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The Quality of Detailed Land Cover Maps in Highly Bio-Diverse Areas: Lessons Learned from the Mexican Experience

Stéphane Couturier
Laboratorio de Análisis Geo-Espacial, Instituto de Geografía, UNAM
Mexico

1. Introduction

The production of Land Use and Land Cover (LULC) maps is essential to the understanding of landscape dynamics in space and time. LULC maps are a tool for the measurement of human footprint and social processes in the landscape and for the sustainable use of finite resources on the planet, a growing challenge in our densely populated societies. LULC maps with detailed forest taxonomy constitute a basis for sustainable forest management, especially in highly biodiverse areas.

However, these maps are affected by misclassification errors, partly due to the intrinsic limitations of the satellite imagery used for map production. Misclassification occurs especially when categories of the classification system (classes) are not well distinguished, or ambiguous, in the satellite imagery. Therefore, statistical information on the quality, or accuracy, of these maps is critical because it provides error margins for the derived trends of land cover change, biodiversity loss and deforestation, these parameters being some of the few means that governmental agencies can provide as a guarantee of sustainable forest management practices associated with international conservation agreements.

Assessing the accuracy of LULC maps is a common procedure in geo-science disciplines, as a means, for example, of validating automatic classification methods on a satellite image. For regional scale LULC maps, because of budget constraints and the distribution of many classes over the large extension of the map, the complexity of accuracy assessments is considerably increased. Only relatively recently have comprehensive accuracy assessments, with estimates for each class, been built and applied to regional or continental, detailed LULC maps. However, the quasi totality of the cartography that has been assessed is for countries located in mainly temperate climates with low biodiversity. Instead, LULC maps in highly bio-diverse areas still lack this information, partly because their assessment faces uncertainty due to a high taxonomic diversity and unclear borders between forest classes.

This research focuses on the evaluation of the accuracy of detailed LULC regional maps in highly bio-diverse regions. These are provided by agencies of countries located in the sub-tropical belt, where no such comprehensive assessment has been done at high taxonomic resolution. This cartography is characterized by a greater taxonomic diversity (number of classes) than the cartography in low biodiversity areas. For example, in the United States of Mexico (USM, thereafter 'Mexico'), located in a 'mega-diverse' area, the map of the National

Forest Inventory (NFI) contains 75 LULC classes, including 29 forest cover classes, at the sub-community level of the classification scheme. Taxonomically, the NFI sub-community level in the USM is comparable to the subclass level of the National Vegetation Classification System (NVCS) of the USA, which contains 21 LULC classes, including 3 forest classes.

Higher taxonomic diversity, combined with highly dynamic landscapes, has several implications on the evaluation of errors. First, the numerous sparsely distributed classes represented in the classification scheme pose additional difficulties to the accuracy assessment of the map in terms of representative sampling. Second, thematic conceptual issues impact the way maps should be assessed, because more diversity introduces more physiognomic similarity among taxonomically close classes. As a result, more uncertainty is introduced in each label of the map as well as in each line of the map.

Confronted with these difficulties, this research presents a recently developed accuracy assessment framework, adapted to maps of environments with high biodiversity and highly dynamic landscapes. This framework comprises two methods derived from recent theoretical advances made by the geo-science community, and has been applied recently to the assessment of detailed LULC maps in four distinct eco-geographical zones in Mexico. The first method is a sampling design that efficiently controls the spatial distribution of samples for all classes, including sparsely distributed classes. The second method consists in a fuzzy sets-based design capable of describing uncertainties due to complex landscapes.

This chapter first describes the status of the accuracy assessment of LULC maps, an emerging branch of research in Geographical Information Science. Another section is focused on the methods employed for accuracy assessments of LULC maps and on the challenges related to the taxonomic diversity contained in maps of highly biodiverse areas. The next section focuses on the case of the Mexican detailed LULC cartography, as well as the framework that has been developed recently. Special emphasis lies on the distinctive features which make this case a pioneer experience for taxonomically detailed map assessments as well as a possibly valuable benchmark for other cartographic agencies dealing with biodiversity mapping in other regions of the world. Finally, the accuracy indices found for detailed LULC cartography in Mexico are presented and compared with the accuracy of other assessed international cartography. A major objective of this chapter is to appeal for the inclusion of accuracy assessment practices in the production of cartography for highly bio-diverse areas, because this kind of practice is still nearly absent to date.

2. Quality, or *accuracy* of land cover maps

2.1 Why is it important to measure the quality, or *accuracy* of a map?

A series of important applications typical of the sustainable management of land cover in bio-diverse areas relies on the information content of detailed Land Use/ Land Cover (LULC) maps: forest degradation and regeneration, biodiversity conservation, environmental services, carbon budget studies, etc. In many or all of these applications, map reliability and quality are usually unquestioned, given for granted, just as if each spatial unit on the map perfectly matched the key on the map, which in turn perfectly matched reality. The minimum mapping unit, which defines the scale of the map, is commonly the only information available about the spatial accuracy of a map and no statistically grounded reliability study is applied as a plain step of the cartographic production process.

In general, the comprehensive LULC cartography of a region is obtained through governmental agencies of a country or group of countries, at regional scale, intermediate between local (> 1:50,000) and continental (1:5,000,000). Since the 1990s, the classification of satellite imagery has become the standard for LULC mapping programs at regional scale. However, the classification process is affected by different types of error (Couturier et al., 2009a; Green & Hartley, 2000) related in part to the limited discrimination capacity of the spaceborne remote sensor. The difficult distinction, on the satellite imagery, between categories (or 'thematic classes') of a cartographic legend can cause a high percentage of errors on the map (see next subsection), especially on maps with high taxonomical detail (high number of thematic classes). This is why a forest management policy or a biodiversity monitoring program whose strategy is simply 'process map information and rely on the quality of the map' is highly questionable.

For example in highly bio-diverse regions within Mexico, typical comprehensive database and cartographic products, such as the cartography generated by the National Institute of Statistics, Geography and Informatics (INEGI) and CONAFOR (the National Commission for Forests), are obtained at scale 1:250,000. However all of these products remain deprived of statistical reliability study. This is most unfortunate since the latter governmental agency produces statements on recent deforestation rates based on these maps (online geoportal: CONAFOR, 2008), and these statements, because of the absence of statistical reliability study, remain the focus of distrust and controversial academic and public discussions. It is worth stating that the online availability of the satellite imagery – a feature advertized by this governmental agency - does *not* make an index derived from the imagery more reliable. The extraction of the index based on colour tones of the satellite imagery available online is far from trivial and it is simply impossible for a user to quantitatively derive the global reliability of the cartography out of internet access to the imagery.

An error bar is sometimes present aside the legend of INEGI maps and indicates an estimate of positional errors in the process of map production. However, the procedure leading to this estimate is usually undisclosed, and any objective interpretation of this estimate by the user is thus discouraged (Foody, 2002). Moreover, such error bar indicates a very reduced piece of information with respect to the thematic accuracy of the map.

Instead, the *accuracy* of a cartographic product is a statistically grounded quantity which gives the user a robust estimate of the agreement of the cartography with respect to reality. Such estimate is essential when indices derived from cartography – i.e. spatial extent statistics, deforestation rates, land use change analysis - are released to the public or to intergovernmental environmental panels, while the absence of such estimate indicates that these indices stand without error margins, and as such, without statistical validity. The accuracy of a map also serves as a measurement of the risk undertaken by a decision maker using the map. Besides, this information allows error propagation modeling through a Geographical Information Systems or GIS (Burrough, 1994) in a multi-date forest monitoring task, for example. The construction of the accuracy estimate is generally named 'accuracy assessment' and is explained in section 3.

2.2 Status of the measured accuracy of land cover maps

Assessing the accuracy of LULC maps is a common procedure in geo-science disciplines, as a means, for example, of validating automatic classification methods on a satellite image. For regional scale LULC maps, because of budget constraints and the distribution of many classes over the large extension of the map, the complexity of accuracy assessments is considerably increased. Only relatively recently have comprehensive accuracy assessments, with estimates for each class, been built and applied to regional or continental, detailed

LULC maps. In Europe, Büttner & Maucha (2006) reported the accuracy assessment of 44 mapped classes (including 3 forest classes) of the CORINE Land Cover (CLC) 2000 project. In the United States of America (USA), Laba et al. (2002) assessed the accuracy of 29 LULC classes and Wickham et al. (2004) the accuracy of 21 classes in maps of year 1992 from, respectively, the Gap Analysis Project (GAP) and the National Land Cover Data (NLCD). As a part of the Earth Observation for Sustainable Development (EOSD) program of Canada, Wulder et al. (2006) provide a plan for the future accuracy assessment of the 21 classes in the 2000 Canadian forest cover map, and the accuracy of this program is assessed in the Vancouver Island for 18 classes (Wulder et al., 2007).

These studies reveal the presence of numerous confusions between classes, which yield a global accuracy index (percent area of the map with correct information) of between 38 and 70%. Consequently, these reliability studies constitute very valuable information in terms of the practical use of the assessed maps as well as in terms of enhanced map production strategies in the future.

The cartography of countries situated in areas of high bio-diversity is characterized by a greater taxonomic diversity, i.e. a greater number of classes for a given taxonomic level, than the above cited cartography. However, as is currently the case of the quasi totality of the countries situated in areas of high bio-diversity, the Mexican NFI map, for example, was until recently deprived of statistically grounded information on its reliability. Table 1 reports a collection of 9 studies in the world where a statistically grounded accuracy assessment has been applied to regional LULC cartography. This collection is thought to be relatively representative of existing studies and therefore reflects the status of international accuracy assessments of regional LULC maps to date. The studies which employ a probabilistic sampling design in the sense of Stehman (2001) over the entire area and not just a partial sampling are highlighted in bold. The list of studies was sorted according to the thematic richness of the assessed map (total number of classes).

Some findings can be derived from this table; for example, at first sight, the assessment efforts seem to be greater on the American continent than in other places. The LULC cartography on the African continent is represented by a study with partial assessment in Nigeria; the regional cartography derived from the Africover 2000 project (part of the Global Land Cover, or GLC, project) has not yet been submitted to a probabilistic accuracy assessment to date. In terms of taxonomic diversity (number of mapped classes), the 2000 NFI map in Mexico ranks second after the Southwest USA map, and ranks first of the mega-diverse areas. Therefore, the study on the 2000 NFI map in Mexico stands out as especially important in the world. Among the probabilistic assessments, the study assesses the highest number of classes (32 assessed classes vs 22 in Europe which holds the second ranking). For comparison purposes, we indicated the equivalent taxonomic level of each map, with respect to the four aggregation levels (*biome*, *type*, *community*, *community with alteration*, also known as *sub-community*) considered for the classification system of the IFN 2000 (Palacio-Prieto et al., 2000), plus two more detailed levels (*community with density grades* and *association with alteration*). The taxonomic level of the maps is generally relevant to applications of regional forest management and biodiversity monitoring (7 studies involve maps of levels *community*, *community with alteration*, *community with density grades*, *association with alteration*, which are the most detailed taxonomic levels). However, the study on the NFI 2000 map is the only accuracy assessment *per class* of these levels of taxonomic detail in a mega-diverse area (the other detailed assessments are in the USA, Europe and Canada), a level of detail which actually allows statistically- based cartographic management schemes in terms of bio-diversity dynamics. Another noteworthy study in a mega-diverse area is the one in South and Southeast Asia (Stibig et al., 2007), but its accuracy assessment was only obtained at the biome level. A study at the biome level does allow a deforestation study (forest – non forest change) with error margins, but does not allow a land cover change study with more detailed processes (e.g. 'forest to forest with alteration'), also important in sustainable management.

However, the assessment of the NFI 2000 cartography in four eco-geographical areas only constitutes a pilot study, confined to a limited extension, in a mega-diverse area. The spatial extent subject to the assessment is about 19,500 km^2, much smaller than the majority of the other studies (seven of the nine studies involve extents of more than one million km^2). Indeed, the enhanced taxonomic diversity, combined with highly dynamic landscapes, increase the difficulty of the accuracy assessment of maps in mega-diverse areas (Couturier et al., 2007), a fact that probably contributes to explain the lack of studies in such areas.

3. How can I measure the quality, or *accuracy* of land cover maps in biodiverse areas?

Generally, map accuracy is measured by means of reference sites and a classification process more reliable than the one used to generate the map itself. The classified reference sites are then confronted with the map, assuming that the reference site is "the truth". Agreement or disagreement is recorded in error matrices, or confusion matrices (Card, 1982), on the base of which various reliability indices may be derived. For regional scale LULC maps, the abundance and distribution of classes over the large extension of the map, confronted with tight budget constraints, add complexity to accuracy assessments. Only relatively recently have comprehensive accuracy assessments, with estimates for each class, been built and applied to regional or continental LULC maps (e.g. Laba et al., 2002; Stehman et al., 2003; Wickham et al., 2004; Wulder et al., 2007). Because of the high complexity of these products, detailed information on the assessment process itself is needed for the reliability figures to be interpreted properly (Foody, 2002). With this understanding, Stehman & Czaplewski (1998) have proposed a standard structure for accuracy assessment designs, divided into three phases:

1. Representative selection of reference sites (sampling design),
2. Definition, processing and classification of the selected reference sites (verification design),
3. Comparison of the map label with the reference label (synthesis of the evaluation).

Wulder et al. (2006) provide a review on issues related to these three steps of an accuracy assessment design for regional scale LULC cartography. We indicate in the next sub-section the features and techniques most commonly employed in the literature for phases 1-3.

3.1 Methods employed in the accuracy assessment of LULC maps in the world

3.1.1 Sampling design

The first phase of the accuracy assessment is the sampling design. The selection of the reference sites is a statistical sampling issue (Cochran, 1977), where strategies have varied according to the application and complexity of the spatial distribution. Stehman (2001) defines the probability sampling, where each piece of mapped surface is guaranteed a non-null probability of inclusion in the sample, as being a basic condition for statistical validity. In most local scale applications, reference sites are selected through simple random

Region of the world	Acronym of project and year of cartography	Prevailing biotic environment	Assessment design	Number of classes		Equivalent taxonomic level	Spatial resolut and satellite sensor
				Total	Forest		
Southwest USA	GAP 2000	Temperate-dry	Partial (near to roads)	125 (85 assessed)	27 (18 assessed)	Association with alteration	30m (Landsat TM)
Mexico (4 areas)	**NFI 2000**	**Mega-diverse**	**Probabilistic**	**75 (32 assessed)**	**29 (19 assessed)**	**Community with alteration**	**1km (Landsat TM)**
European Union	**CorineLC 2000**	**Temperate**	**Probabilistic**	**44 (22 assessed)**	**3**	**Community**	**30m (Landsat TM)**
South and Southeast Asia	**TREES 2000**	**Mega- diverse**	**Probabilistic for *biome level***	**40 (= 4 *biome* classes assessed)**	**17 (only 'forest' class assessed)**	**Community with alteration**	**1km (SPOT-VEGETATIO**
India	ISRO-GBP 1999	Mega- diverse	Partial (in 3 states of the country)	35	14	Community	188m (WiFS, I
USA	**NLCD 1992**	**Temperate**	**Probabilistic**	**21**	**3**	**Community**	**30m (Landsat TM)**
Canada (1 area)	**EOSD- Forest 2000**	**Temperate**	**Probabilistic**	**18**	**10**	**Community with density**	**25m (Landsat TM)**
Nigeria	1990	Tropical humid	Partial	8	3	Biome	1km (NOAA AVH
Legal Amazon, Brasil	GLC 2000	Tropical humid and dry	Partial	5	3	Type	1km (SPOT-VEGETATION

USA: United States of America.
Prevailing biotic environment: If large areas of different environments exist, e.g. temperate and sub-tropical, dry 'mega-diverse'.
Assessment design: 'probabilistic' if the design is associated with the total area mapped, and 'partial' if not; the c criteria of statistical rigor established by Stehman (2001).
Equivalent taxonomic level: equivalence in terms of the classification system of the National Forest Inventory 20 *Biome ('Formación' in Spanish)*, *Type*, *Community*, *Community with alteration* (or *sub-community)*, sorted from the mo (Palacio-Prieto et al.: 2000). Two additional more detailed levels were considered: *Community with density* (vegeta *with alteration*.
Spatial extent of the map effectively assessed: M km2 = millions of square kilometers. In case of partial assessme report sufficient information that indicate the effective area actually assessed; if this is the case we indicate '?', ar represents the total extent of the map (not the one actually assessed).

Table 1. List of major published studies on assessments of regional land use/ land cover maps in the exhaustive of institutional programs which aim a probabilistic sampling design. The studies are sort number of classes contained in the legend of the map.

sampling. Two stage (or double) random sampling has been preferred in many studies in the case of regional cartography; in a first step, a set of clusters is selected through, for example, simple random sampling. This technique permits much more control over the spatial dispersion of the sample, which means much reduction of costs (Zhu et al., 2000), and was adopted for the first regional accuracy assessments in the USA, for LULC maps of 1992 (Laba et al., 2002; Stehman et al., 2003).

A random, stratified by class sampling strategy means that reference sites are sampled separately for each mapped class (Congalton, 1988). This strategy is useful if some classes are sparsely represented on the map and, therefore, difficult to sample with simple random sampling. This strategy was adopted at the second stage of their double sampling by Stehman et al. (2003) and Wickham et al. (2004).

Systematic sampling refers to the sampling of a partial portion of the mapped territory, where the portion has been designed as sufficiently representative of the total territory. This strategy, adopted as a first stratification step, is attractive for small scale datasets and reference material of difficult access: Wulder et al. (2006) define a systematic stratum for the future (and first) national scale accuracy assessment of the forest cover map in Canada.

3.1.2 Verification design

For regional scale detailed land cover maps, the frame for reference material of phase 2 is typically an aerial photographic coverage (e.g. Zhu et al., 2000), and ground survey is only occasional. For all studies cited in the text of section 3 so far, the classification of reference sites was based on more precise imagery i.e. imagery with higher spatial resolution, than the imagery that was employed during the map production process. In these cases the map was produced using Landsat imagery (spatial resolution of 30m), and was assessed using aerial photographs (spatial resolution better than 3m) or aerial videography (Wulder et al., 2007). The map of South and Southeast Asia (Stibig et al., 2007, table 1) was produced using the SPOT-VEGETATION sensor (spatial resolution of 1km) and assessed using Landsat imagery (resolution 30m). An alternative reference material for recent LULC cartography could be a wide coverage of very high resolution satellite imagery such as the one available on the online Google Earth database. For all studies, remote sensing based reference data has been preferred as the primary material instead of ground survey for its cost-effectiveness in large areas.

Double sampling techniques are effective at controlling the spatial dispersion of the sample among image/ photograph frames if these are taken as the cluster, or Primary Sampling Unit (PSU), for first stage sampling (see previous subsection).

Congalton & Green (1993) relate errors of the map to imprecise delineation and/or misclassification. Additionally, the imperfect process of the assessment itself also generates erroneous statements on whether the map represents reality or not. A main topic is the positional error of the aerial photograph with respect to the map. To this respect, a procedure ensuring geometric consistency must be included in the evaluation protocol. For example, the procedure of visually locating sample points on the original satellite imagery, described in Zhu et al. (2000), reduces the inclusion of errors due to geometric inconsistencies. Other sources of fictitious errors occur in phase 3 (labeling protocol), and are related to the thematic and positional uncertainties of maps. This topic is introduced in section 3.2 and fully devised in Couturier et al. (2009a).

3.1.3 Synthesis of the evaluation

The comparison between the information contained on the map and the information derived from the reference site yields an agreement or a disagreement. Typically, the numbers of agreements and disagreements are recorded and form a confusion matrix. However, these numbers are reported in the matrix with weights that depend on the probability of inclusion of the reference site in the sample (Stehman, 2001). This probability of inclusion is defined by the sampling design. For example, a simple random selection is associated with a uniform (constant) inclusion probability among all reference sites. For a two stage sampling, the probability of inclusion follows Bayes law: The probability of inclusion p_{2k} of a reference site at the second stage is a multiplicative function of the inclusion probability p_{1k} of the cluster it pertains to, and of the inclusion probability of the reference site, once the cluster has been selected $p_{2|1}$ (conditional inclusion probability)(equation 1):

$$p_{2k}=p_{2|1} * p_{1k} \tag{1}$$

Accuracy indices per class are derived from these calculations: 'user's accuracy' of class k is the account of agreements from all sites of mapped class k while the 'producer's accuracy' of class k counts agreements from all reference sites labeled as class k. The respective disagreements correspond to 'commission errors' and 'omission errors' (Aronoff, 1982). The global accuracy index, or proportion correct index, which indicates the accuracy of the map as a whole (all thematic classes), integrates the accuracy level of all classes, weighted by the probability of inclusion specific to each class. In this calculation, weights usually correspond to the relative abundance of the class on the map. Other reliability indices are popular, such as the Kappa index, which takes into account the contribution of chance in the accuracy (Rosenfíeld and Fitzpatrick-Lins, 1986). However, in regional scale accuracy assessments, the proportion correct indices are preferred, because they are coherent with the interpretation of confusions according to area fractions of the map (Stehman, 2001).
A confidence interval of the accuracy indices can be estimated, although only few accuracy assessments provide this information. A popular estimate of the confidence interval is based on the binomial distribution theory: the confidence interval of the accuracy estimate depends on the sample size and on the reliability value (accuracy estimate) in the following manner (Snedecor & Cochran, 1967, cited by Fitzpatrick-Lins, 1981)(equation 2):

$$d^2 = t^2 p (1-p) / n \tag{2}$$

where d is the standard deviation (or half the confidence interval) of the estimate, t is the standard deviate on the Gaussian curve (for example, $t = 1.96$ for a two-sided probability of error of 0.05), p is the reliability value, and n is the number of sampled points. Although most accuracy assessments refer to it, this binomial distribution formula is only valid for simple random sampling. For more sophisticated sampling designs (e.g. two stage sampling) the confidence interval is influenced by the variance of agreements among clusters. Estimators integrating inter-cluster variance (Stehman et al., 2003) are seldom employed in map accuracy assessments because of their complexity (Stehman et al., 2003). For the cartography assessment in Mexico, an estimator which includes an inter-cluster variance term was used in Couturier et al. (2009a). The estimate was built on a stratified by class selection in the second-stage of the sampling design (Särndal et al., 1992).

3.2 Methodological challenge for the accuracy assessment of detailed LULC maps

The detailed cartography of highly bio-diverse regions is characterized by a greater taxonomic diversity (number of classes) than the cartography of regions in mainly temperate climates. Greater taxonomic diversity, combined with highly dynamic landscapes, has several implications on the evaluation of errors.

First, the numerous sparsely distributed classes represented in the classification scheme pose additional difficulties to the accuracy assessment of the map in terms of representative sampling.

Second, thematic conceptual issues impact the way maps should be assessed, for reasons illustrated in three cases:

- More diversity introduces more physiognomic similarity among taxonomically close classes: for example, cedar forest is an additional conifer forest class in sub-tropical environments, so mixed conifer forest patches are more difficult to classify, and boundaries between conifer forests are more difficult to set. As a result, more uncertainty is introduced in each label of the map as well as in each line of the map.
- Highly dynamic landscapes mean more classes placed along a continuum of vegetation, where some classes are a temporal transition to other classes. For example, the sequence of classes 'pasture to secondary forest to primary forest' is characteristic of sub-tropical landscapes. The extremes of such sequence may be spectrally distinct and easily separated, however boundaries between intermediate classes are difficult to interpret.
- More diversity combined with highly dynamic landscapes means more fragmented landscapes composed of small patches of different classes. The interpretation of these results in heterogeneous patches is difficult to assess.

Third and last, ambiguity between classes on satellite imagery, related to the above situations, becomes more likely. In these conditions, the information on spectral separability could be a systematic tool to prioritise future cartographic efforts (Couturier et al., 2009b).

Confronted with the three implications, we developed two methods based on recent theoretical advances made by the geo-science community.

The first method comprised a sampling design that efficiently controlled the spatial distribution of samples for all classes, including sparsely distributed (or fragmented) classes. Previous assessments have relied on two-stage sampling schemes where simple random or stratified by class random sampling was employed in the first stage. Couturier et al. (2007) demonstrated that these strategies fail in the context of the Mexican NFI. Section 3.2.1 presents a two-stage hybrid scheme where proportional stratified sampling is employed for sparsely distributed (rare) classes. This scheme was applied to four areas in distinct eco-geographical zones of Mexico (see section 4.3).

The second method was to design a fuzzy sets-based design capable of describing uncertainties due to complex landscapes. We will see in section 3.2.2 that it is traditionally possible to incorporate a thematic fuzzy component in accuracy assessment designs, but this component, as well as positional uncertainty, are implicitly fixed by the map producer, with no possible change after the design has been applied. Recently, advances in fuzzy classification theory have permitted the comparison of maps incorporating thematic and positional uncertainties.

3.2.1 The sampling design for fragmented (rare) classes

In order to find a sampling design well suited to an abundant set of fragmented, sparsely distributed (or rare) classes, several double sampling designs (DS) were previously tested in a pilot study, the closed watershed of the Cuitzeo lake in Mexico (Couturier et al., 2007);

DS1 was defined as the simple random selection of the Primary Sampling Units (PSUs), as in Laba et al. (2002).
DS2 was characterized by the random, stratified by class, selection of PSUs, as in Stehman et al. (2003).
DS3 was defined as a proportional, stratified by class, selection of PSUs. For the latter design, not applied in previously published research, the probability of inclusion of a PSU is proportional to the abundance of the class in the PSU. The abundance of a class equates its area fraction, easily obtainable via attribute computation in a GIS. Then, the probability of inclusion of Secondary Sampling Units (SSUs) at the second stage was defined as being inversely proportional to the abundance of the class in the PSU. Proportional sampling is a known statistical technique (Cochran, 1977) and some characteristics of its application to map accuracy assessment are devised in Stehman et al. (2000). However, DS3 had never been applied in published studies, maybe because it was not necessary for maps with classification systems of mainly temperate countries.
Finally, an entirely novel, hybrid design (DS4) includes a simple random selection of PSUs (as in DS1) for common classes (area fraction above 5%, 7 classes in Cuitzeo), and a proportional stratified selection of PSUs (as in DS3) for rare classes (area fraction below 5%, 14 classes in Cuitzeo). After selection of the PSUs, the sample size of SSUs was fixed at 100 per mapped class, a value widely adopted in similar assessments (Stehman & Czaplewski, 1998).
With fixed operational costs, the only design that systematically provided statistically representative estimates for all classes was the hybrid design DS4 (Couturier et al., 2007). Additionally, the hybrid design achieved a spatial dispersion of the sample similar to the dispersion achieved by DS1, with simple random selection of Primary Sampling Units (PSUs). DS1 is known for generating a good dispersion of the sample in regional map assessments. For this reason, DS1 was successfully applied in the accuracy assessment of the NLCD project in the USA (Stehman et al., 2003). However, DS1 was discarded in our pilot study because it was not able to handle the high number of rare classes of the NFI. Instead, the hybrid design maintains simple random selection of PSUs for common classes, but applies a proportional stratified selection of PSUs for rare classes. This way, DS4 cumulates the advantages of a wide-spread sample dispersion for common classes, and the advantages of a sufficient sample size and easy estimate calculation for rare classes.

3.2.2 The fuzzy approach for positional and thematic uncertainties

In traditional accuracy assessment, the labeling protocol (phase 3 of the accuracy assessment) consists in attributing one and only one category of the classification scheme to each reference site. However, this procedure assumes that each area in the map can be unambiguously assigned to a single category of the classification scheme (or LULC class). In reality, the mapped area may be related to more than one LULC class because of the characteristics of the landscape in the reference site. This conceptual difficulty is ignored in the traditional (or Boolean) labeling protocol, and may conduce to an under-estimation of map accuracy (Foody, 2002). In particular, this difficulty arises in the following cases:

- The landscape in the reference site has physiognomic similarities with more than one LULC class. For example, a one hectare forest patch containing oak trees and two or three pine trees has physiognomic similarity with forest class ‘oak forest’ and forest class ‘oak-pine forest’. As a result, the map label for this site is affected with uncertainty. The reference site could be in a transition zone between an oak forest and a oak-pine forest.

- The landscape in the reference site is a patch within a continuum of vegetation, where the LULC classes represented are a temporal transition to other classes. For example, the sequence of classes 'pasture to secondary forest to primary forest' is characteristic of some sub-tropical landscapes. As a result, the map label for this site is affected with uncertainty. The extremes of such sequence may be easily identified on the ground, however boundaries between patches of intermediate classes are difficult to set. As a result, lines between mapped objects for this site are affected with uncertainty.
- The landscape in the reference site is a fragmented landscape, composed of small patches (below minimum mapping unit) of different land use or land cover. The interpretation of this mixed reference site, because of the scale of the map, must be a non unique label. As a result, the map label for this site is affected with uncertainty.

Due to the above described continuous or fragmented aspects of land use and land cover in a landscape, maps with discrete representation (discrete, or crisp, class assignation) and infinitely small line features (crisp boundaries of objects) necessarily describe reality with a certain margin of uncertainty. In order to take this uncertainty aspect into account, it has been referred to the concept of fuzzy sets (Zadeh, 1965).

In the crisp approach, an element x of the map X belongs totally to a class k of the set C or does not belong to it. A way of representing this is to define a membership function μ, which takes the value '1' if the element x belongs to class k and '0' otherwise. This assignation process can be called Boolean labeling. In a typical case of photo-interpretation for map accuracy assessment, a forest reference site with a crown cover close to 40% may pertain to a transition zone between closed forest (crown cover > 40%) and open forest (crown cover < 40%). If the photo-interpreter characterizes this site as closed forest and the corresponding label on the map is open forest, then this site is interpreted as an error on the map.

In fuzzy sets theory, an element belongs to a set or class with a certain degree of similarity, probability or property, some of these notions being contained in a 'degree of membership', depending on the application. One element x may belong to various classes at a time with different degrees of membership $\mu_k(x)$. For example, quantitative degrees of membership take a value between 0 and 1 to express the partial membership to various classes of the set. With this approach, the reference site with a tree cover close to 40%, would be characterized for instance by a 0.5 degree of membership in both classes (open and closed forest).

Many authors have rejected the term “fuzzy set theory” to characterize landscape interpretation, in favor of “soft” or “continuous” classification. Critiques have noted that the use of a continuous range of membership values does not entail employment of the concepts of fuzzy logic (Haack, 1996). Nevertheless, the term “fuzzy classification” will be used here as a compromise, recognizing the heritage of these techniques but emphasizing the classification process over the logic of set theory.

Cartographical models that present a fuzzy classification approach were developed (Equihua, 1990, 1991; Fisher & Pathirana, 1990; Foody, 1992; Wang, 1990). These models allow the representation of the landscape features previously enumerated in this subsection. Despite the perspective of a more lawful representation of real landscapes, these models present two limitations:

- The interpretation and manipulation of fuzzy classified maps by users already accustomed to crisp maps is still a pending challenge; each point on the map represents various LULC classes with different degrees of membership. The vast majority of maps, including the existing LULC maps in Mexico and in territories with high biodiversity, are crisp.

- The coherent production of fuzzy classified maps with quantitative degrees of membership is not possible in all mapping situations. One of the situations where such fuzzy classified map can be easily produced is a binary map of, for example, forest/non-forest where percent crown coverage represents one of the fuzzy labels. A second situation is a map made of ordinal categories, where uncertainty between categories can be modeled by a fuzzy matrix (illustrated in Hagen, 2003). A third situation occurs when automatic processing is constructed so as to generate the quantitative fuzzy labels. A typical example of this third situation is a map of unmixed fractions of LULC classes, extracted from automatic spectral mixing analysis, where the classes are represented by pure end-member pixels. However, the assignment of quantitative fuzzy labels during visual interpretation, for example, can be affected by subjectivity. This is possibly a reason why quantitative fuzzy labeling has generally not been adopted in mapping situations with visually interpreted material.

Consequently, for the challenge concerning land cover over highly bio-diverse regions, the focus was made on assessing a crisp map with fuzzy classified reference material. As mentioned in section 3.1, the typical reference material of regional accuracy assessments is aerial photographs. We were confronted with the subjectivity of interpreters in preliminary attempts at classifying the material with quantitative degrees of membership. For these reasons, we settled for the fuzzy classification technique expressed by linguistic rules, introduced for visual interpretation by Gopal & Woodcock (1994), and commonly employed. This technique of fuzzy classification is described in the verification design of Couturier et al. (2008) for the case of detailed land cover map assessment in Mexico.

The use of fuzzy classification techniques in the labeling protocol permits the reduction of fictitious errors in the process of map assessment, fictitious errors being due to the thematic uncertainty of maps. However, as said earlier, maps are also characterized by positional uncertainty. This uncertainty may also affect the accuracy results when the assessed map is compared with the reference material. As a result of advances in fuzzy classification theory, much research have focused on the comparison of fuzzy classified maps and on the multi-scale comparison of maps (Pontius & Cheuk, 2006; Remmel & Csillag, 2006; Visser & de Nijs, 2006). In Couturier et al. (2009a), the systematic inclusion of positional uncertainty within regional accuracy assessments is proposed, formalized, and applied to the case of land cover maps of highly bio-diverse regions.

4. Mexican detailed land cover cartography and the application of the methods developed recently

4.1 Mexican detailed LULC cartography

As a consequence of its extension over a wide range of physio-graphical, geological and climatic conditions, the Mexican territory is composed of a remarkably large variety of ecosystems and diversity of flora (Rzedowski, 1978), is among the five richest countries in biological diversity and therefore considered as a mega-diverse area (Velázquez et al., 2001). In turn, this range of environmental conditions predetermined transformations of the landscape by humans in a variety of ways. The intensification of land uses over the last century and the response of the eco-systems to this intensification altogether shaped the complex landscapes in the contemporary Mexico.

In the past three decades, governmental agencies in the North American sub-continent have promoted the production of geographic information at a regional scale, which we define intermediate between continental (1:5 000 000) and local (> 1:50 000). The major historical data set of regional scale (1:250 000) LULC maps in Mexico was developed by the National Institute of Statistics, Geography and Informatics (INEGI). In the nineteen eighties, the first set of 121 LULC maps was published for the entire territory, based on the interpretation of aerial photography collected from 1968 to 1986 (average date 1976) and considerable ground work (INEGI, 1980). This dataset was part of the INEGI first series ('INEGI serie I', in Spanish) cartography. In the mid nineteen nineties, INEGI produced the second series cartography ('INEGI serie II') in a digital and printed format. The LULC maps of INEGI serie II were elaborated using the former series I maps, and visual interpretation of Landsat Thematic Mapper (TM) images acquired in 1993, printed at scale 1:250 000. The INEGI cartography legend included 642 categories to consistently describe LULC in the entire country. For land cover categories, or classes, this detailed classification scheme was based on physiognomic, floristic and phenological attributes of plant communities (table 1) and degrees of anthropic modification.

Formation	Vegetation Types
Temperate Forest	1. Cedar forest , 2. Fir forest, 3. Pine forest, 4. Conifer scrubland, 5. Douglas fir forest, 6. Pine-oak woodland, 7. Pine-oak forest , 8. Oak-pine forest, 9. Oak forest, 10. Mountain cloud forest, 11. Gallery forest.
Tropical forest	*Perennial & sub-perennial tropical forests:* 12. Tropical evergreen forest, 13. Tropical sub-evergreen forest, 14. Tropical evergreen forest (medium height), 15. Tropical sub-evergreen forest (medium height), 16. Tropical evergreen forest (low height), 17. Tropical sub-evergreen forest (low height) , 18. Gallery forest.
	Deciduous & sub-deciduous forests: 19. Tropical sub-deciduous forest (medium height), 20. Tropical deciduous forest (medium height), 21. Tropical sub-deciduous forest (low height), 22. Tropical deciduous forest (low height), 23. Tropical spiny forest.
Scrubland	24. Sub-montane scrubland, 25. Spiny Tamaulipecan scrubland, 26. Cacti-dominated scrubland 27. Succulent-dominated scrubland, 28. Succulent-cacti-dominated scrubland, 29. Sub-tropical scrubland, 30. Chaparral, 31. Xerophytic scrubland, 32. Succulent-cactus-dominated cloud scrubland,, 33. Rosetophilous scrubland, 34. Desertic xerophytic rosetophilous scrubland, 35. Desertic xerophytic microphilous scrubland,, 36 Propospis spp.-dominated, 37. Acacia spp.-dominated, 38. Vegetation of sandy desertic conditions.
Grassland	39. Natural grassland, 40. Grassland-huizachal, 41. Halophilous grassland, 42. Savannah, 43. Alpine bunchgrassland, 44. Gypsophilous grassland.
Hygrophilous vegetation	45. Mangrove, 46. Popal-Tular (hygrophilous grassland), 47. Riparian vegetation.
Other vegetation Types	48. Coastal dune vegetation, 49. Halophilous vegetation.

Table 2. Classification scheme of the INEGI land use and vegetation cartography (only natural land cover categories are indicated):

In the year 2000, the Ministry of the Environment in Mexico (SEMARNAP) attributed the task of updating the LULC map of the country (at scale 1:250 000) to the Institute of Geography of the Universidad Nacional Autónoma de México (UNAM). This task was intended as an academic-driven methodological proposal for rapid nation-wide detailed forest assessments. In this perspective, the cartographic project was named the National Forest Inventory (NFI) map of year 2000. An important objective of the project was the compatibility with previous cartography in view of LULC change studies. Rapidity (8 months) and low cost of execution were constraints that guided the planning of the project.

Visual interpretation of satellite imagery, with the aid of INEGI previous LULC digital cartography, was selected as the best classification strategy. However, the classification scheme was adjusted to the capacity of the Landsat Enhanced TM plus (ETM+) imagery at discriminating classes, according to previous classification experience in Mexico (e.g. Mas & Ramírez, 1996). The 642 categories of the INEGI cartography legend (including 49 vegetation types in table 2) were aggregated into 75 thematic classes (community level, with the inclusion of two levels of human induced modification) and further into three coarser levels of aggregation.

Visual interpretation was done on ETM+ imagery of the drier season, acquired between November 1999 and April 2000. The best option for interpretation was visually selected among various colour composites. The methods and results of the IFN 2000 cartographic project have been published (Mas et al., 2002a; Palacio-Prieto et al., 2000; Velázquez et al., 2002). Figure 1, taken from Mas et al. (2002a), illustrates the 2000 NFI map at formation level (coarsest level of aggregation). The present research focuses on the cartographic product with the finest level of aggregation (community level, with the inclusion of degradation levels), because of the availability of abundant quasi synchronous aerial photograph cover all throughout the country which can be used as independent reference data for accuracy assessment.

Since 2001, the National Commission of Forests (CONAFOR), an agency dependent of the National Environmental Agency in Mexico (SEMARNAT), is in charge of updating the vegetation cover change in Mexico, in parallel with the INEGI regional LULC cartography (year 2002: 'Serie III' map, and year 2007: 'Serie IV' map). None of this cartography so far has been generated with an international standard accuracy assessment scheme as described in this chapter. Since 2004, CONAFOR has established a 5 year repeat forest inventory of the Mexican territory ('Inventario Nacional Forestal y de Suelos', INFyS, 2008), based on a systematic grid of ground plots over the entire vegetation cover of Mexico.

4.2 Developing the framework for assessing the Mexican detailed LULC cartography

As stated previously, if we except the material presented in this chapter, all detailed LULC cartography in Mexico is characterized by the absence of quantitative, reliable information on its quality. Consequently, only qualitative statements can characterize the reliability of archive and recent Mexican cartographic products, based on a judgment on the quality of the data that was employed in the map production process. For example, the INEGI serie I data (1968-1986) are expected to be very reliable in terms of thematic accuracy, because of the quality of the field reference data, but their temporal coherence (accuracy) is low. Conversely, the LULC maps of INEGI serie II are characterized by a high temporal coherence. However, because the visual interpretation of only one colour composite of

Landsat imagery (bands 4,3,2) was used to update a map with very high taxonomic precision (INEGI legend of 642 classes), the thematic accuracy of INEGI serie II is likely to be poorer than that of INEGI serie I (Mas et al., 2002b).
In the case of the National Forest Inventory (NFI) map of Mexico, a preliminary accuracy assessment was conducted immediately after map production in year 2000. A systematic sampling of the entire country was planned, but the assessment could only take place on a small portion of the planned coverage, in the Northern part of the country (Mas et al., 2002a). The assessment yielded reliability levels for a few homogeneously distributed classes, and was not designed to attend, in a cost-effective way, the high number of classes of the NFI map and their complex distribution over the entire territory.
In 2003, a research project was initiated at the Institute of Geography, UNAM, with the proposed tasks of building academic capacity for the assessment of LULC maps in Mexico and developing a framework for future accuracy assessments of the INEGI cartography. Such a framework was built in accordance with the typically available verification materials, skills and resources in Mexico. In order to implement the methodology, a pilot study was launched over a set of four distinct eco-geographical areas described in the following section. The accuracy assessment fulfilled the following desirable criteria (see section 3): 1) a probability sampling scheme (sensu Stehman & Czaplewski 1998), comprising a sampling design, a response design and the synthesis of evaluation; 2) an operational design for future INEGI map updating missions; 3) a reasonable compromise between the precision (standard error) of accuracy estimates and operational costs.

4.3 An accuracy assessment in four eco-geographical areas in Mexico

We fixed a set of eco-geographical areas (located on figure 2) that captured parts of the mega-diversity of the Mexican territory, with special focus on some of the main forest biomes (see Tables 2 and 3). They also included contrasted levels of modification of the original vegetation cover.
Two areas are located on the transversal volcanic chain and contiguous altiplano in central western Mexico. These are the closed watershed of the Cuitzeo Lake, later referred as Cuitzeo, and an area encompassing both the natural reserve of the Tancítaro peak and the Uruapan avocado production zone, later referred as Tancítaro. Both areas are included in the state of Michoacán and are covered with temperate sub-humid and tropical dry vegetation (Table 3). A third area includes the core and buffer zones of the biosphere reserve of Los Tuxtlas, in the state of Veracruz. This area is mainly characterised by tropical humid conditions although temperate humid micro-climates prevail on the relief of the two coastal volcanic chains. The fourth area corresponds to the Mexican side of the Candelaria river watershed in the state of Campeche. This area includes a portion of the Calakmul forest reserve and is mainly characterized by tropical sub-humid conditions.
The Candelaria and Tancítaro areas comprise extensive forests (of low and high levels of human management, respectively) while most of Cuitzeo and Los Tuxtlas is covered with non forested agriculture land (crop and grazing land, respectively). Apart from the informative contrast in LULC, the selection and definition of these areas were guided by the availability of reference data for independently verifying the NFI-2000 map. These reference data are detailed in table 4.
Within each eco-geographical region (stratum), the sampling design incorporated a two-stage sampling design where aerial photographic frames formed the Primary Sampling Units (PSUs), as in most regional accuracy assessments of Landsat-based maps (Wulder et

al. 2006). A regular 500 m-spaced two dimensional grid (hereafter referred to as the 'second stage grid') formed the set of points, or Secondary Sampling Units (SSUs) of the second stage. Indeed, a scale criterion used during map production was to leave out polygons less than 500 meters wide.

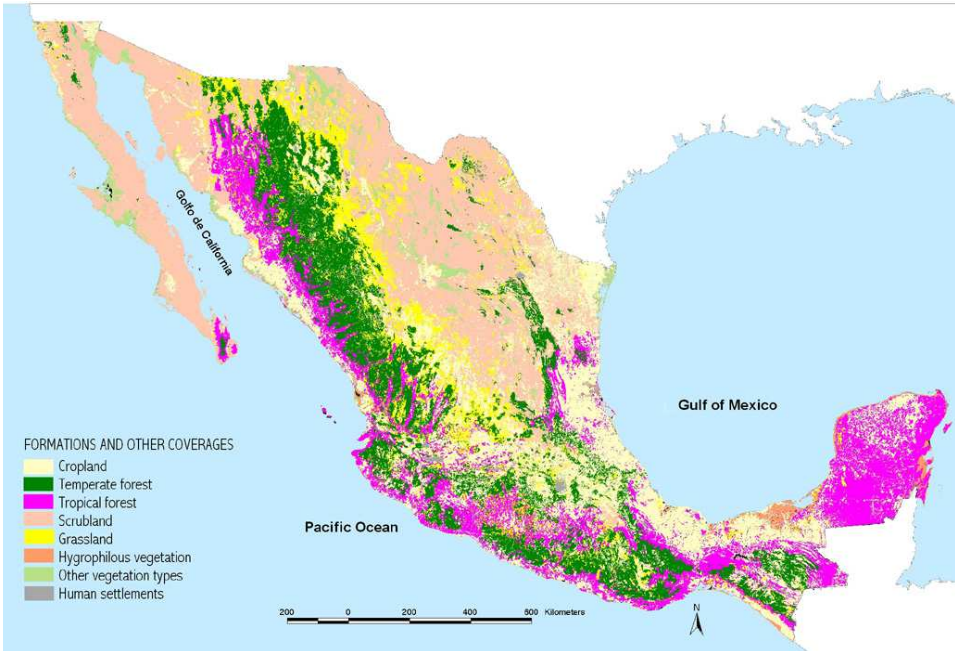
The first stage of the sampling design consisted in the selection of two subsets of PSUs. The first subset of PSUs was obtained with a simple random selection and was used for the assessment of common classes (classes whose area fraction is above 5%, a total of 7 classes in Cuitzeo, for example). The second subset of PSUs was obtained with a proportional random selection of PSUs, and was used for the assessment of rare classes (classes whose area fraction is below 5%, a total of 14 classes in Cuitzeo, for example). In the latter selection, the probability of selection attributed to each PSU was proportional to the abundance of the rare class in that PSU, as described in Stehman et al. (2000, further discussed via personal communication); this mode of selection was retained as an appropriate way for including all scarcely distributed (or 'rare') classes (a frequent occurrence in our case), in the sample while maintaining a low complexity level of statistics (i.e. standard stratified random formulae to compute estimators of accuracy). As a compromise between the precision of the estimates and our budget for undertaking the pilot research, the number of selected PSUs approached but was maintained below one quarter of the total number of PSUs in each area. According to this scheme, the PSU selection process is made independently for each rare class and a given PSU can be potentially selected multiple times (for rare classes as well as for the common classes). This hybrid selection scheme, differentiated according to 'common' and 'rare' classes, was proposed and detailed in Couturier et al. (2007), where its potential advantages with respect to sampling designs formerly applied in the literature were evaluated.

Once the sample PSUs were selected, all points of the second stage grid included within these PSUs were assigned the attribute of their mapped land cover class. The full second stage sample consisted of the selection of 100 points (SSUs) for each class mapped in the area. For each common class, the selection was a simple random sorting of points within the second stage grid in the first subset of PSUs. For rare classes, the selection of points was obtained via proportional random sampling in the second subset of PSUs, this time with a probability inversely proportional to the abundance of the class. This mode of selection could preserve equal inclusion probabilities at the second stage within a rare class (see the option of proportional stratified random sampling advocated in Stehman et al. 2000). A sequence of ArcView and Excel-based Visual Basic simple routines, for easy and fast repeated use on vector attributes of each class, was specifically designed to perform this proportional selection at both stages.

5. Quality of detailed LULC cartography in Mexico vs. quality of international cartography

5.1 Accuracy indices of the National Forest Inventory map in Mexico

Global and per class accuracy indices are presented in table 5 for each eco-geographical area. Confusion patterns among classes were presented in error matrices by Couturier et al. (2010) and permitted a detailed study of the quality of the cartography in terms of biodiversity representation. The global accuracy indices ranged from 64 per cent (Candelaria) to 78 per cent (Los Tuxtlas). Accuracy levels were lower in forest-dominated Candelaria (64 per cent) and Tancítaro (67 per cent) areas than in nonforest-dominated Cuitzeo (75 per cent) and Los



Source: Mas et al. (2002a)

Fig. 1. National Forest Inventory map of Mexico in year 2000 (NFI-2000 map)

Fig. 2. Location (shaded in grey) of the four eco-geographical areas in Mexico.

Class	Name	Biome	Cuitzeo		Tancítaro		Tuxtlas		Candelaria		Total
			Area frac	Area (km²)	Area frac	Area (km²)	Area frac	Area (km²)	Area frac	Area (km²)	area per class (km²)
100	Irrigated crop	Cropland	0.1411	564.97	0.0106	13.45					578.42
110	Hygrophilous crop		0.0048	19.04							19.04
130	Cultivated grassland						0.6058	1839.75	0.1708	1908.25	3748.01
200	Perennial crop		0.0021	8.27	0.2904	367.70	0.0129	39.16			415.13
210	Annual crop		0.2356	943.14	0.0803	101.69	0.1765	535.84	0.0070	77.85	1658.51
300	Forest plantation		0.0071	28.24							28.24
410	Fir forest	Temperate forest	0.0037	14.72							14.72
420	Pine forest		0.0041	16.32	0.1658	209.99	0.0011	3.36			229.67
421	Pine forest & secondary vegetation		0.0036	14.31	0.0634	80.23	0.0011	3.37			97.90
510	Oak-pine forest		0.0958	383.34	0.1907	241.47					624.82
511	Oak-pine forest & secondary vegetation		0.0325	130.29	0.1284	162.54	0.0028	8.48			301.31
600	Oak forest		0.0232	92.88			0.0011	3.44			96.32
601	Oak forest & secondary vegetation		0.0553	221.54	0.0017	2.16	0.0041	12.49			236.20
700	Cloud forest	Tropical forest	0.0029	11.73			0.0035	10.78			22.51
800	Median/high perennial tropical forest						0.1213	368.43			368.43
801	Median/high perennial tropical forest & secondary vegetation						0.0292	88.56			88.56
820	Median/high subperennial tropical forest								0.5010	5595.31	5595.31
821	Median/high subperennial tropical forest & secondary vegetation								0.0880	982.82	982.82
830	Low subperennial tropical forest								0.1765	1971.60	1971.60
831	Low subperennial tropical forest & secondary vegetation								0.0025	27.57	27.57
920	Subtropical scrubland	Scrubland	0.0194	77.58							77.58
921	Subtropical scrubland & secondary vegetation		0.0768	307.25							307.25
1000	Mezquital		0.0004	1.51							1.51
1200	Chaparral										0.00

1320	Savanna	Grassland							0.0108	120.13	120.13
1330	Induced grassland		0.1594	638.04	0.0032	4.02	0.0004	1.08	0.0039	43.65	686.80
1400	Mangrove	Hygrophil ous vegetation					0.0066	20.15	0.0060	66.93	87.08
1410	Hygrophilous grassland		0.0209	83.50			0.0019	5.86	0.0225	251.24	340.60
1510	Halophilous vegetation	Other vegeta-tion types	0.0069	27.78					0.0039	43.56	71.34
1600	No apparent vegetation cover	Other cover types			0.0390	49.43	0.0007	2.11			51.54
1700	Human settlement		0.0250	100.02	0.0265	33.59	0.0065	19.82	0.0009	10.19	163.62
1800	Water		0.0796	318.75			0.0244	74.01	0.0063	70.11	462.87
	All		1.0000	**4003.23**	1.0000	**1266.28**	1.0000	**3036.69**	1.0000	**11 169.21**	**19 475.41**

Area frac: Fraction of the eco-geographical area. The ’community with alteration’ taxonomic level refers to the ‘sub-community’ level in Palacio-Prieto et al. (2000).

Table 3. Class distribution (subcommunity and biome aggregation levels) of the NFI-2000 map in the four ecogeographical areas

Aerial photography	Data type/ interpretation	Scale/resolution	Year	Number of photographs
Cuitzeo	Prints/stereoscopic	1:37 000	1999	244
Tancítaro	Prints/stereoscopic	1:24 000	1996	152
Tuxtlas	Digital/on screen	1:75 000 / 1.5 m grain	2000 1996	12 14
Candelaria	Prints/stereoscopic	1:75 000	Jan 2000–Mar 2002	174

Table 4. Aerial photography used for the accuracy assessment of the NFI-2000 map.

Tuxtlas (78 per cent), possibly because of the higher (confusion prone) diversity of forest classes than nonforest classes in the NFI classification scheme.

For ‘other cover types’ (‘no vegetation cover’, ‘water’ and ‘human settlement’), a high accuracy (79 per cent and above) was registered, with the only exception of ‘water’ in Candelaria, where water bodies are small, dispersed and often seasonal. Visually, the spectral separability of these land covers within their group and with respect to other groups is indeed among the highest on conventionally used Landsat colour composites (e.g. 342). The mangrove class also recorded high accuracy in both Candelaria and Los Tuxtlas areas where mangroves are present. Conversely, very high interconfusion within aquatic non tree vegetation covers is evident when hygrophilous grassland and halophilous vegetation are both present (Cuitzeo and Candelaria). We also found high levels of commission error in hygrophilous grassland at the expense of induced grassland in Los Tuxtlas and Candelaria. The spectral ambiguity and variability (across inundation phases) of these aquatic vegetation types is probably one of the key explanations for this observed high confusion. Former INEGI maps mostly confirm the reference data in exhibiting such errors of the NFI-2000 map. Finer trends registered for forest types and land use categories vary according to the ecogeographical area as described in Couturier et al. (2010).

By contrast with the relatively high levels of accuracy of vegetation cover with little modification (classes without ‘secondary vegetation’), many errors were reported for classes

Class Code	Taxonomic name (Community with alteration)	(Biome)	Cuit-zeo User's	 Prod-ucer's	Tancí-taro User's	 Prod-ucer's	Tux-tlas User's	 Prod-ucer's	Cand-elaria User's	 Prod-ucer's	Total area per class (km2):
100	Irrigated crop	Cropland	87	90	22	23					578.42
110	Hygrophilous crop		63	75							19.04
130	Cultivated grassland						83	90	69	78	3748.01
200	Perennial crop		99	100	86	84	57	9			415.13
210	Annual crop		71	78	87	64	52	99	75	9	1658.51
300	Forest plantation		83	33							28.24
410	Fir forest	Temperate forest	76	100							14.72
420	Pine forest		79	59	41	44	85	31			229.67
421	Pine forest & sec veg		12	5	8	44	0	-			97.90
510	Oak-Pine forest		96	92	77	67					624.82
511	Oak-Pine forest & sec veg		45	68	56	55	6	83			301.31
600	Oak forest		92	40		-	28	32			96.32
601	Oak forest & sec veg		46	95	5	100	70	82			236.20
700	Cloud forest	Tropical forest	0	-			100	100			22.51
800	Median/high perennial trop forest						92	66			368.43
801	Median/high perennial trop forest & Sec Veg						63	42			88.56
820	Median/high subperennial trop forest								70	89	5595.31
821	Median/high subperennial trop forest & Sec Veg								55	45	982.82
830	Low subperennial trop forest								52	61	1971.60
831	Low subperennial trop forest & Sec Veg								32	1	27.57
920	Sub-tropical scrubland	Scrubland	78	29							77.58
921	Sub-tropical scrubland & Sec Veg		88	63							307.25
1000	Mezquital		0	-							1.51
1200	Chaparral			-							0.00
1320	Savanna	Grassland							22	-	120.13
1330	Induced grassland		60	91	36	66	69	11	67	26	686.80
1400	Mangrove	Hygrophilous vegetation					86	99	87	96	87.08
1410	Hygrophilous grassland		47	68			53	100	70	44	340.60
1510	Halophilous vegetation	Other vegetation types	25	21					9	41	71.34
1600	No apparent vegetation	Other cover types			82	92	87	100			51.54
1700	Human settlement		100	63	97	88	92	92	80	72	163.62
1800	Water		89	92			100	98	48	96	462.87
	Total		**74.6**		**67.3**		**77.9**		**64.4**		**19475.41**

Same conventions as table 2. Trop: Tropical; Sec Veg: Secondary Vegetation; Taxonomic level *Community with alteration* refers to level *Sub-community* in Palacio-Prieto et al. (2000)

Table 5. Accuracy indices (user's and producer's) per class of the National Forest Inventory (*Community with alteration*) in the four eco-geographical areas.

of highly modified vegetation cover (classes 'with secondary vegetation'). For instance in Cuitzeo, the accuracy of sub-tropical scrubland (78%), oak-pine forest (97%), pine forest (79%) and fir forest (76%) contrast with the accuracy of highly modified oak forest (46%), highly modified pine forest (12%) and highly modified mixed forest (45%). From both the taxonomical and landscape points of view, a class of highly modified vegetation cover is close to a wide set of land use classes as well as low modification vegetation cover classes, which makes it prone to more confusions than a class of low modification vegetation cover. These low accuracy levels, however, appear as a real challenge for improving the quality of future cartography because degradation studies are an important part of forest management and biodiversity monitoring.

Region of the world	Acronym of project and year of cartography	Prevailing biotic environ-ment	Assessment design	Number of assessed classes		Global accuracy index	Reference publication
				Forest	Total		
Mexico (4 areas)	**IFN 2000**	**Mega-diverse**	**Probabilistic**	**19 (29)**	**32 (75)**	**64-78%**	**Couturier et al. (2010)**
Southwest USA	GAP 2000	Temperate dry	Partial (near to roads)	18 (27)	85 (125)	*61%*	Lowry et al. (2007)
India	ISRO-GBP 1999	Mega-diverse	Partial (in 3 states of the country)	14	35	*81%*	Joshi et al. (2006)
Canada	**EOSD-Forest 2000**	**Temperate**	**Probabilistic**	**10**	**18**	**67%**	**Wulder et al., (2007)**
European Union	**CorineLC 2000**	**Temperate**	**Probabilistic**	**3**	**22 (44)**	**74.8%**	**Buttner & Maucha (2006)**
USA	**NLCD 1992**	**Temperate**	**Probabilistic**	**3**	**21**	**46-66% (per administrative region)**	**Stehman et al. (2003)**
Nigeria	1990	Tropical humid	Partial	3	8	*74.5%*	Rogers et al. (1997)
Legal Amazon, Brasil	GLC 2000	Tropical humid and dry	Partial	3	5	*88%*	Carreiras et al. (2006)
South Southeast Asia	**TREES 2000**	**Mega-diverse**	**Probabilistic for biome level**	**1 (17)**	**4 (40)**	**72% (biome level)**	**Stibig et al. (2007)**

Same conventions as table 1.

Table 6. Global accuracy indices of regional Land Use Land Cover cartography, derived from major published assessment studies in the world. The list is sorted by the number of assessed forest classes.

5.2 Comparison with other assessed international cartography

Table 6 presents the global accuracy indices found in each study listed in table 1. As a means of acknowledging the difficulty of mapping forest classes, the list in table 6 was sorted by the number of forest classes actually assessed in the study. With the exception of the GAP2000 very detailed study, the partial (non probabilistic) assessments yield higher accuracy indices (from 74.5 to 88%) than probabilistic assessments (in bold; from 46 to 74.8%). However, a partial assessment is possibly optimistically biased because it is not representative of the quality of the entire map, although it is impossible to estimate the magnitude of this bias (Stehman & Czaplewski, 1998). Among probabilistic assessments, the accuracy index in both densely forested areas (Tancítaro: 64.4% and Candelaria: 67.3%) is comparable with the results of assessments with a high amount of forest classes, en Canada (67%). Likewise, the accuracy index in areas where land use classes prevail (Cuitzeo: 74.6% and Los Tuxtlas: 77.9%) is comparable with the results of other assessment, such as the CorineLC 2000, mainly focused on land uses in Europe (74.8%)and with TREES2000 in South and Southeast Asia (72%). The accuracy indices in Cuitzeo and Los Tuxtlas, nevertheless, are higher than the range of results in other probabilistic assessments (46-66%). The NFI and the TREES 2000 cartographies have similar spatial detail (1km2 resolution) although the assessment of TREES 2000 was at biome level (only 4 assessed classes). The cartographic challenge of the NFI 2000 was greater at taxonomical detail of 'community with alteration' (32 classes).

The NFI map is also characterized by a higher taxonomic diversity than the other probabilistically assessed maps in the USA, Canada and Europe. However, the Minimum Mapping Unit (MMU) of those maps is much smaller (approximates the Landsat pixel size) than the MMU of the NFI, which in turn is a greater challenge for mapping accuracy. Considering these compensating factors (taxonomic richness but poorer spatial precision), the NFI map achieves comparable or better accuracy indices than the cited cartography, in a limited extent of the Mexican territory but in an extent that may reflect several scenarios and complexity of the national LULC.

The low accuracy registered for highly modified vegetation classes has been observed in the EOSD Canadian experience for forest covers of various density grades. Wulder et al. (2007) conclude that the highest source of errors in their map is caused by confusions among density grades. The confusion among density/ alteration classes caused by ambiguity on the Landsat imagery could be related, in the case of the NFI map, to the inclusion of the secondary vegetation in a great number of forest classes. This inclusion may be simpler and less confused in other projects such as GAP2000, TREES2000, or the NFI of year 1994 in Mexico where in spite of many forest classes, the presence of secondary vegetation is aggregated in very few classes.

A possible improvement of the detailed LULC cartography in Mexico could derive, therefore, from aggregating secondary vegetation classes into, for example, forest subtypes such as 'temperate forest with secondary vegetation' and 'tropical forest with secondary vegetation'. Such grouping could reflect a better matching of the classification system with the discrimination capacity of Landsat-like sensors in complex forest settings.

6. Conclusion

Land cover maps with detailed forest taxonomy are an essential basis for sustainable forest management at regional scale. This cartography is especially useful in highly biodiverse areas. A deforestation rate, a biodiversity conservation program or a land use change study critically depend on the quality of such cartographical datasets. Yet, for the overwhelming majority of governmental agencies in the world, the quality of the cartography is easily confounded with the spatial resolution, or temporality of the satellite imagery used in the map production process. Confusions between thematic classes on the imagery that lead to errors on the map are simply ignored, so that the derived deforestation rates, forest extent baselines, etc. are quantities without error margins and therefore these quantities lack statistical validity.

Based on a review on accuracy assessment studies in the world, this chapter first reports the occurrence of substantial errors in detailed regional land cover maps. The chapter then reports the recently developed research on the quality assessment of the LULC cartography in Mexico. A probabilistic accuracy assessment framework was developed for the first time in a mega-diverse area for taxonomically detailed maps and applied to four distinct eco-geographical areas of the Mexican NFI map of year 2000.

As a first feature of the accuracy assessment, a two-stage hybrid sampling design was applied to each of the four eco-geographical areas. Proportional stratified sampling was employed for sparsely distributed (rare) classes. This design had been fully tested and compared with existing designs in Couturier et al. (2007).

Second, with the utilization of reference maplets and GIS techniques, this research incorporated thematic and positional uncertainty as two parameters in the design, which created the possibility for a map user to evaluate the map at desired levels of positional and thematic precision. Couturier et al. (2009a) illustrated the practical usefulness of this possibility in the case of the NFI map, with landscapes composed of intricate tropical forest patches.

The accuracy of the NFI map was then compared with published error estimates of regional LULC cartographic products. We found that the quality of the NFI 2000 map (accuracy between 64% and 78%) is of international standards. This information is valuable given that the taxonomical diversity enclosed in the NFI is much higher than the currently assessed international cartography. Additionally, we found that the majority of land use classes and of low modification vegetation cover classes in the NFI are characterized by accuracy indices beyond 70%. By contrast, the NFI map registers low accuracy for highly modified vegetation cover classes. It is suggested that the quality of the cartography could be improved in the future by grouping categories containing secondary vegetation.

The assessment of the NFI 2000 cartography in four eco-geographical areas still constitutes a pilot study, confined to a limited extension, in a mega-diverse area. Since 2003, the monitoring of vegetation cover in Mexico is partly ensured using the MODIS sensor (CONAFOR, 2008), which is comparable with the SPOT-VEGETATION sensor used by Stibig et al. (2007) in Asia. We recommend the method presented here be extended to the national level for comprehensive accuracy assessment of future INEGI Serie V or vegetation cover annual maps of SEMARNAT. This method would ensure very reasonable costs and would contribute to solve the polemical discussions on the reliability of deforestation rates and land use change rates in the country.

We conclude that the work presented here sets grounds, as the first exercise of its kind, for the quantitative accuracy assessment of LULC cartography in highly bio-diverse areas. Among assets of this work is the knowledge, for the first time in a highly bio-diverse region, of the LULC quality that can be expected from the interpretation of medium resolution satellites.

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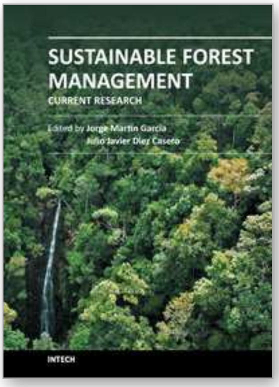

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Sustainable forest management (SFM) is not a new concept. However, its popularity has increased in the last few decades because of public concern about the dramatic decrease in forest resources. The implementation of SFM is generally achieved using criteria and indicators (C&I) and several countries have established their own sets of C&I. This book summarises some of the recent research carried out to test the current indicators, to search for new indicators and to develop new decision-making tools. The book collects original research studies on carbon and forest resources, forest health, biodiversity and productive, protective and socioeconomic functions. These studies should shed light on the current research carried out to provide forest managers with useful tools for choosing between different management strategies or improving indicators of SFM.