Data quality reporting: good practice for transparent estimates from forest and land cover surveys

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Abstract

The need to provide transparent and reliable Greenhouse Gas (GHG) emission estimates is strongly emphasized in the context of international reporting under the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. Yet it is difficult to find specific guidance about what information is really needed to evaluate the quality of the emission factors or activity data used for GHG emission estimates. The most commonly used indicator of the reliability of an estimation procedure (and one of the few indicators explicitly mentioned in the 2006 IPCC guidelines) is the so-called confidence interval, usually at a confidence level of 90% or 95%. This interval, however, is unlikely to be a meaningful indicator of the quality of the estimate, if not associated with additional information about the estimation and survey procedures (such as on the sampling design, measurement protocols or quality control routines, among others). We provide a review of the main sources of error that can have an impact on the precision and accuracy of the estimation of both emission factors and activity data and a list of the essential survey features that should be reported to properly evaluate the quality of a GHG emission estimate. Such list is also applicable to the reporting of national forest inventories and of area estimation of activity data, and includes the case in which confidence intervals are obtained using error propagation techniques.

Keywords: Emission factor, Activity Data, Greenhouse gas inventory,

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1. Introduction

In order to account for green house gas emissions from the Land Use, Land Use Change and Forestry (LULUCF) sector two approaches are commonly used: *stock change*, when emissions are estimated as a carbon stock difference between two consecutive surveys, and *gain-loss*, whenever emissions are estimated as the product of areas of land use or land use change (aka *activity data*) and the specific carbon coefficient (aka *emission factors*) associated to them (IPCC 2006, Vol.4 Chap.2, GFOI 2016). The Intergovernmental Panel on Climate Change (IPCC) guidelines provide a hierarchical classification of estimation methods, consisting of three levels of methodological complexity, called tiers (IPCC2003, Chap.3.1.5; IPCC 2006, Vol.1 Chap.1.2). Tier 2 and tier 3 methods, which are considered the most certain and reliable, both rely on sampling up to a certain extent. In order to account for the emissions from LULUCF under these higher tiers, sampling techniques are commonly used for the estimation of both emission factors and activity data. The former are usually derived from in-situ assessments, such as forest inventories or from permanent or temporary experimental plots (Chirici et al., 2011; Köhl et al., 2015), the latter from model-based map classification (wall-to-wall maps) or design-based area estimation through visual, or augmented visual (Bey et al., 2016) interpretation (McRoberts, 2014; FAO, 2016). More advanced methods can involve the use of large-area forest biomass maps, however their use is still limited in the context of GHG inventory and REDD+ reporting (Sandker et al., 2018). In any case, in order for a country to produce reliable higher-tier estimates it is necessary to largely rely on data coming from sampling (IPCC, 2003).

These sample-based estimates are required to be: (1) “accurate, in the sense that they are neither over- nor underestimates as far as can be judged”, and (2) precise, “in the sense that uncertainties are reduced as far as practicable” (IPCC 2003, Chap.5.2; IPCC 2006, Vol.1 Chap.3). Precision and accuracy, as they are defined in the 2003 and 2006 IPCC guidelines, are well known concepts in the literature on probability sampling, where they are usually expressed in terms of variance of an estimator (alternatively called sampling variance) and bias, respectively. As mentioned in the IPCC guidelines, it is worthwhile to mind the difference between the variance of the

35 population and the variance of an estimator. The former provides a measure
 36 of how dispersed the values of a population are, while the latter provides a
 37 measure of the precision of the estimator used. Even though under simple
 38 random sampling there is a direct relationship between these two quantities¹,
 39 they still describe different features, have different applications and should
 40 not be confused.

41 As for any other probabilistic survey, the precision and accuracy of a
 42 GHG inventory or of a REDD+ results report can be fully ascertained only
 43 in the unrealistic case in which the exact values of interest for all elements in
 44 the population are known. In all other cases, precision and accuracy need to
 45 be estimated from the sample itself and/or evaluated based on the available
 46 information on the studied population, sampling design, statistical assump-
 47 tions and measurement methods used to obtain the estimates. The so-called
 48 confidence interval is one of the most commonly reported indicators of the
 49 reliability of an estimation. However, it does not usually include all sources
 50 of error in the survey. Confidence intervals typically include the sampling
 51 error and in some cases may also partially include some non-sampling er-
 52 rors, such as measurement or model error (cf. Section 2.4 below), but do
 53 not measure the bias and other types of non-sampling error (Hanson, 1978).
 54 In addition, the confidence interval is a random variable itself and is also
 55 estimated from the sample (that is, different random samples will produce
 56 different intervals). Several alternative estimation methods may exist to ob-
 57 tain a confidence interval and not all of them are adequate for the specific
 58 sampling design adopted (Cochran, 1977; Särndal et al., 1992). In many ap-
 59 plications, bias and sampling variance are often treated separately, but they
 60 still remain closely interrelated and if the survey is substantially biased, the
 61 resulting confidence interval will also be distorted (cf. Raj 1968, Chap. 2.11;
 62 Cochran 1977, Chap 1.8). In fact, a point estimate and its associated con-
 63 fidence interval do not reveal whether the reported results are precise and
 64 accurate.

65 Uncertainty is defined in the IPCC (2006) guidelines as the lack of knowl-
 66 edge of the true value of a variable and the word is often used in a broader
 67 sense that encompasses both precision and accuracy. The need to esti-

¹Under a simple random sampling design the variance of the estimator of the sample mean is given by the variance of the population divided by number of elements in the sample.

mate and report the uncertainties associated with the estimates is repeatedly stressed in the IPCC guidelines (2003; 2006). They distinguish between uncertainties that are amenable to quantification and others which are non-quantifiable (IPCC, 2006, Vol. 1, Chap. 3). The former, typically including sampling and measurement errors, can be expressed using a confidence interval, while the latter, which may include bias or any type of conceptual or inferential imperfections, cannot. As reported in the IPCC guidelines quantitative uncertainty analysis is performed by estimating the 95 percent confidence interval of the emission and removals. In contrast, non-quantifiable errors, if they cannot be prevented, should be identified, documented and possibly corrected by the compilers. To this end, the guidelines provide eight broad causes of error to be considered by the inventory developers (IPCC, 2006, Vol. 1, Chap. 3) and general guidance on the procedures needed to assess and maintain the quality of the inventory (IPCC 2003, Chap. 4.4; IPCC 2006, Vol.1, Chap.6). However, this recommendation proves to be quite generic and mainly focused on integrity and completeness of the data and does not provide detailed guidance on how to report information stemming from a probability survey.

In the context of a GHG inventory, uncertainty analysis is rather considered as a means to help prioritize national efforts to reduce the uncertainty of inventories in the future, and to guide decisions on methodological choice. They do not set any specific standards concerning which aspects of the survey should be documented. However, it can be beneficial for the reporting Parties to duly demonstrate that their estimates are reliable and that the methods used to obtain them are adequate. From a statistical point of view the confidence interval alone should not be the only quality indicator. Paradoxically, an improvement in survey methods or an increased knowledge of the studied population can lead to wider confidence intervals and give the misleading idea of a decrease in the quality of the estimates. This manuscript aims to provide a comprehensive list of information that: (1) sheds light to reporting parties into confronting this paradox, and (2) should be reported to properly evaluate the quality of a GHGI/REDD+ report estimate for the LULUCF sector. This information is mostly focused on improving the quality declaration of the data, its sources, and the reported estimates as a good practice guidance.

103 2. Guidelines for reporting survey research

104 Since the 1950s, there have been policies to describe the quality of statis-
 105 tics derived from survey sampling (Statistical Office of the United Nations,
 106 1950; Gonzalez et al., 1975) and many national survey organizations have
 107 developed their own quality declaration guidelines (Statistics Canada, 2000;
 108 Full et al., 2001; Brackstone, 2003; Office for National Statistics, 2007; Jack-
 109 son et al., 2013; Brancato et al., 2016). Even though many of those recom-
 110 mendations are certainly useful and applicable in the context of REDD+ or
 111 GHG reporting, there are still certain aspects that are somewhat peculiar
 112 to the LULUCF sector that are not fully elaborated in those more generic
 113 policies. Moreover, the rapid developments in many methodological (and
 114 technological) aspects of land use and forest monitoring call for urgent and
 115 specific updates in their guidelines. We provide below a description of the
 116 main sources of errors which can arise during the estimation of emission
 117 factors and activity data from LULUCF sector survey data. For each er-
 118 ror source we propose a set of key questions which should be considered by
 119 those engaged in reporting or reviewing survey results. The answers to such
 120 questions will constitute the essential body of information that should be
 121 reported to allow reviewers, reporting Parties and practitioners to properly
 122 evaluate the quality of a GHGI/REDD+ report estimate. When the emission
 123 factors and activity data have been estimated through independent surveys
 124 the answers should be provided for each of them. Guidance for the reporting
 125 of the combined uncertainty of emission factors and activity data using error
 126 propagation techniques is provided in section 2.3.

127 2.1. General information about the survey

128 This section aims to provide general information about the survey, includ-
 129 ing a description of the population sampled, the data collected, the methods
 130 of measurement and the sampling design adopted. We assume that readers
 131 already have some knowledge about the basics of sampling.

132 2.1.1. Information about the sampled population

133 The term *sampled population* denotes the “aggregate from which the sam-
 134 ple is chosen” (Cochran, 1977). The population is composed of *elements*, to
 135 which one or more variable of study are associated (Särndal et al., 1992,
 136 Chap. 1.2). The sampled population is identified at the planning phase of a
 137 survey and should be defined in such a way that there cannot be any ambi-
 138 guity about whether or not an element is part of the population (Köhl et al.,

2006). When sampling for emission factor or activity data for the LULUCF sector the sampled population is often defined as a geographic area. In this case, the population includes all locations that have non-zero probability of being included in the sample. In National Forest Inventories (NFIs) the population typically corresponds to the whole country area or, in some cases, to the area of the country that is considered forest. When subnational surveys are carried out, the sampled population may correspond to a specific administrative unit or to a particular ecological zone.

When ground-surveys are carried out it is possible to define the population as a continuous areal frame. That is, it comprises an infinite number of spatial locations (Gregoire and Valentine, 2008; Köhl et al., 2006). In remote sensing applications, in contrast, the population is often defined as a finite set of non-overlapping spatial units that form a partition of the region of interest, typically pixels, block of pixels or polygons. In this case, the choice of the type of spatial units that tessellate the population has an impact on the survey estimates (Stehman and Wickham, 2011) and should be adequately described.

Set 1 of key questions: Sampled population

- (a) What is the population from which the sample is chosen?
- (b) If the sampled population is defined as a geographic area, are you able to provide a map of it?
- (c) Is the sampled population defined as a finite set of discrete spatial units? If so, which ones? are they uniform? what is their area?

2.1.2. Information about the target population

The term *target population* denotes the population about which the information is wanted. Similarly to above, when sampling for emission factors or activity data for the LULUCF sector the targeted population is often defined as a geographic area (McRoberts et al., 2015). This may or may not coincide with the sampled population. In fact, in GHG inventories the population of interest is often a sub-group of the sampled population, created after (and independently of) the sample selection, such as a specific land use, forest type or climatic zone (cf. Section 2.2.3 below). Figure 2 provides a visual representation of some cases in which target and sampled population differ.

Set 2 of key questions: Target population

- 173 (a) What is the population for which we want to estimate emissions/removals?
- 174 (b) For which time period do we need the emissions/removals?
- 175 (c) If the target population is defined as a geographic area, are you able
- 176 to provide a map of it?
- 177 (d) If the target population is not defined as a geographic area, are you
- 178 able to provide a list of the elements that compose it?

179 *2.1.3. Sampling selection*

180 There are many existing approaches to select a sample from the popu-
 181 lation. The choice of the sampling method has an important effect on the
 182 quality of the estimates and should be carefully described. In NFIs or in land
 183 cover area estimation the sample is usually composed of a set of locations
 184 selected from a continuous areal frame (such as a geographical region). The
 185 unit of area that is observed is often called a plot. A sampling unit can
 186 also be composed of a group (cluster) of subplots located near each other
 187 (Kangas and Maltamo, 2006) and/or of one or more nested smaller subplots
 188 (Köhl et al., 2006).

189 **Set 3 of key questions: Sampling selection**

- 190 (a) Is the survey based on a probability sample²?
- 191 (b) What sampling design has been used?
- 192 (c) What was the planned size of the sample?
- 193 (d) What is the size and shape of the sampling units?
- 194 (e) Is the sampling unit composed of a cluster of subplots?
- 195 (f) Is the sampling unit composed of one or more nested smaller subplots?

²Non-probabilistic sample selection is sometimes carried out in the context of REDD+ and the LULUCF sector. This can happen, for example, whenever the sample is selected based on expert choice (it can be the case of training point selection for supervised land cover classification). As a result, it is not possible to calculate the probability of each population element to be included in the sample (the so-called inclusion probability). Under a design-based inference this results in the fact that sampling variances (and therefore the sampling error) cannot be calculated *unbiasedly*. Conversely, it might not affect the predictions in a model-based framework

- 196 (g) Was the sample selected following stratified sampling?
- 197 (h) If so, which are the strata? how were they constructed? What is their
198 size?
- 199 (i) If so, when the strata are defined as geographical areas, are you able
200 to provide a map of them?
- 201 (j) Repetition: Is the survey isolated or is it part of a series of repeated
202 surveys? If so, what is the proportion of samples that were repeated?

203 2.1.4. Data collection, labeling, coding and editing

204 Once the sampling design is established, the data are collected according
205 to the prescribed measurement protocol, coded and entered into a database.
206 In NFIs, the protocol for collecting the data in the sampling units is usually
207 described in a field manual, and in remote sensing applications (such as ac-
208 curacy assessment of maps) the procedure used to collect information from
209 each sampling unit is often referred to as *evaluation protocol* (Stehman and
210 Czaplewski, 1998). The choice of the data labeling and of the data manage-
211 ment system has a large impact on the precision and accuracy of the results.
212 While conceiving the survey, a particular attention should be put in the def-
213 inition of categorical variables, such as for example land cover. In order to
214 assign each element to a certain land cover class it is necessary to have a
215 consistent and complete land cover classification system. The classification
216 system should be defined in such a way that each land cover element can
217 clearly be assigned into one and only one land cover class. In remote sensing
218 applications, the set of procedure to assign a classification to each sampling
219 unit is often called *labelling protocol* (Stehman and Czaplewski, 1998) and
220 should be adequately described.

221 **Set 4 of key questions: Data collection and processing**

- 222 (a) Which attributes have been observed in the sampling units?
- 223 (b) What was the measurement protocol used to measure the variables of
224 interest?
- 225 (c) Has a written field manual or evaluation protocol been produced? Can
226 the party provide it?

- 227 (d) Can the party provide a clear and unambiguous definition for each class
228 of categorical variables in the survey, including a land cover classifica-
229 tion system (if any)?
- 230 (e) Has the classification system (if any) been modified during the imple-
231 mentation of the survey? If so, the final estimates? Did the party put
232 in place any system to account for this change?
- 233 (f) Has the field measurement protocol been changed during the implemen-
234 tation of the survey? If so, how does that impact the final estimates?
235 Did the party put in place any system to account for this change?
- 236 (g) How were the data stored and processed?

237 2.2. *Information about error sources*

238 This section aims to provide specific information about the potential
239 sources of error in the survey which require description and analysis. In
240 the literature on survey sampling the sources of error are typically divided
241 into the two broad categories of sampling and non-sampling errors. Abiding
242 by the terminology used in Särndal et al. (1992), non-sampling errors can be
243 further divided into 1) *errors due to nonobservation*, when it is not possi-
244 ble to obtain data from parts of the population of interest and 2) *errors in*
245 *observations*, when the recorded value of the sampled element differs from
246 its real value. The former includes frame imperfections and non-response
247 issues, the latter measurement and processing errors. All these sources of
248 errors can affect both the precision and the accuracy of the estimates and
249 will be discussed in detail in the next sections, all enumerated and linked
250 to corresponding sets of key questions (Fig. 1). A complete theory of non
251 sampling error has not been elaborated yet (cf. Särndal et al., 1992, Chap.
252 14.6) and the schema proposed in Fig. 1 does not intend to provide a ex-
253 haustive and consistent classification. Moreover, Figure 1 does not define in
254 detail all sources of uncertainty that can arise during the estimation of emis-
255 sion factors or activity data. The aim here is rather to provide a conceptual
256 framework to group the errors into major broad categories. The workflow
257 for satellite data processing or, for example, for tree field measurement, in-
258 volves multiple steps that are not explicitly mentioned in Fig. 1 (such as
259 satellite sensor calibration or tree biomass allometric model selection). All
260 these steps, however, can always be classified into one of the broad categories
261 mentioned above. More detailed lists of the error sources typically arising

in the processing chain to calculate forest emission factors/activity data are provided elsewhere (Hill et al., 2013; Sandker et al., 2018).

There are two essential complementary approaches to deal with each of the error sources: 1) measures put in place to prevent (or possibly avoid) the error before it occurs (Duvemo and Lämås, 2006; Gasparini et al., 2009) and 2) apply methods to properly account for the error once it has occurred (Pollard et al., 2006; Ferretti et al., 2009; Gormanson et al., 2018). A complete assessment of any survey result cannot be done without a thorough analysis of these two aspects. Hence, as a matter of transparency, reporting parties should take care to describe both of them. In the following sections for each error we provide recommendations to ensure that both aspects are duly included in the reporting.

Figure 1: **Categories of potential error sources in the LULUCF sector.** Broad categories of error sources in surveys sampling and a reference to the corresponding set of key questions in this paper. This schema is aimed to provide a practical framework for reporting survey results.

2.2.1. Sampling error

The sampling error denotes the error caused by the fact that only a subset (a sample) of the population is measured. Even if no error is made in

measuring or processing the data, it is still evident that the estimates based on the sample will differ from the real population values. On the other hand, it is intuitive that different samples of the same population will provide different estimates (unless the population is composed of identical elements). The *variance* of an estimator (or sampling variance) provides a measure of the sample-to-sample variation and the *bias* of an estimator is the difference between the real population value and the average of all possible sample estimates. Under many sampling designs it is possible to provide a quantitative unbiased estimate of the sampling variance. For any given estimator of a population parameter many statistics manuals also provide: 1) the formula for the *estimator variance* (in practice an unknown quantity which depends on the complete set of population values) and 2) a formula to estimate unbiasedly the estimator variance from the sample data (cf. Särndal et al., 1992, Remark 2.8.2). The latter is the one ordinarily used to compute the sampling error. Hence, in most of the cases the sampling variance falls within the IPCC category of errors amenable to quantification and can be expressed using a confidence interval. In practice, confidence intervals calculated on the sampling variance are the most commonly reported indicators of the reliability of an estimation. Larger sampling variances will result in wider confidence intervals, hence in an overall decrease of precision. The bias of the estimator, conversely, is often not quantifiable in practice and its magnitude can only be inferred from the sampling design, the estimators used and the population parameters being estimated.

Sampling error will always be present, unless the population is enumerated in its entirety. Typical examples of surveys sampling used in REDD+ and GHG reporting are national forest inventories (for forest emission factors) or area estimation (for land use/land use change activity data) (Olofsson et al., 2014). For a given sampling design there may exist several alternative estimators, each one having different statistical properties. The reporting Parties should take care in selecting the best estimator, where best here means having small variance and being unbiased (or approximately unbiased). The properties of the estimators under the most common sampling designs have been thoroughly investigated, so that it is usually possible to estimate their variances and to ascertain whether or not they are unbiased (or approximately unbiased). A plethora of manuals has been dedicated to the theory and practice of sampling methods, including the renowned texts of Cochran (1977) and Särndal et al. (1992). de Vries (1986), Kangas and Maltamo (2006), Köhl et al. (2006), Gregoire and Valentine (2008) and

315 Mandallaz (2008), among others, provide a more detailed review of sampling
316 strategies for natural resources and forest inventories.

317 **Set 5 of key questions: Sampling error**

318 (a) Which estimator has been used to estimate the emission/removal? Can
319 the party provide the mathematical formula used?

320 (b) Has the variance of the estimator been estimated? If so, which estima-
321 tor was used to compute it? Can the party provide the mathematical
322 formula used?

323 (c) Is the estimator for the population parameter and its variance estimator
324 unbiased (or approximately unbiased) under the sample design adopted
325 in the survey?

326 *2.2.2. Model error*

327 Many of the variables of interest in REDD+ or GHG reporting are not
328 directly measured in the field but estimated from other observed variables.
329 This is the case of tree biomass, carbon or volume, usually predicted using
330 allometric models with one or more easy-to-measure explanatory variables
331 (such as tree height or diameter at breast height). The fact that the variables
332 of interest are predicted and not measured adds additional uncertainty to the
333 estimation process and is likely to result in a decrease of both precision and
334 accuracy. Model error is used here to denote the error between the real
335 element value (such as the aboveground biomass of a certain tree) and the
336 value predicted by the model (assuming no measurement or precessing error
337 are made). Two main sources of uncertainty contribute to this type of error:
338 the uncertainty in the estimation of model parameters and the random model
339 residuals. In large area surveys such as NFIs, however, the latter is typically
340 very small (Chambers and Clark, 2012) and only the error in the estimation
341 of the model parameters contributes significantly to the total error (Ståhl
342 et al., 2016).

343 Ideally, model development constitutes a phase of the survey sampling
344 itself and data needed for model predictions are sampled using the NFI de-
345 sign. In this case (and if an adequate sampling design is used) it can be
346 possible to demonstrate that the model prediction is unbiased (or approxi-
347 mately unbiased). In practice, the application of models developed before and
348 independently of the survey sampling is common in NFI and GHG reporting.
349 Regional models, or models constructed by global macro ecological zone, such

as the pantropical biomass regression of Chave et al. (2014), are extensively used worldwide. The implicit (and often critical) assumption here is that the population for which the model was developed is very similar (if not identical) to the population of which we want to report the emissions/removals (Cunia, 1986). If this assumption does not hold, the model predictions are very likely to be biased and such a bias will propagate throughout the whole estimation process. Some authors also quantify the error in model choice, that is, the uncertainty due to the fact that more than one models exists in the literature and the reporting party does not know how to arbitrate between them (Chave et al., 2004; Picard et al., 2015; Duncanson et al., 2017). Reporting parties should pay attention to justifying the choice of the models used and possibly demonstrate their applicability to the target population. In theory, the model bias can be quantified using specific validation techniques based on national data (Claeskens et al. 2008, pp. 172 and 232; Woodall et al. 2010). In addition, previously constructed models available in the literature often do not provide the key statistics needed to compute the model error. In some cases, methods exist to estimate the model error in absence of the covariance matrix (Magnussen and Carillo Negrete, 2015) or through simulation of pseudo-data (Wayson et al., 2015). Methods for accounting for model errors in NFI when model data are sampled using the NFI design are presented in Cunia (1986) and Ståhl et al. (2014). Monte Carlo simulations are also often used to account for the model error (see also section 2.3 below) and specific statistical software or packages have been developed for this purpose. Réjou-Méchain et al. (2017) provide a Monte Carlo algorithm in R (R Core Team, 2016) to account for the error in the parameters of the model of Chave et al. (2014). Specific guidelines for documenting and reporting tree allometric equations are provided in Cifuentes Jara et al. (2015).

Model errors also abound in satellite-derived data. Image preprocessing is necessary to account for sensor, solar, atmospheric, and topographic effects; however, it can increase the potential to introduce error (Kennedy et al., 2009). Supervised and unsupervised image classification errors are particularly pervasive under the LULUCF sector approaches for the generation of activity data (Potapov et al., 2014) and tend to introduce considerable bias (Hill et al., 2013; Olofsson et al., 2013, 2014), filtering choices, spatiotemporal averaging, interpolation and extrapolation, among others, can contribute to increased uncertainties from satellite-derived data when linked to sampling through the use of training datasets (Hill et al., 2013).

387 **Set 6 of key questions: Model error**

- 388 (a) Was the variable of interest observed or estimated using a model?
- 389 (b) If so, what model was used?
- 390 (c) What auxiliary variables have been used to estimate the variable of
391 interest? How have they been collected?
- 392 (d) Were the auxiliary variables available for all population elements?
- 393 (e) Was the model developed independently of the survey (i.e. selected
394 from models already published in the literature)?
- 395 (f) How was the model selected and how can the party ensure that the
396 population for which the model was developed is similar to the target
397 population?
- 398 (g) If the data used to develop the model were collected within the survey,
399 can the party provide a description of the survey design and of the
400 model fitting method?
- 401 (h) Was the error in model parameters estimated? how?

402 *2.2.3. Frame imperfections*

403 Ideally, the sampled population should coincide with the population about
404 which emission factors or activity data are wanted. Any differences between
405 these two populations may constitute a departure from the ideal conditions
406 for the probability sampling approach and should be accounted for (Lesser
407 and Kalsbeek, 1999). Figure 2 shows three examples of frame imperfections
408 that can arise during the estimation of emissions/removals from LULUCF
409 sector survey data.

410 *2.2.4. Frame imperfections: under-coverage*

411 If the population that has been sampled is only a subset of the popula-
412 tion of which we want to estimate emissions/removals, the properties of the
413 estimates will be affected. In the literature on survey sampling this issue
414 is often referred to as under-coverage and it is very likely to result in some
415 bias in the estimates (Särndal et al., 1992; Särndal and Lundström, 2005).
416 In the context of the REDD+/LULUCF sector this can occur if the Party
417 wishes to report emissions/removals at national level but without the use

Figure 2: **Non-response and frame imperfections.** Three cases in which the target population (delimited by the solid line) does not coincide with the sampled population (the gray area delimited by the dotted line): a) the sampled population is smaller than the target population and entirely included in the target population; b) the target population is smaller than the sampled population and entirely included in the sampled population; c) the target population is not entirely included in the sampled population and vice versa. Circles represent the sample units and include both the non respondent units (crossed circles) and the respondent ones (black circles).

418 of data from a national level survey; instead sampling only limited areas of
 419 the country such as a specific region, ecological zone, forest type or ad hoc
 420 research plots. Special estimation techniques (such as weighting or imputa-
 421 tion) can be used to adjust for under-coverage but they often require the use
 422 of auxiliary variables and/or strong assumptions regarding the population of
 423 interest. Even if no advanced modeling techniques are used, a party should

424 still duly report the assumptions and the expert judgments on which they
425 have relied to correct for under-coverage.

426 **Set 7 of key questions: under-coverage**

427 (a) Is the area over which we want to report the emission/removals entirely
428 included in the area that has been sampled?

429 (b) If not, how did the party ensure the estimates are representative of
430 whole target population?

431 *2.2.5. Frame imperfections: over-coverage (domain estimation)*

432 Specific statistical techniques should be used in case the population for
433 which we want to report the estimate is smaller than the population sam-
434 pled, that is, the opposite of the case described in section 2.2.4. This can
435 occur frequently in REDD+/GHG reporting, whenever data from national
436 or subnational surveys are used to obtain different emission factors/activity
437 data for a set of subpopulations of interest (such as by forest type, ecological
438 zone, district, etc.). In the literature on survey sampling these subpopula-
439 tions of interest are also called domains. The problem stems from the fact
440 that the number of samples falling into a certain domain is random (i.e. it is
441 not controlled by the inventory designers) and, most likely, small. This can
442 result in a decrease in precision (that is, wider confidence intervals) and, if
443 the right statistical approach is not used, in a bias in the estimate. A detailed
444 review of basic estimation methods for domains is provided in Section 10.3
445 of Särndal et al. (1992). A more specific discussion about domain estimation
446 in the context of GHG and REDD+ reporting is presented in Birigazzi et al.
447 (2018). If the sample size of a certain domain is particularly small (which
448 is likely to occur when also the domain size is small, such as a very small
449 administrative unit or a very rare ecosystem), the estimation may require the
450 use of ancillary data or model-based inference, which may in turn compound
451 uncertainties with the model errors previously discussed. In the literature
452 this issue is often referred to as small area estimation (Schreuder et al., 1993;
453 Rao and Molina, 2015).

454 **Set 8 of key questions: over-coverage (domain estimation)**

455 (a) Is the area over which we want to report the emission/removals (the
456 target population) smaller than the area that has been sampled and
457 included in it?

- 458 (b) If so, has the party used any domain estimation techniques? Which
459 ones?

460 2.2.6. *Non-response*

461 Non-response is the term used in statistical literature to refer to the fail-
462 ure to measure some of the units in the selected sample (Cochran, 1977). In
463 national forest inventories this typically occurs whenever, for example, some
464 sample plots cannot be accessed by the field crews, and the tree variables
465 cannot be measured. In the context of remotely sensed area estimation it
466 can occur if some images are not available or masked by clouds and cannot
467 be interpreted. Non-response in remote sensing applications can also be due
468 to a malfunction in the satellite data collection mechanisms, such as the fail-
469 ure of the Scan Line Corrector of Landsat-7 (Markham et al., 2004), which
470 results in gaps in the imagery. Both the variance and the bias are likely to
471 increase together with the non-response rate. The fact that actual sample
472 size turns out to be smaller than what was originally planned can result in an
473 increase in variance (i.e. a wider confidence interval). On the other hand, the
474 bias can derive from the fact that non-responding elements may be system-
475 atically different from the responding ones (Särndal and Lundström, 2005).
476 In general, the wider the difference in terms of average values between the
477 non-respondents and the respondents, the bigger the bias. Methods exist for
478 dealing with non-response both before and after the data collection. The
479 latter, which are often referred to as non-response adjustment may include
480 the use of auxiliary data, as in the case of weighting and imputation meth-
481 ods, or include an additional subsampling of the non-respondents. General
482 principles to assist the estimation in the case of non-response are provided
483 by Särndal and Lundström (2005).

484 **Set 9 of key questions: Non-response**

- 485 (a) Did the party put in place any measure for the prevention or avoidance
486 of non-response before the data collection? If yes, which ones?
- 487 (b) How many of the selected sampling units have proven to be not mea-
488 surable/not accessible?
- 489 (c) Which are the main causes for the non-response? Are there any reason
490 to believe that non-responding elements may be systematically different
491 from the responding ones?

- 492 (d) Did the party adjust the estimate to overcome the fact that not all the
493 sampling units have been measured/accessed? If so, how?

494 2.2.7. Time coverage issues

495 A survey is typically carried out in different consecutive phases. Sam-
496 ple selection, data collection, data processing and the estimation obviously
497 do not occur at the same point in time. Since the attributes of interests of
498 the population elements are likely to change over time, it is fundamental to
499 specify the time point in which such attributes were observed. On the other
500 hand, the reporting parties need to report emissions/removals for a specific
501 time period. In the literature on survey sampling this is often called *reference*
502 *time point for the target population*. The lag between the moment in which
503 the variables are observed and the reference time point for the target pop-
504 ulation should be as short as possible to reduce the potential time coverage
505 error (Särndal and Lundström, 2005). In case this time lag is particularly
506 large it is possible to use specific interpolation and extrapolation techniques
507 and develop time series for the variables of interest (cf. IPCC, 2006, Vol. 1,
508 Chap. 5).

509 Set 10 of key questions: Time coverage issues

- 510 (a) When was the data collection carried out? What is the time period in
511 which the variables of interest were observed?
- 512 (b) Is the period over which we want to report emissions/removals included
513 in the data collection period?
- 514 (c) If not, how did the party ensure that estimates are representative of
515 the reporting time period?

516 2.2.8. Measurement error

517 The measurement error denotes the difference between the real element
518 value and the values that are measured during data collection. In the context
519 of an NFI this typically includes the errors in measuring tree dendrometric
520 parameters (such as tree height, diameter and species, among others), and
521 in the remotely sensed estimation of activity data, such as through visual
522 interpretation of aerial or satellite imagery, it may encompass the interpreter
523 error. The spatial uncertainty associated with the location of the observa-
524 tions (aka *position error*) is another example of measurement error which
525 can have considerable impact on the estimation, especially in the remote

sensed assisted estimation of land use change (Cressie and Kornak, 2003). Measurement errors affect both the bias and precision of the estimators. Measurement error from human interpretation can be reduced by ensuring adequate training of the field operators or interpreters and by making use of more accurate measuring instruments. There exist methods to account for the measurement error after the data collection. They rely on the use of repeated measurements, re-measurements using more accurate devices or on the development of more complex measurement models. Cochran (1977, Sect. 13) and Särndal et al. (1992, Sect. 16) discuss general methods for dealing with measurement errors. Measurement error computation in tree height (Larjavaara and Muller-Landau, 2013), or among-interpreter error through augmented visual interpretation (Bastin et al., 2017) are common examples. A recent paper by McRoberts et al. (2018) investigates the effect of the interpreter error on remote sensing-assisted estimators of land cover class proportions. Measurement errors purely rooted in satellite products may also include sensor calibration and degradation, irradiance variation, radiometric resolution, signal digitization, sensor drift or atmospheric attenuation and path radiance, and will further introduce systematic errors in later processing and modelling phases (Curran and Hay, 1986; Hill et al., 2013).

Set 11 of key questions: Measurement error

- (a) Which measuring instruments were used to measure the variables of interest? Is there any information available about the nominal precision of the measuring instruments used?
- (b) Which instruments were used to record the geographical location of the observations? Is there any information available about the nominal precision of the instruments used?
- (c) Can the party provide the precision with which each measurement is taken (for example, diameter at breast height to be recorded in cm to the nearest 0.1 cm)?
- (d) Did the party put in place any measure for the reduction of the measurement error (including position error)? If yes, which ones?
- (e) How many observers/field teams have been employed in the survey?
- (f) which satellite products were used to estimate activity data? what are the product specifications?

560 2.2.9. *Processing errors*

561 These include the errors occurring during the coding, editing and pro-
 562 cessing of the data. In NFIs this can encompass the mistakes made while
 563 entering the data in the field forms and/or in the database. Since thousands
 564 of elements (such as trees, or land cover sample units) are usually observed
 565 in large area environmental surveys, it is almost inevitable that some incor-
 566 rect values are recorded. The number of potential processing errors is such
 567 that it would be difficult to provide a complete list. This will depend on the
 568 survey type, on the data processing chain and on the nature of the different
 569 variables collected. In NFIs, in the context of GHG or REDD+ reporting,
 570 dendrometric variables (such as tree height, diameter, species, among oth-
 571 ers) are of great importance and the reporting parties should ensure all of
 572 them have been carefully assessed for quality. Processing errors affect both
 573 the precision and accuracy of the results. Given the multifarious nature
 574 of this source of error, it is difficult to provide a measure of its impact on
 575 the estimates, but it can certainly prove to be extremely relevant when no
 576 preventive or corrective measures are taken. The use of electronic tablets
 577 instead of paper forms (possibly associated with validation rules to warn the
 578 users whenever potentially erroneous values are entered) is an example of a
 579 measure to prevent data entry error in the field. Protocols for data cleaning
 580 in the office may include routines for the identification of outliers or missing
 581 data using graphical or statistical approaches. Methods for filling missing
 582 data and correcting incorrect values may include modelling or interpolation
 583 techniques and should be carefully described by the reporting parties. An
 584 overview of good practice for data entry and data quality control for NFI is
 585 provided by Morales-Hidalgo et al. (2017).

586 **Set 12 of key questions: Processing errors**

- 587 (a) Did the party put in place any measure(s) for the prevention of data
 588 entry error in the field and in the office? If yes, which?
- 589 (b) Which methods were used for the identification of invalid or aberrant
 590 values after the data were entered?
- 591 (c) Which methods were used for correcting missing data and outliers?

592 2.3. *Total (propagating) errors*

593 International reporting of errors to provide a final uncertainty estimate
 594 in the context of REDD+ and GHGI may involve the propagation of some

or all of these errors as the total error, in some cases combining both emission factors and activity data uncertainties. Reporting parties are so far free to choose which errors to report, although typically they report the sampling error as a minimum. It is trivial, but very important to recall that the more errors accounted for, the wider the total error reported. In the simplest scenario, often linked to Tier 1 approaches, reporting parties will delve into the standard formulas for the propagation of error (aka delta method or Taylor series) (Ku 1966; IPCC 2006, Vol. 1, Chap. 3). These formulas, much older than some more computational approaches, such as re-sampling, rely often heavily on assumptions of distributional symmetry, trivial covariance structures, or model misspecifications. However, they are in most cases standard formulas easy to implement. Monte Carlo approaches are typically used under higher Tiers estimation methods (Birdsey et al., 2013). They rely on repetitive random draws of values based on probability density functions for emission factors and/or activity data. By their very nature, they can in many cases propagate errors without assuming particular distributions in residuals and can tackle better correlations between variables or situations where widespread distributions are the norm (IPCC, 2006). However, they must be carefully developed and entail larger computational requirements. In some cases, they may inherit some simple assumptions from purely design-based estimators or traditional error propagation approaches. As a result, uncertainty outputs from Monte Carlo approaches are typically provided in the form of probability density functions, or more simply, as a result of the likely asymmetric distributions resulting from the computation, they can be reported through the resulting quantiles (McMurray et al., 2017). Careful use of assumptions regarding correlations between variables and the use of sensitivity analyses can not be forgone (Heath and Smith, 2000). Monte Carlo outputs can often be re-sampled to obtain the final confidence intervals. Rubinstein and Kroese (2008) provide a good textbook to delve into the topic. Although not too often used so far, example calculations in the context of REDD+ are gaining momentum (Pelletier et al., 2011; Köhl et al., 2015; McRoberts and Westfall, 2016).

Currently not included as a calculation option by IPCC, Bayesian approaches use a form of Monte Carlo computation, but rely on prior information to obtain uncertainties (Fox et al., 2011; Molto et al., 2013). Uncertainty comes in the form of the so-called credible intervals. It is unclear, however, how these uncertainties should be reported within the context of this manuscript.

633 Set 13 of key questions: error propagation

- 634 (a) Did the Party propagate errors to establish the total error?
- 635 (b) Were all the errors symmetric or normally distributed? If not, how
636 were those errors reported?
- 637 (c) Which assumptions were taken in regard to the existence of correlations
638 among the different errors?
- 639 (d) If errors were propagated, which method was used and how was it
640 justified?
- 641 (e) If the total error followed an asymmetric distribution, how was it re-
642 ported?

643 2.4. Good practice for reporting confidence intervals

644 Confidence intervals (CI) are meant to provide a measure of how well
645 the parameter of the population has been estimated and are one of the few
646 indicators of the quality of the estimate explicitly mentioned in the IPCC
647 guidelines. Even though they usually include only the sampling error, they
648 may also include one or more of the other errors indicated in Figure 1 (cf.
649 Fig. 3). It is evident that as more sources of error are included, the wider
650 the confidence interval will be. In addition to that, the confidence intervals
651 are also a function of the confidence level: the larger the confidence level,
652 the wider the confidence interval (the most commonly used confidence levels
653 being at 90% or 95%). To foster clarity and comparability it is necessary that
654 the reporting parties, when reporting a CI, clearly specify at least: (1) which
655 error components have been included in the CI; (2) the confidence level and
656 (3) the method used for calculating the confidence interval.

657 3. Conclusions

658 Estimations of GHG emissions and removals for the LULUCF sector are
659 often obtained using a combination of remotely sensed and ground-based
660 observations. In both cases this information is usually collected through
661 survey sampling techniques. In order to be compliant with the IPCC good
662 practice guidance for greenhouse gas inventories the estimation is required to
663 be transparent, unbiased and as precise as possible. However, assessing the
664 precision and accuracy of large-area surveys is not a easy task, requiring a

Figure 3: **Compounding errors.** Graphic representation of confidence intervals (at 95%) of two estimates of average tree volume density in Minnesota (Minnesota Survey Unit 1, USA). Both confidence intervals include three error sources: sampling error (in gray), measurement error (in yellow) and model error (in blue). In both cases the sampling error is the one that contributes the most to the total error. The confidence intervals are derived from data presented in McRoberts et al. (2016, Table 1)

considerable amount of information on the planning and implementation of the survey, on the data analysis and on the elaboration of the estimates.

In the context of LULUCF reporting, better (i.e., higher quality) uncertainty assessments including more error sources estimates will necessarily bring along wider compounded uncertainties, while systematic errors will be hardly avoided. This apparent absurdity can be rooted in the *uncertainty paradox*, wherein uncertainty aversion determines choices in individuals/institutions (Roeser, 2014). In the current context it would imply that

Parties may prefer to report less accurate estimates as long as they present narrower errors. In fact, under UNFCCC (2009) guidance, the paradox is unsolved, since countries are advised to reduce uncertainties through increasing transparency. Technical assessments of Forest Reference Level submissions further advice countries to improve coverage on additional sources of errors (Sandker et al., 2018), which may factually balance the paradox on the side of transparency.

In order to improve the transparency of the reporting, we propose a list of the survey features that should be reported to enable judgment of the quality of the survey results. In this manuscript, the questions proposed for the interrogation of estimates for quality and the sources of error described apply both to ground-based surveys and remote sensing-assisted estimation of activity data. The impact of many sources of errors is often not measurable, difficult to quantify or in the worst case, unknown. Further research is required especially on non sampling errors and techniques to propagate errors in general. It is important for a Party aiming to demonstrate the transparency of its results to explain whether and how they have tackled the main issues that may have an influence on the quality of the estimates.

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Supplementary Materials

Summary of the key questions

General information about the survey

1. Sampled population

- (a) What is the population from which the sample is chosen?
- (b) If the sampled population is defined as a geographic area, are you able to provide a map of it?
- (c) Is the sampled population defined as a finite set of discrete spatial units? If so, which ones? are they uniform? what is their area?

2. Target population

- (a) What is the population for which we want to estimate emissions/removals?
- (b) For which time period do we need the emissions/removals?
- (c) If the target population is defined as a geographic area, are you able to provide a map of it?
- (d) If the target population is not defined as a geographic area, are you able to provide a list of the elements that compose it?

3. Sampling selection

- (a) Is the survey based on a probability sample?
- (b) What sampling design has been used?
- (c) What was the planned size of the sample?
- (d) What is the size and shape of the sampling units?
- (e) Is the sampling unit composed of a cluster of subplots?
- (f) Is the sampling unit composed of one or more nested smaller subplots?
- (g) Was the sample selected following stratified sampling?
- (h) If so, which are the strata? how were they constructed? What is their size?

- 996 (i) If so, when the strata are defined as geographical areas, are you
997 able to provide a map of them?
- 998 (j) Repetition: Is the survey isolated or is it part of a series of re-
999 peated surveys? If so, what is the proportion of samples that
1000 were repeated?

1001 4. Data collection and processing

- 1002 (a) Which attributes have been observed in the sampling units?
- 1003 (b) What was the measurement protocol used to measure the variables
1004 of interest?
- 1005 (c) Has a written field manual or evaluation protocol been produced?
1006 Can the party provide it?
- 1007 (d) Can the party provide a clear and unambiguous definition for each
1008 class of categorical variables in the survey, including a land cover
1009 classification system (if any)?
- 1010 (e) Has the classification system (if any) been modified during the
1011 implementation of the survey? If so, how does that impact the
1012 final estimates? Did the party put in place any system to account
1013 for this change?
- 1014 (f) Has the field measurement protocol been changed during the im-
1015 plementation of the survey? If so, how does that impact the final
1016 estimates? Did the party put in place any system to account for
1017 this change?
- 1018 (g) How were the data stored and processed?

1019 Information about error sources

1020 5. Sampling error

- 1021 (a) Which estimator has been used to estimate the emission/removal?
1022 Can the party provide the mathematical formula used?
- 1023 (b) Has the variance of the estimator been estimated? If so, which
1024 estimator was used to compute it? Can the party provide the
1025 mathematical formula used?

- 1026 (c) Is the estimator for the population parameter and its variance
1027 estimator unbiased (or approximately unbiased) under the sample
1028 design adopted in the survey?

1029 6. Model error

- 1030 (a) Was the variable of interest observed or estimated using a model?
1031 (b) If so, what model was used?
1032 (c) What auxiliary variables have been used to estimate the variable
1033 of interest? How have they been collected?
1034 (d) Were the auxiliary variables available for all population elements?
1035 (e) Was the model developed independently of the survey (i.e. se-
1036 lected from models already published in the literature)?
1037 (f) How was the model selected and how can the party ensure that
1038 the population for which the model was developed is similar to
1039 the target population?
1040 (g) If the data used to develop the model were collected within the
1041 survey, can the party provide a description of the survey design
1042 and of the model fitting method?
1043 (h) Was the error in model parameters estimated? how?

1044 7. Under-coverage

- 1045 (a) Is the area over which we want to report the emission/removals
1046 entirely included in the area that has been sampled?
1047 (b) If not, how did the party ensure the estimates are representative
1048 of whole target population?

1049 8. Over-coverage (domain estimation)

- 1050 (a) Is the area over which we want to report the emission/removals
1051 (the target population) smaller than the area that has been sam-
1052 pled and included in it?
1053 (b) If so, has the party used any domain estimation techniques? Which
1054 ones?

1055 9. Non-response

- 1056 (a) Did the party put in place any measure for the prevention or
1057 avoidance of non-response before the data collection? If yes, which
1058 ones?
- 1059 (b) How many of the selected sampling units have proven to be not
1060 measurable/not accessible?
- 1061 (c) Which are the main causes for the non-response? Are there any
1062 reason to believe that non-responding elements may be systemat-
1063 ically different from the responding ones?
- 1064 (d) Did the party adjust the estimate to overcome the fact that not
1065 all the sampling units have been measured/accessed? If so, how?

1066 10. Time coverage issues

- 1067 (a) When was the data collection carried out? What is the time period
1068 in which the variables of interest were observed?
- 1069 (b) Is the period over which we want to report emissions/removals
1070 included in the data collection period?
- 1071 (c) If not, how did the party ensure that estimates are representative
1072 of the reporting time period?

1073 11. Measurement error

- 1074 (a) Which measuring instruments were used to measure the variables
1075 of interest? Is there any information available about the nominal
1076 precision of the measuring instruments used?
- 1077 (b) Which instruments were used to record the geographical location
1078 of the observations? Is there any information available about the
1079 nominal precision of the instruments used?
- 1080 (c) Can the party provide the precision with which each measurement
1081 is taken (for example, diameter at breast height to be recorded in
1082 cm to the nearest 0.1 cm)?
- 1083 (d) Did the party put in place any measure for the reduction of the
1084 measurement error (including position error)? If yes, which ones?
- 1085 (e) How many observers/field teams have been employed in the sur-
1086 vey?

- 1087 (f) which satellite products were used to estimate activity data? what
1088 are the product specifications?

1089 12. Processing errors

- 1090 (a) Did the party put in place any measure(s) for the prevention of
1091 data entry error in the field and in the office? If yes, which?
1092 (b) Which methods were used for the identification of invalid or aber-
1093 rant values after the data were entered?
1094 (c) Which methods were used for correcting missing data and outliers?

1095 Information about the total error

1096 13. Error propagation

- 1097 (a) Did the Party propagate errors to establish the total error?
1098 (b) Were all the errors symmetric or normally distributed? If not,
1099 how were those errors reported?
1100 (c) Which assumptions were taken in regard to the existence of cor-
1101 relations among the different errors?
1102 (d) If errors were propagated, which method was used and how was
1103 it justified?
1104 (e) If the total error followed an asymmetric distribution, how was it
1105 reported?