed further in WP 2.13 of the project which aims to develop Bayesian methods for UQ related to land-use change matrices. Chapter 3 of GPG-LULUCF provides the necessary data and methodological advice on estimating uncertainties associated with carbon stock changes and emissions estimation. Chapter 3.2.1 deals with forest land remaining forest land and gives extensive advice, including default values, on uncertainties in wood density, biomass expansion factors, root-shoot ratio, products, forest areas, SOM, litter, dead wood, soil bulk density, CO_2 and N_2O emission actors, fertilisation rates etc. However, this information is not used in the current UK inventory as we choose the option of assuming forest-remaining-forest to be carbon-neutral. In future, application of process-based forest modelling may change that approach: see the use of the forest model BASFOR in WP 2.11. Chapter 3.2.2 deals with afforestation and the role of uncertainty in changes in biomass-C-stocks, dead organic matter and litter and SOC after land-use change to forest. The key activity data here are rates of forest area increase which are found to have much lower uncertainty than the associated emission factors. The chapter tabulates a variety of sources of uncertainties in emissions and stock changes after afforestation. The remaining chapters in section 3 of GPG-LULUCF deal in a similar vein with the other considered land uses and land-use changes.

Chapter 4 of GPG-LULUCF describes supplementary methods and good practice guidance arising from the Kyoto Protocol. Overall, the uncertainty approaches are as for UNFCCC. Chapter 5 shows how to combine uncertainty estimates into overall uncertainties, reiterating much of guidance provided by GPG2000. An interesting addition, relevant to WP3, is given in Chapter 5.5.4 which deals with a specific aspect of quality control, i.e. evaluating the models that are used. The chapter recommends checking – for each model used in the inventory – the appropriateness of model assumptions, any extra- and interpolations, calibration-based modifications etc. From the perspective of WP3, we may view such model evaluation as quantifying uncertainty regarding model structure rather than input or parameter uncertainty. The Bayesian techniques used in WP3 can handle model structural uncertainty as well, but only if multiple models are available for single tasks – allowing us to define a pdf over model structures. This technique will be used for example whenever we consider replacing existing calculation methods with new ones. An example could be the replacement of Tier 2 approaches by Tier 3 ones. Finally, Chapter 5.7 of GPG-LULUCF gives a good overview of international programs and networks that are relevant to LULUCF. Obviously that list is now partly outdated and incomplete, but it still contains useful links to sources of information that can be used in UQ in WP3 (www-eosdis.ornl.gov/FLUXNET/index.html, www.bgc-jena.mpg.de/public/carboeur/, www.igbp.net/, www.gcte.org/, www.lternet.edu/, www.fao.org, www.icp-forests.org/, www.ymparisto.fi/default.asp?contentid=17110&lan=en, www.emep.int/, www.globalcarbonproject.org/, www-eosdis.ornl.gov/).

The 2006 IPCC Guidelines are consistent with GPG2000 and GPG-LULUCF, but provide an even clearer overview of issues and methods for dealing with uncertainties in GHG inventories (Vol. 1, Ch. 3). Included is a detailed example of the UQ reported for the national GHG inventory of Finland (Statistics Finland, 2005). This UQ refers to the whole inventory, not just the part associated with LULUCF, and is based on expert judgement regarding uncertainties in activity data and emission factors. Detailed examples showing how Monte Carlo methods have been used for UQ starting from pdf's for activity data and emission factors are given in UK-GHG-1990-1999-A8 (Salway *et al.* 2001, UK Greenhouse Gas Inventory, 1990 to 1999, Appendix 8) and AEAT/ENV/R/1039 (Passant 2003, Estimation of Uncertainties in the National Atmospheric Emissions Inventory).

Finally, for those parts of the inventory where dynamic modelling is used, the GMP-handbook published by STOWA and the Protocol-UQ/UA issued by NitroEurope provide advice on good practice in process-based modelling, including UQ. The latter protocol includes a brief explanation of the Bayesian approach, as advocated here in WP3, and several modelling groups in NitroEurope are now carrying out Bayesian calibration and UQ (Van Oijen *et al.*, 2006).

In summary, the documents discussed in this section give sound methodological advice that can be used in WP3, including default values for uncertainties associated with input factors used in the inventory calculations. The Bayesian methodology is covered in less detail, but as explained in section 2 of this report, it is conceptually easy and is applied in the current inventory also in WP's 2.11 and 2.13.

20.3.2 Prior estimation of uncertainties

The work in WP3 builds on input from various WP2 activities. The role of Bayesian techniques used in WP's 2.11 and 2.13 has already been mentioned. The work in 2.3, 2.12 and 2.13 helps formulating pdf's for input factors on forests and land-use change matrices, and the work in WP's 2.9-2.11, where process-based models are being developed, produce results that can be compared with the simpler calculation methods now used in the inventory. That will allow analysis of uncertainty about the extent to which individual calculation methods are correct, and WP's 2.9-11 are likely to provide information on input factors that can partly be used in the current calculation methods as well. Many of the other WP2-activities can contribute calibration data, which can be used in the Bayesian approach to calculate the likelihood for different values of input factors.

However, in the short term the UQ in WP3 largely depends on other sources of information. These include literature data on measurements of input and output variables, default uncertainties provided by the IPCC (as discussed above) and expert judgement primarily provided by the project partners. Furthermore, detailed examples of UQ associated with the LULUCF sector of the GHG inventory in Finland have been provided by Peltoniemi *et al.* (2006) and Monni *et al.* (2007). These include uncertainty quantifications – with specification of the type of pdf (normal, lognormal, triangular or uniform) - of more than 60 parameters included in the calculation of forest biomass and soil C-stock, many of which can be adapted for use in the UK, i.e. in WP3. Among the regular sources of biogeochemical data – from international projects and databases – we only mention further the IPCC Emission Factor Database (http://www.ipcc-nggip.iges.or.jp/EFDB/main.php) which currently mainly holds default IPCC values but is expected to be of increasing importance over the coming years.

20.4 Outlook

The work in year 1 has put the methodology for uncertainty quantification in place, and sufficient sources of information on input factors for the inventory calculation were identified to allow the first practical tests of the approach. That will be the main the task for year 2 of the project.

20.5 References

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