A Method to Compare and Improve Land Cover Datasets: Application to the GLC-2000 and MODIS Land Cover Products

Linda M. See and Steffen Fritz

Abstract—**This paper presents a methodology for the comparison of different land cover datasets and illustrates how this can be extended to create a hybrid land cover product. The datasets used in this paper are the GLC-2000 and MODIS land cover products. The methodology addresses: 1) the harmonization of legend classes from different global land cover datasets and 2) the uncertainty associated with the classification of the images. The first part of the methodology involves mapping the spatial disagreement between the two land cover products using a combination of fuzzy logic and expert knowledge. Hotspots of disagreement between the land cover datasets are then identified to determine areas where other sources of data such as TM/ETM images or detailed regional and national maps can be used in the creation of a hybrid land cover dataset.**

Index Terms—**Fuzzy logic, image classification, remote sensing, uncertainty, vegetation mapping.**

I. Introduction

THE production of global land cover datasets is vital for providing accurate baseline land cover information to address issues such as sustainable development, estimation of forest cover and climate change. The United Nation's Millennium Ecosystem Assessment [1], the Convention on Biological Diversity [2], the Global Environmental Outlook project [3], and the World Conservation Monitoring Centre (WCMC) are just a few of the many users of these global products. Two of the most recent products include the Global Land Cover 2000 (GLC-2000) dataset produced by the Global Vegetation Monitoring Unit of the Joint Research Centre of the European Union and the MODIS land cover product from Boston University (MOD12Q1 V004).

The GLC-2000 was created in collaboration with partners around the world [4]. It makes use of 14 months of preprocessed daily global data at a resolution of 1 km acquired by the VEGETATION instrument on board the SPOT 4 satellite [5]. The MODIS land cover product from Boston University (MOD12Q1 V004) was created using the Moderate Resolution Imaging Spectoradiometer instrument on the NASA Terra Platform using data from the period mid-October 2000 to mid-October 2001 [6]. The resolution of the sensor is 250 (band 1 and 2) to 500 m (band 3 to 7) and 1 km (band 8–36). The land cover product (MOD12Q1) was produced at a resolution of 1 km and uses information from a number of other MODIS products [7].

The method proposed in this paper is intended to complement larger scale validation exercises such as those undertaken in [8]. The methodology involves using fuzzy logic to capture classification uncertainty. Fuzzy membership matrices reflecting the degree of difficulty in classifying different land cover types are derived from a questionnaire administered to classification experts. The membership values are then applied on a pixel-by-pixel basis to map spatial disagreement. This allows us to identify where differences between the two land cover datasets occur as well as the severity of the differences. Differences occur due to a number of factors such as the sensor used, the spectral similarities of classes, the amount of and quality of reference data and the classification techniques employed. Areas for improvement in either land cover dataset are then identified using spatial clustering. The areas of highest disagreement are validated using additional information such as Landsat TM/ETM scenes and/or other detailed regional and national maps. The two individual datasets are then combined into a hybrid land cover dataset using the parts of the datasets that are closest in agreement to the validation site. The methodology is demonstrated on one area of disagreement to illustrate the process.

II. Approaches to Capturing Uncertainty

Fuzzy logic has been used in many remote sensing and GIS applications to address the problem of uncertainty [9]. One of the most common applications has been the use of fuzzy classification of land cover and soil [10], [11]. This allows for membership in more than one class and provides one solution to the mixed pixel problem.

Fuzzy logic can also be used to incorporate expert knowledge. In [12] and [13], experts were asked to use a linguistic scale to capture their perception of how well a land use class at a given reference site was described by a map category. The experts were then asked to express this comparison as one of five linguistic values ranging from absolutely wrong (1) to absolutely right (5). These fuzzy values were then hardened to create a set of tables describing the nature, distribution, magnitude and frequency of the errors, but they were not expressed spatially. In [14], fuzzy evaluation measures were developed for comparing raster maps of categorical data. The uncertainty associated with the classes and neighborhood effects were considered. A fuzzy

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kappa measure was derived, as well as a map showing the degree of similarity on a cell-by-cell basis, demonstrated on land use changes in Dublin, Ireland.

III. Creating a Spatial Disagreement Map

In this paper, fuzzy logic was used to capture expert knowledge and create maps of fuzzy disagreement. The approach is illustrated using the GLC-2000 dataset and the MODIS (MOD12Q1 V004) land cover product, but can be applied to any pair of land cover datasets. The first step involves creating maps of spatial disagreement between the land cover datasets. Work in this area has already been undertaken in [14], but the approach required here differs because the land cover classes must be harmonized before they can be compared. Similar problems have been identified in [15] and [16] in the comparison of U.K. land cover datasets over time. The need to harmonize legends as outlined in [15] is indicative of a much larger problem that surrounds the comparison of different land cover maps in general, which is highlighted in [17] in this special issue. The authors call for an international initiative on land cover harmonization. They propose the use of the FAO/UNEP Land Cover Classification System (LCCS) [18] as a basis for building land cover legends and comparing existing legends. The advantage of our approach over that in [17] is that it allows one to compare spatial datasets with differing legend classes without having to use an existing reference system and without having to aggregate classes in order to make them compatible. However, we acknowledge that a later harmonization of two land cover products with fundamentally different legends will result in the loss of detail. We, therefore, strongly support the call for an international initiative on land cover harmonization [17].

The GLC-2000 was developed using a bottom up approach in which more than 30 research teams contributed to 19 regional windows, where the regional legends used the LCCS as a common language to produce 22 global classes [4]. The MODIS land cover dataset uses all 17 classes of the IGBP legend [19], and unlike the GLC-2000, a global classification approach has been used.

The correspondence between the GLC-2000 and IGBP legends is rarely 100%. A comparison of the legends and their definitions shows that some classes have identical names, some appear to have partial overlap, and some appear to be present in only one of the two legends [20]. This means that a direct comparison of all classes in the GLC-2000 and the MODIS land cover datasets is not possible. One GLC-2000 legend class can correspond to more than one MODIS legend class and vice versa. The different possibilities that must be considered when the two data products are compared are provided in a matrix in [20]. By assuming 100% overlap, we take into account all possible cases where any degree of overlap might occur.

Classification of the 19 regions that make up the GLC-2000 was carried out by different teams of people so the difficulty involved in classifying different areas will vary between classes and between different experts. To capture this uncertainty in classification, a questionnaire was administered to the GLC-2000 partners who were responsible for the classification process within their particular region and were, therefore, the most knowledgeable. An example of the questionnaire given to the experts is provided in [20].

The GLC-2000 and MODIS land cover datasets were then compared on a pixel-by-pixel basis using a Boolean and two fuzzy operators: maximum and minimum. The full algorithm is detailed in [20]. From this analysis, it is also possible to calculate the overall agreement between the two land cover products, which is simply the number of pixels where there is 100% agreement divided by the total number of pixels expressed as a percentage. Likewise, one can calculate the percentage of agreement for the two fuzzy agreement maps as follows:

$$\%\text{fuzzy agreement} = 100 - \frac{\sum_{p=1}^{q}\left[w_p^* \sum_{i=1}^{n_{w_p}} j_i\right]}{j} * 100$$

where w_p is the membership value ranging from 0 to 1 for q distinct membership values, j_i is the number of pixels n with a given membership value w_p, and j is the total number of pixels. The overall agreement for the Boolean map is 55.7%, but this value increases significantly when considering a fuzzy approach, i.e., 81.7% for the map generated using a maximum operator and 75.6% for a minimum operator. This result is in line with what classification experts would generally agree, i.e., that the disagreement is more severe if, for example, a pixel-by-pixel comparison shows a bare area class on one map and a forest class on the other. In contrast, if a needle-leaved evergreen forest class corresponds to a mixed forest class, then the disagreement is, in general, considered to be less severe. The maps of spatial disagreement along with a description of the main areas of disagreement are available in [20].

The next step is to pinpoint those areas that should be checked using either a higher resolution image or information from other sources such as TM/ETM Landsat images, national and regional data, and any expert knowledge from the field. To highlight those areas with a high incidence of disagreement, hotspot maps were created using a spatial clustering algorithm that was applied to both the fuzzy minimum and maximum maps. At each pixel, this algorithm sums the value of all pixels within a specified radius. The result is a hotspot map that pinpoints areas of high disagreement. A radius of 100 pixels was used to correspond to the approximate size of a single Landsat image. The hotspot maps are shown in Fig. 1 and correspond to the fuzzy maximum and minimum maps as inputs.

The fuzzy maximum hotspot map [Fig. 1(a)] shows areas of disagreement from the most conservative perspective [20]. An equal area top-slice was performed on the map to highlight those areas with the highest 10% of disagreement in red, the next 10% slice of disagreement in orange and so on. Large red and orange hotspots occur in the Middle East, Australia, northern Canada, northern Russia, eastern and southern Africa, Scandinavia and South America, Argentina, in particular, and parts of highland Bolivia. The large hotspot in Australia is an example of where the GLC-2000 land cover type is Bare Areas or Sparse Herbaceous or Sparse Shrub Cover while the MODIS map classifies most of these same areas as Open Shrubland. Other large areas in Southern America and the large red area of disagreement in Kazakhstan show the same pattern. In fact, many of the hotspots

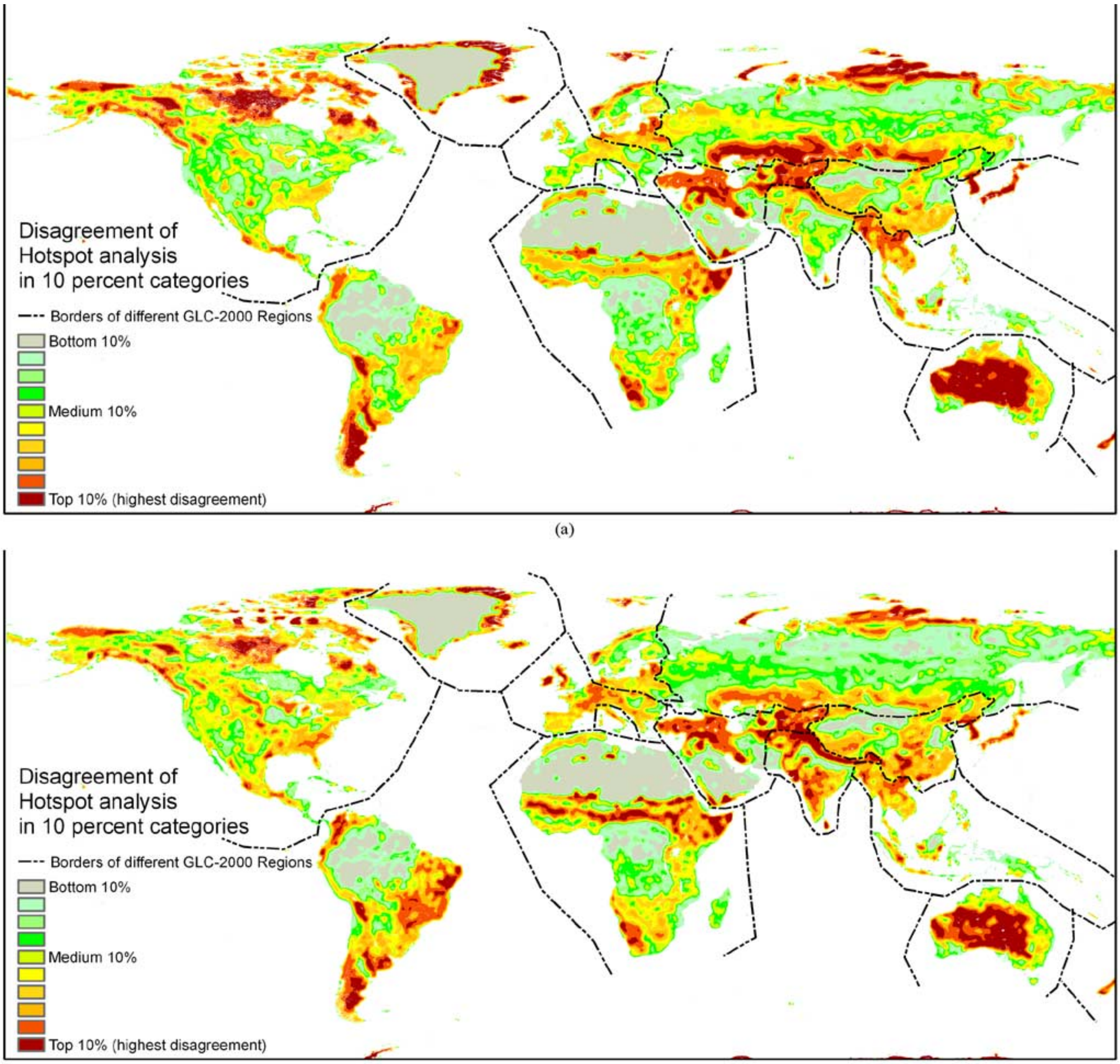

Fig. 1. Hotspot maps of spatial disagreement between the GLC-2000 and MODIS land cover products for (a) the fuzzy maximum and (b) fuzzy minimum maps.

located on the map record these types of discrepancies. Most of these areas result because both experts agreed that it was easy for them to differentiate between Shrubland (or Open Shrubland for the MODIS expert) and sparse vegetation. This may simply be a labeling or classification error as a result of the use of different ontologies, i.e., different specifications of the way in which the world is abstractly represented [15], or due to the different backgrounds of the interpreter. The more interesting patterns are the hotspots within a given region, e.g., in Africa and Europe.

The less conservative fuzzy minimum hotspot map, shown in Fig. 1(b), highlights additional areas including large sections of eastern Brazil, the middle United States, India, and a whole range of new hotspots in the northern central African agricultural belt. The sections in eastern Brazil are examples where most of these areas contain Cultivated and Managed Areas in the GLC-2000 and natural vegetation (Open, Closed Shrublands, or Herbaceous Cover) or a mosaic of cropland/natural vegetation in the MODIS map.

IV. Developing a Hybrid Land Cover Map

We will consider only one area to highlight the method: Northern Europe. The hotspot map for Northern Europe is provided in Fig. 2(a), which shows five areas. We will concentrate on three of the hotspots (labeled 1 to 3), which are signified by the occurrence of Managed and Cultivated or Natural Vegetation in the GLC-2000 and forest cover in MODIS. They occur in Northern Germany, the Baltic regions, and Russia. In hotspot

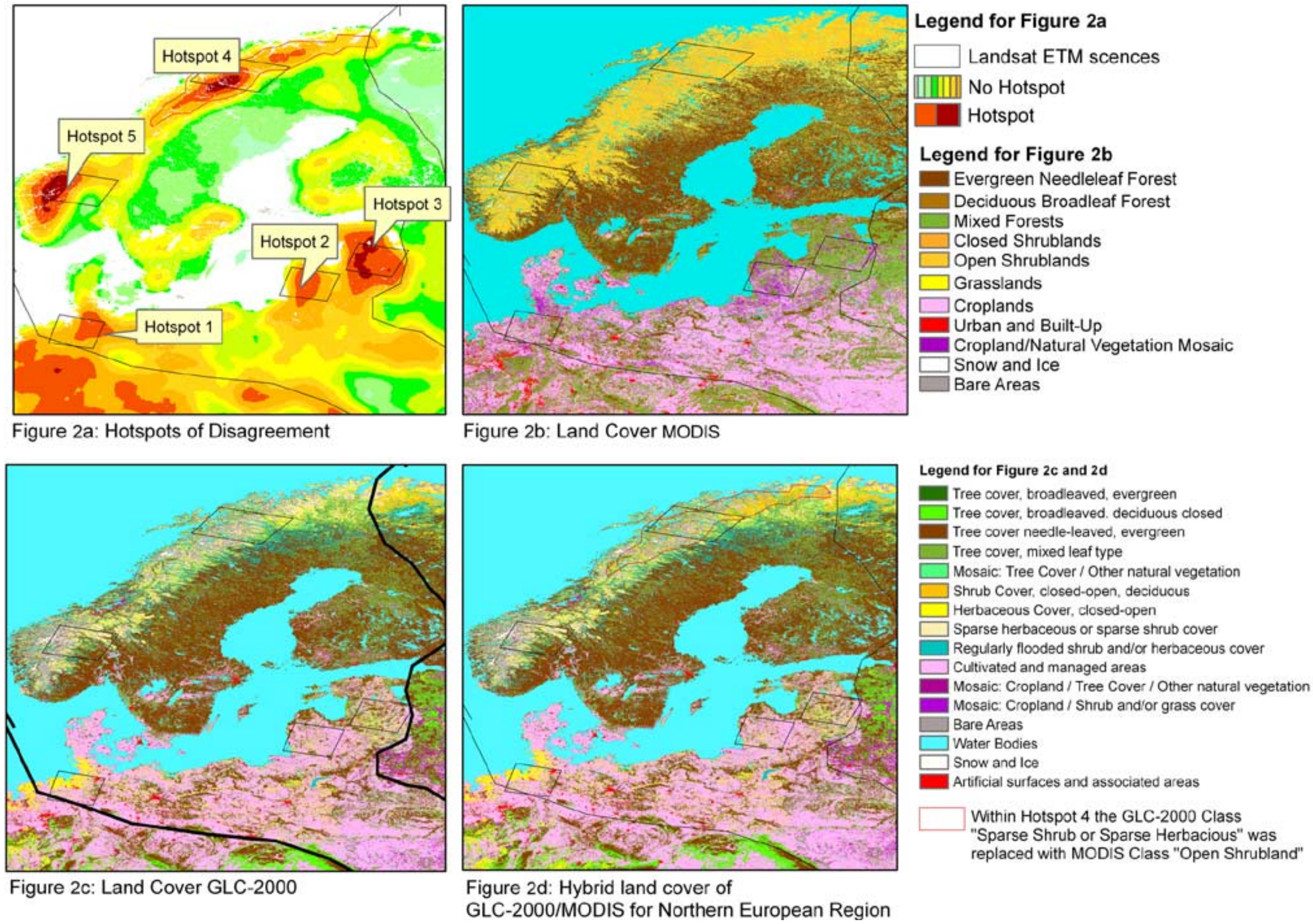

Fig. 2. Producing a hybrid map for Northern Europe showing (a) hotspots of disagreement, (b) the GLC-2000 land cover map, (c) the MODIS land cover map, and (d) the hybrid map.

one, the disagreement results from the high percentage of the area that appears to be Cultivated and Managed or Grassland in the GLC-2000 and Mixed forest or Cropland/Cropland-Nat. Vegetation Mosaic in the MODIS dataset. A comparison with the Landsat ETM scene (196/23) [Fig. 3(a)] indicates that MODIS overestimates forest cover in that area. In hotspot two the land cover class Cultivated and Managed of CORINE (Coordination of Information on the Environment) [21] appears as forest cover in the MODIS map. The high-resolution ETM image (188/22) [see Fig. 3(b)] of hotspot two records mostly nonforest for these areas and indicates that the GLC-2000 dataset is more accurate in this place. In hotspot three, the land cover class Cultivated and Managed appears as Mixed Forest cover in MODIS. The Landsat scene (186/20) [Fig. 3(c)] clearly shows that the forest cover of MODIS is overestimated.

To create a hybrid map and to decide which map is more accurate, information from ETM images was selected that falls in the hotspots. The location of the ETM images is shown on each of the maps in Fig. 2 as black squares. These images are included in Fig. 3(a)–(c) as the first image from the left, where the second image is the high-resolution CORINE land cover map [21], followed by the GLC-2000 and MODIS maps for this area. The CORINE land cover dataset was produced at a resolution of 100 m with 44 legend classes using a three-tier nomenclature. The CORINE product is based on a visual classification of Landsat and Spot scenes, and detailed local knowledge. Although no accuracy assessment has been undertaken on CORINE as a whole, there was a minimum thematic accuracy requirement of 85% and a minimum geometric accuracy requirement of 100 m, which was imposed at a national level [22].

We initially start with a visual examination of the ETM scenes, the CORINE land cover map, and the GLC-2000 and MODIS datasets. Undertaking visual interpretation of high-resolution images, as well as their use in the validation of coarser resolution datasets, has been a common exercise in a number of studies, e.g., [23]. The GLC-2000 has already been validated in the Tropics with validation sites from the TREES-II project, a study which was based on high-resolution TM data to assess tropical deforestation between 1992 and 1997 [24]. Examining the ETM scenes and the CORINE land cover map of Fig. 3, it becomes obvious that MODIS overestimates forest cover for the three hotspots. We can confirm this by undertaking a more quantitative analysis. The CORINE land cover dataset was compared to both the GLC-2000 and MODIS datasets. Since CORINE is quite detailed with 44 classes, a corresponding GLC-2000 or MODIS class could be found. In order to make a quantitative analysis, the GLC-2000 and MODIS products were first projected into the Lambert Azimuth projection of the CORINE dataset and then disaggregated to a 100-m resolution so that no information from CORINE was

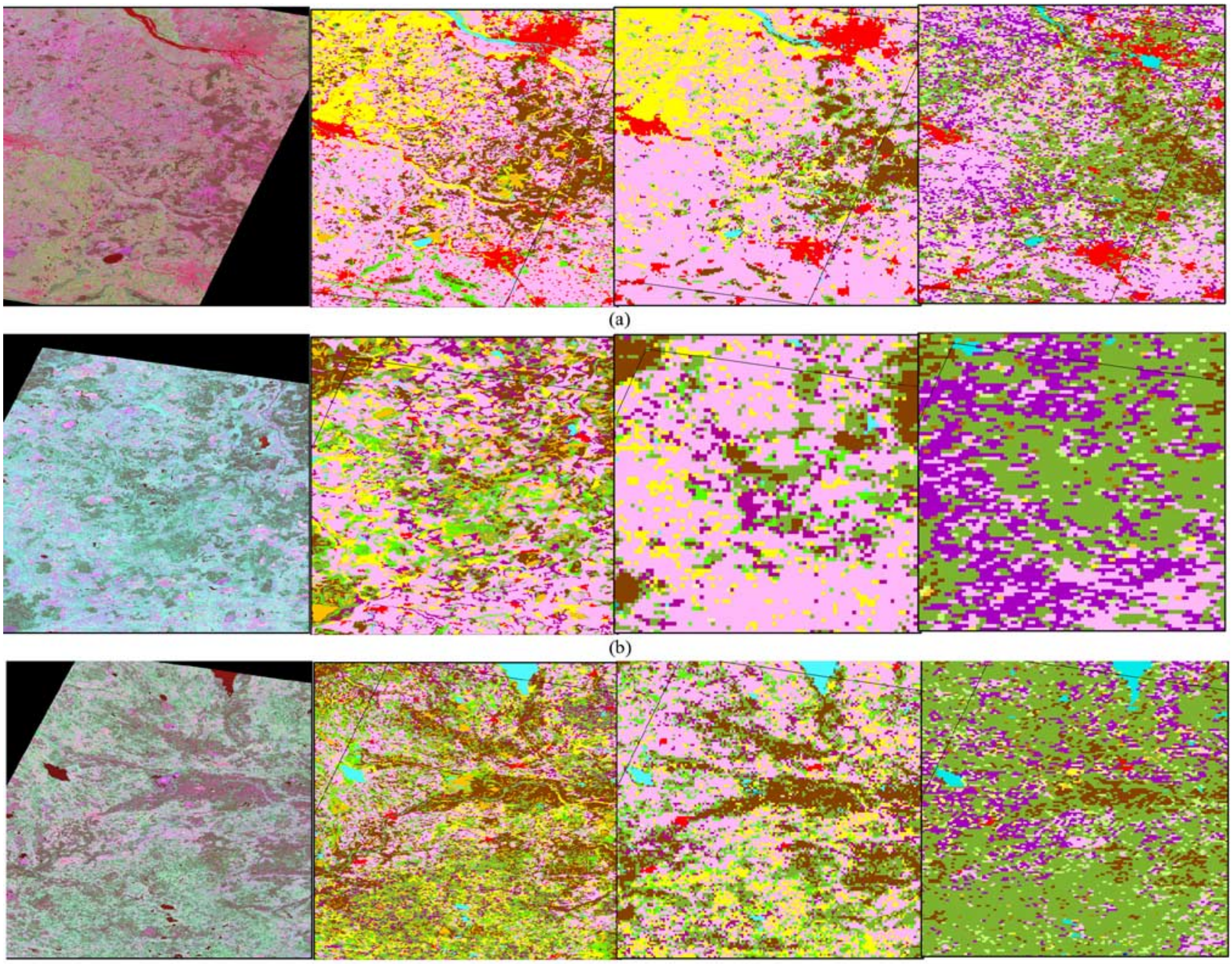

Fig. 3. Landsat scenes overlapping hotspots 1 to 3. (a) ETM scene 196/23, CORINE, GLC-2000, and MODIS. (b) ETM scene 188/22, CORINE, GLC-2000, and MODIS. (c) ETM scene 186/20, CORINE, GLC-2000, and MODIS. The legend used for MODIS and GLC-2000 are the same as in Fig. 2.

lost. A confusion matrix containing the area for each land cover combination, which records a pixel-by-pixel comparison, was derived for the three hotspots. The patterns for all three hotspots were similar in terms of the over prediction of forested areas by MODIS. The correspondence of the main land cover type Cultivated Areas has a much higher correspondence in the GLC-2000 (1 080 677 ha) compared with the MODIS land cover dataset (751 647 ha). Instead of cultivated land, MODIS shows a high proportion of Mixed Forest. An overall agreement was also calculated and is 62% for GLC-2000 and CORINE and 41% for MODIS and CORINE.

We can better illustrate this pattern of overprediction of forested area in the MODIS dataset by aggregating the forest classes of the GLC-2000, MODIS and CORINE and plotting the total area (Fig. 4). This clearly illustrates that MODIS is overpredicting the forest cover in these hotspot areas. The GLC-2000, on the other hand, although underpredicting, is much closer to the results from the CORINE land cover dataset.

From the visual and quantitative analysis of the hotspot areas in Northern Europe, one can see that the MODIS land cover product overestimates forest in those areas that are mostly cultivated land. Although, in general, experts found differentiation between forest and cultivated land quite easy, a significant error has still occurred. This could also mean that for the MODIS processing chain an additional training site would be needed in this area. Fig. 2(b) shows the MODIS land cover product for the northern European window, Fig. 2(c) shows the GLC-2000 and

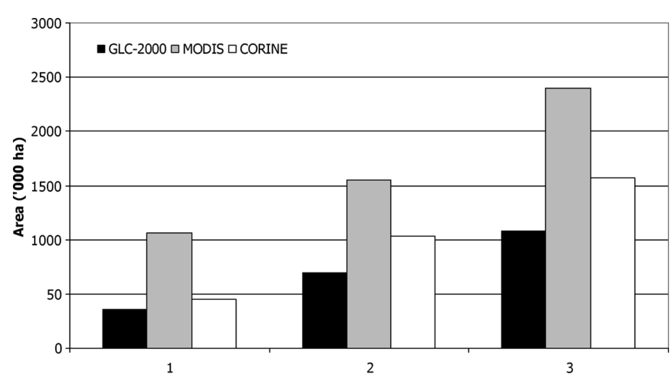

Fig. 4. Comparison of the total area of forest cover from the GLC-2000, MODIS, and CORINE land cover dataset for the hotspot areas.

TABLE I
CORRELATION COEFFICIENTS

MODIS Legend Class	Global	N European
Evergreen Needleaved Forest	0.26	0.23
Evergreen Broadleaf Forest	0.63	-0.05
Deciduous Needleleaf Forest	0.04	0.02
Deciduous Broadleaf Forest	0.22	0.14
Mixed Forests	0.16	0.02
Closed Shrublands	0.01	-0.01
Open Shrublands	-0.13	-0.07
Woody Savannas	-0.04	0.04
Savannas	-0.02	-0.10
Grasslands	-.016	-0.06
Permanent Wetlands	-0.07	0.05
Croplands	0.21	0.17
Urban and Built-Up	not available	not available
Cropland/Natural Veg	0.02	0.05
Snow and Ice	0.37	0.24

Fig. 2(d) shows the resulting hybrid map. The GLC-2000 legend was chosen for the hybrid map because it is easier to map onto more classes and, therefore, less information is lost. In this situation, it was shown that the GLC-2000 land cover dataset was more accurate in terms of forest cover than the MODIS product, and the GLC-2000 was, therefore, used for the hybrid map.

An additional quantitative analysis was carried out in which the confidence layer that accompanies the MODIS land cover product was correlated with the values of fuzzy disagreement. This was carried out in order to see if high areas of disagreement between the GLC-2000 and MODIS land cover products match areas of low confidence in the MODIS classification. Spearman correlation was first applied globally and then regionally for the Northern European window. A correlation by MODIS land cover class was then undertaken at the global and Northern European level in order to see if there were specific classes for which the correlation was high. The correlation coefficients are provided in Table I. At a global level, there is a very weak correlation of 0.25 for all classes. Looking at the MODIS confidence layer (http://duckwater.bu.edu/lc/mod12q1.html), one can see areas where the confidence layer and the disagreement map correlate quite well: the desert areas, the tropical forests, and the ice sheet of Greenland. However, for other areas, a correlation cannot be directly observed, which, therefore, explains the low overall correlation coefficient of 0.25. Examining the class by class correlation, with the exception of the classes Evergreen Broadleaf Forest with a correlation of 0.63, Barren or Sparsely Vegetated with 0.45 and Snow and Ice with 0.37, there is a very weak or no relationship between the areas of disagreement and the MODIS confidence layer. At a regional level, the class by class correlation analysis produces even worse results. Therefore, this analysis has shown that the MODIS confidence layer alone does not provide sufficient information when deciding on which land cover product to use in the case of high disagreement between the two global land cover products.

V. Discussion and Conclusion

The *a posteriori* validation of land cover datasets is an important, but necessary and difficult, task. The confusion matrix and other global accuracy measures are commonly used but provide no spatial information on the errors. Even though the GLC-2000 and the MODIS (MOD12Q1 V004) land cover product differ fundamentally in terms of how they were produced, a comparison based on input from expert knowledge was undertaken. The GLC-2000 is a one-off product developed using a bottom up approach based on a regional classification with subsequent harmonization and mosaicing while the MODIS land cover dataset is a fully operational product that is produced automatically on an annual basis. Although these differences are very clear to the producers of these products, one must consider the user's perspective (e.g., exercises such as the Millennum Ecosystems Assessment). For the user, the goal is deciding which product is more suitable and thematically better at a specific location. This paper has provided the means for comparing products like the GLC-2000 and MODIS land cover datasets and illustrated where a hybrid product could be created by merging the land cover types that are the most accurate based on validation with reference information. The methodology uses expert knowledge about classification uncertainty to provide maps of spatial disagreement and was applied to two recent global land cover maps. Hotspot maps were then created to help locate and prioritize areas of severe disagreement that require further validation with TM/ETM images or other high-resolution images, regional and national maps, and expert knowledge from the field. It can also, however, be used to focus attention on problematic zones in a larger scale validation exercise such as that undertaken in [8] and avoid the remapping of areas where there is already a high level of confidence in the classification. Using hotspot maps and validation information, the potential then exists to determine which team has mapped a given area more accurately or if the disagreement simply results from a different understanding of the land cover type definitions or the presence of different ontologies. If one class from one map is more accurate at the specific point of validation, the probability is quite high that it is also accurately mapped in the surrounding neighborhood. By choosing the correct label, which has been validated or cross-checked with other maps or expert knowledge, a mosaic can be created containing information from both the GLC-2000 and MODIS land cover products. In this way, the best of both maps can be combined and a higher quality global hybrid map can be produced. Such an approach does not necessitate the remapping of large areas and, therefore, requires very few additional resources, despite the fact that the method is not automated. This methodology is applicable to local, national and global land cover maps.

It should be noted that the resulting hybrid map is based on the answers from the experts regarding how easy it was for them to distinguish between different land cover classes. It might seem as if there is a highly subjective element to this methodology and that it would be logical to use a more objective measure such as the difference in spectral signatures. However, knowledge from the expert who carried out the classification implicitly carries with it information about the spectral similarity. Moreover, spectral similarity cannot be used as a sole criterion as there were situations where other ancillary datasets were used in the classification procedure as well as incorporation of local knowledge. Some areas might be mapped inaccurately in both maps. For example, the expert for Africa (GLC-2000) as well as the MODIS expert said that it was difficult to separate agriculture from herbaceous cover; however, disagreement of the agriculture-herbaceous combination is not highlighted in red as both experts agree that in this area spectral separation of classes is difficult. It would, therefore, have been very difficult to better classify this point on the two maps. If at least one expert agrees that separation was easy, then, in the minimum fuzzy map, the area would appear in red. However, this will not be the case on the maximum fuzzy map as the conservative expert opinion was used to arrive at the final agreement.

In this paper, we have shown that areas of disagreement can be located. We have also demonstrated that TM/ETM images or information from secondary sources such as CORINE and national land cover information can then be used to determine which map is more accurate for a given land cover type(s) or in a given area for a global dataset. However, sometimes it is not possible since the truth lies somewhere in between. This necessitates further work in order to produce a confidence layer that will accompany the hybrid map. Further work will also address the issue of tailoring the production of the hybrid map to the specific needs of a user or to a specific application.

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