The Way Forward

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Abstract

This paper focuses on the lessons learned in the conduct of the International Geosphere Biosphere Program's Data and Information System (IGBP-DIS), global 1-km Land-Cover Mapping Project (DISCover). There is still considerable fundamental research to be conducted dealing with the development and validation of thematic geospatial products derived from a combination of remotely sensed and ancillary data. Issues include database and data product development, classification legend definitions, processing and analysis techniques, and sampling strategies. A significant infrastructure is required to support an effort such as DISCover. The infrastructure put in place under the auspices of the IGBP-DIS serves as a model, and must be put in place to enable replication and development of projects such as DISCover.

Introduction

The articles in this special issue document the International Geosphere Biosphere Program Data and Information System (IGBP-DIS) Land Cover Working Group (LCWG) global 1-km land-cover (DISCover) mapping effort. The articles document the project rationale (Belward *et al.*, 1999, in this issue); data acquisition, processing, and creation of the DISCover product (Loveland *et al.*, 1999, in this issue); and the applications of that database (Brown *et al.*, 1999, in this issue). There are articles concerning specific validation implementation issues by Husak *et al.* (1999, in this issue), Kelly *et al.* (1999, in this issue), and Scepan *et al.* (1999, in this issue). There are also articles covering the core validation effort by Scepan (1999, in this issue) and confidence site mapping by Muchoney *et al.* (1999, in this issue). Finally, an article by DeFries and Los (1999, in this issue) describes the accuracy and suitability of DISCover for global climate modeling. In all these articles, project specific methods and results are emphasized.

This article looks across the specifics presented in these articles with a view toward the future. Emphasis is placed on lessons learned in the areas of land-cover database development, core validation, confidence site mapping, and international collaboration and participation. Conclusions are based on our collective experience.

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Land-Cover Database Development

Many important lessons were learned during the development of the global land-cover database that highlight future research priorities. Issues of source data quality and availability, classification methods, and the suitability of DISCover specifications merit discussion and evaluation. These issues ultimately may be best judged by users of the DISCover database based upon data utility for large-area environmental applications. To best understand user satisfaction, the applications of the DISCover database should be monitored. Feedback from users can also provide vital insights into new global land-cover specifications, applications, and requirements. This process is supported by the LANDDAAC at the EROS Data Center, where all user comments are collected and analyzed (**http://edcwww.cr.usgs.gov/landdaac/glcc/globdoc1_2.html**).

Concerning improvements in source data, the following emerge as priorities.

- Improvements in the geometric and radiometric quality of the Advanced Very High Resolution Radiometer (AVHRR) data must be a top research priority. This may simply require switching to new data from the Terra Moderate Resolution Imaging Spectrometer (MODIS) or SPOT Vegetation instruments. Both appear to warrant consideration because of improved calibration and spectral channels better suited for land-cover classification. MODIS data offer significant new potential due to both it's their true multi-resolution and their near hyperspectral properties (Barnes *et al.*, 1998).
- Improved strategies are needed for dealing with the uneven distribution of land-cover reference data. Solutions may include continued development of site databases or land-cover keys, as advocated by Muchoney *et al.* (1999, in this issue) and Kelly *et al.* (1999, in this issue), respectively. In addition, data from new high-resolution land-cover mapping projects throughout the world could be of significant value. The Global Observation of Forest Cover project, started to test the concept of an Integrated Global Observing Strategy (IGOS), could be a catalyst for the provision of high resolution land-cover mapping data (Ahern *et al.*, 1999). Another example is the Global Map project of the International Steering Committee for Global Mapping (ISCGM). This multi-national project lead by National Mapping Organizations (NMOs) is working to create global framework data sets a 1: 1,000,000 scale. These framework data layers are land use, transportation, elevation, boundaries, drainage systems, and vegetation (Nonomura, 1999). More information concerning this project can be found at **http://www1.gsi-mc.go.jp/iscgm-sec/**.

Experience with DISCover mapping methods highlights the following:

- This study demonstrated that one method-unsupervised classification of multi-temporal AVHRR data with post-classification improvement using ancillary data-provides adequate overall

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accuracy. However, there is legitimate concern with respect to the objectivity and repeatability of methods that rely heavily on interpretation and convergence of disparate data sources with unknown accuracy. The Holy Grail of land-cover mapping is a strategy based solely on remotely sensed data and completely automated classification methods. Based on the results of this study, just as the search for the Grail has thus far proven unsuccessful, the quest for accurate results with fully automated classification may not be achievable. Research on the quality and repeatability of supervised classification methods is underway and must continue (DeFries *et al.*, 1995; McGwire *et al.*, 1996). It is quite likely that future global land-cover characterization methods will be based on the analysis and synthesis of multi-resolution remotely sensed data coming from a wide range of platforms (e.g., SPOT Vegetation and Terra MODIS moderate resolution instruments, and the Landsat 7 enhanced thematic mapper high resolution instrument).

- Rather than being based on a single-source design, a future global land-cover mapping project should strive to be data independent and take advantage of the best and most appropriate data and methods available. At this time we believe that the key features of an improved mapping system can be characterized as (1) data independence, (2) use and reuse of land-cover knowledge in advanced processing strategies, and (3) generation of quantitative landscape variables (e.g., fraction of absorbed photosynthetically active radiation, leaf area, canopy density) as inputs to the refinement of land-cover classifications, and for direct use in applications.

The following are priorities for future aspects of land-cover database development driven by the DISCover validation results:

- Urban land-cover characterization improvements are required. The Digital Chart of the World urban layer used in the IGBP DISCover initiative is both dated and inadequate. Strategies, such as the recent work by Elvidge *et al.* (1997) with Defense Meteorological Satellite Program data should be explored. Other possibilities include manual interpretation of high-resolution satellite imagery (although there are significant logistical challenges), compilation based upon country-level base cartographic products (again a logistical challenge from which little might be gained), or modeling based on population data.
- Better methods and more appropriate remotely sensed data are needed for characterizing wetlands. Accurate wetlands mapping methods may require approaches based on both coarse and high resolution data from active microwave and optical sensors, and ancillary data.
- Improved consistency of forest-cover classes is needed. The process used for determining DISCover forest density classes and separating mixed from other forests was inconsistent due to the manual class labeling process and limitations related to reference materials. An alternative is to first derive quantitative measures of canopy density, leaf type, and phenology directly from spectral data prior to forest-cover interpretation (Defries *et al.*, 1995).

There is also a clear need for more research on the information content of land-cover databases:

- While considerable attention has been devoted to mapping algorithms, little attention has been given to the information content of land-cover databases. Applications of land-cover data are increasingly more sophisticated and quantitative. Innovation in land-cover database design, format, and content is essential if the needs of emerging and future applications are to be satisfactorily met. While the DISCover legend provides an important representation of general land cover patterns across the globe, maps based on other legends are needed, particularly those with an ecological orientation (Brown *et al.*, 1999).
- Better understanding of the stability of the characteristics of global land cover as represented in DISCover is also required. For example, the interannual variability of land cover at the global scale should be documented by comparing the results of this classification to data from other years in order to determine the historical variance of phenology and productivity.

Core Validation

The research on the application of the core validation strategy represents an important step towards the development of procedures to operationally validate global-scale thematic land-cover products at regular intervals. This research demonstrated that such validation is possible, but depends upon the good will, support, cooperation, and collaboration of interested organizations and institutions. This effort can serve as a foundation for future systematic global land-cover validation efforts. Currently, however, there are no plans in place to extend this validation effort. Efforts are needed to garner support for future validation activities.

Key points to emerge include

- Through the DISCover Program, we have demonstrated that validation of the thematic accuracy of global land-cover data sets is both possible and practical. This validation effort may appear to have produced relatively modest accuracy numbers if we only examine statistics such as per class accuracy or overall area weighted accuracy. DISCover accuracy figures (Scepan, 1999, in this issue) are at least comparable with those achieved in other studies (Gervin *et al.*, 1985; Fleischmann and Walsh, 1991; Frederiksen and Lawesson, 1992; Nelson and Horning, 1993), albeit studies conducted in more limited geographic areas with less inherent landscape variation than that faced by the developers of DISCover. There is also evidence that, for a major class of intended users, the global climate modeling community, the DISCover product has almost 90 percent overall accuracy (Defries and Los, 1999, in this issue). Nevertheless, increasing the accuracy of future global land-cover products and the rigor of the validation process remain important areas of future work.
- Based upon the validation results seen in the paper by Scepan (1999, in this issue), it cannot be assumed that all DISCover classes can be mapped with 85 percent or better accuracy. DISCover project results more than adequately demonstrate the difficulty associated with the interpretation of many of the DISCover legend thematic classes from higher resolution Landsat TM and SPOT data sets. Thus, an open question remains regarding the strength of the relationship between the AVHRR-based DISCover classes and a number of the DISCover land-cover classes interpreted from TM and SPOT data.
- Our level of uncertainty is amplified by the variations in accuracy achieved if one considers the decision rule for verifying agreements between the AVHRR-based product and the high-resolution verification data. For instance, the overall area-weighted accuracy based on the original validation protocol is 68.9 percent, while the majority rule accuracy is 73.5 percent (Scepan, 1999, in this issue). Should a determination of the correct or "true" land cover require all interpreters to agree, should a majority rule apply (as was the case here) or, if all interpreters disagree, should that sample point be disregarded in any final accuracy calculation? This is an area that demands more thorough study.
- The global validation effort showed the difficulty of randomly selecting an adequate number of samples for classes that are spatially small in size and found in relatively few locations. This presents two problems. First is an algorithm computational power problem in selecting 1-km samples until classes that are very small are selected a sufficient number of times. This problem may be solved with access to better code and more compute power (now or in the future as Joy's Law continues to work for us). Second is the problem of acquiring high-resolution images for the selected sites. This issue is somewhat more problematic. It depends on the acquisition strategies and capabilities of future satellite systems. High-resolution satellite sample validation data collected as near to the time of the acquisitions of the data set that forms the basis for the global land-cover product are needed. This makes it more important that we continue to strive for increased international cooperation and collaboration in future validation efforts. High-resolution systems abound. The use of data from all available platforms would significantly ease the sampling problems, but of course would increase problems of data pre-processing, cost of data acquisition, and harmonizing interpretation of diverse data

types. In the future, we should also be able to use the Window Observational Research Facility (WORF) on the International Space Station, and any of the commercial very high-resolution systems.

- The DISCover sampling strategy meant that validation sample sites could only be located once the thematically classified base land-cover product was complete. With this strategy, there will always be a time lag between completion of the baseline product and commencement of the validation exercise. The experience gained in validation of DISCover V1.0 also highlighted the necessity for repeated sampling where certain classes were significantly under represented just to make up the quota, and ensure acceptable confidence intervals. It is thus imperative that we continue to examine alternative sampling designs. The United Nations Food and Agriculture Organization Forest Resource Assessment, the European Commission's TREES project, and a number of Earth Observing System (EOS) instrument and interdisciplinary science teams are using and exploring alternative strategies. Future global validation efforts will need to choose methods based on user needs, logistics, and cost considerations.
- The validation effort demonstrated that the larger and less fragmented the land-cover class, the higher the accuracy of labeling, and the more confidence interpreters have in their validation labels. On the other hand, smaller and more fragmented classes exhibited lower accuracy figures. While conforming to basic scale principles that are fundamental in remote sensing, this reinforces the need for having both users and remote sensing specialists involved in the development of classification schemes for global geospatial products.
- Additional research is needed on the impact of image misregistration, interpreter consistency, and the availability and quality of ancillary data on the use of high-resolution data as a reference. The impact of misregistration has been an area of discussion and concern dating back to early Validation Working Group (VWG) meetings. We now know that a directional bias exists in Landsat TM imagery processed using systematic geometric corrections (e.g., the satellite ephemeris) covering the U.S. One question that can be raised is whether we should have used data with only simple geometric corrections. Cost was the deciding factor. However, we believe that greater attention to the spatial accuracy of reference data would result in an improved validation.
- The use of expert interpreters was judged to be appropriate and beneficial, and future efforts should continue this practice. This could occur through the establishment of a more formal relationship among remote sensing agencies, institutions, and centers around the globe who have a vested interest in accurate land-cover data. We could immediately begin the development of the image keys discussed in the paper by Kelly *et al.* (1999, in this issue). Key development has importance well beyond validation, and would help other aspects of remote sensing science applications, education, and technology transfer activities.
- A significant challenge involves the unambiguous demonstration that the validation of global land cover is worth the effort. This will only come with feedback from end users. The use of the LANDDAAC feedback should be extended to include comments on the value of the validation information once it is supplied alongside DISCover V1.0.

Confidence Site Analyses

The mapping and definition of land-cover characteristics for the confidence sites was an integral part of the DISCover validation effort. Photointerpreters were able to map basic attributes such as dominant life-form, percent cover, and periodicity. The result was the acquisition of a consistent, global, land-cover polygon data set for training, testing, and comparing alternative global land-cover classifications.

Acquisition of the confidence site database would not have been possible without the supporting core validation effort. The core validation effort provided the large number of representative remotely sensed images needed for the database. It also brought together experienced photointerpreters capable of exercising a consistent methodology for land-cover information extraction and inference.

- The confidence site database provides a test bed for answering a number of questions about the nature of core validation and the accuracy of the DISCover product. For example, the secondary core samples, centered at distances of 19 and 26.9 km for the primary sample, can provide additional information about classification accuracy. When corrected for spatial autocorrelation and conditional probability of selection given the core sample type, these samples can serve to reduce the confidence interval on individual entries in the core site confusion matrix. There remains, however, the application of proper statistical theory and subsequent data analysis to complete this task.
- Another application of the confidence site database to the core sample validation lies in better understanding of geo-location errors. By overlaying the DISCover product or one of its underlying composited AVHRR images onto the continuous polygon land-cover map of each confidence site, the degree of congruence can be assessed and errors due to geo-location can be separated from thematic classification errors. Ideally, such a comparison should be made for each core sample, but in practice a witness sample may be sufficient to characterize the geo-location error structure.

International Collaboration and Participation

Since preparing IGBP Report # 20 (Townshend, 1992), the IGBP-DIS LCWG has provided a catalyst for the creation of global terrestrial data sets. The creation of the global AVHRR data set and the creation and validation of DISCover have paved the way for new global products and have provided important benchmarks. They set a pattern of international collaboration to discuss the nature of the products, discuss scientific issues, identify problems and solutions, arrive at community consensus on methodologies, and divide and perform the work.

The LCWG provided the forum for this debate. At the beginning of this decade, no other international forum existed in which to frame such a specific discussion. Scientific meetings undoubtedly provide opportunities for public debate and peer review, but they always embrace a range of issues, rather than specifics, and discussion time is always limited. The LCWG, in comparison, has involved around 100 scientists concerned with global terrestrial ecosystem mapping and monitoring through 15 dedicated meetings over a five-year period. This level of focus and commitment could only be achieved through an internationally recognized forum. The debate is not over, and a suitable forum must continue.

The hard-won experience gained through the generation and validation of the 1997 DISCover product must be built upon. A forum for progress review, for verifying the quality of the IGBP's land-cover data set, for proposing future developments, and for optimizing exploitation of the products is required. As clearly seen in the paper by Scepan (1999, in this issue), another round of debate and experiment is clearly needed for the validation of global land-cover products.

Initiatives such as the Integrated Global Observing Strategy (IGOS, 1999) raise the stakes even higher. IGOS will lead to new requirements to coordinate and steer the transition of scientific output to operational terrestrial observations. This is not possible without structured validation programs. A complementary requirement arising from this process will be to provide advice to space agencies concerning future terrestrial products and an assessment of currently provided products.

CEOS, formed in 1984 under the sponsorship of the Economic Summit of Industrialized Nations' Working Group on Growth Technology and Employment, is a key forum for international cooperation in space. CEOS membership includes all the world's civil agencies responsible for Earth observation satellite programs along with international user organizations, including the IGBP. The goals of CEOS are to promote cooperation so as to maximize the benefits of space-borne Earth observations, to aid members and users by acting as a focal point for international coordination of space related Earth observation activities and to exchange policy and technical information.

There are two CEOS working groups, the Working Group on Information Systems and Services, and the Working Group on Calibration and Validation (WGCV). WGCV addresses sensor-specific calibration and validation, and geophysical parameters and derived product validation. In this context, calibration is defined as the process of quantitatively defining the system response to known, controlled signal inputs. Validation is defined as the process of independent assessment of the quality of the data products derived from the system outputs (CEOS, 1995).

The WGCV has made important contributions to the process of international cooperation, ensuring long-term confidence in the accuracy and quality of Earth observation data and products. Users benefit from better quality data, better documentation, and sustained commitments to provide calibration updates. Debate at the working group level and in the WGCV sub-groups results in recommendations to the CEOS Plenary. These recommendations can be highly specific, such as the best practice for calibration of specific instrument types, or more programmatic, such as data sharing for WGCV joint experiments. The CEOS Members and Associates in Plenary then judge these recommendations, and, if accepted, act upon them. Scientific debate within WGCV can thus influence space agency policy.

There are four established sub groups (Infra-red and Visible Optical Sensors, Microwave Sensors, Synthetic Aperture Radar, and Terrain Mapping). These all deal with particular aspects of calibration and validation as described above. The WGCV is acutely aware of the need for sustained debate on instrument calibration, but increasingly recognizes the demand from users for validated higher level products and is responding by an increasing focus in this area (Belward, 1999).

The WGCV's workplan foresees the creation of new subgroups to deal with new topics. The Validation of land surface parameters has emerged as one such topic, both as a result of the DISCover experience and in the light of the IGOS initiative. In consequence, a new Validation of Land Surface Parameters group is being created. The group's objectives are to

- promote the quantification and characterization of satellite land product accuracy;
- share land product validation past experience and lessons learned;
- move towards the generation of "standardized products with known accuracy" from similar sensing systems in the context of data continuity;
- establish relationships between like products, e.g., Vegetation Indices;
- develop *in-situ* validation measurement standards, protocols, and traceability;
- coordinate international validation activities; and
- improve access to validation data sets.

Participation in and support for this sub group will assure that the DISCover experience is not lost, and that the debate on land-cover validation continues.

Conclusions

What have we learned during the course of the DISCover project? Certainly we have learned that there is still a great deal of work that needs to be done if we are to reach a point where thematic data sets at any scale are routinely validated in an acceptable fashion. The results presented in the articles of this special issue are likely to spark debate, because even the authors of this article have some levels of disagreement. If this work does no more than stimulate discussion and provides insight into possible future research and development activities, it has accomplished something important.

What the articles in this special issue do not do is lead us to believe that the obstacles we encountered in this effort are insurmountable. What is required is cooperation and understanding between the user community and producers of the data. On the user side, recognition of the importance of validated data must increase and the resources necessary to accomplish that validation must be given priority. It is important that IGBP Validation Working Group personnel or others familiar with this effort participate in future CEOS, WGCV, validation sub group activities. On the mapping side, the development of an infrastructure and the continuing development of improved operational methods must receive attention. This infrastructure should be broadened to include both the remote sensing and emerging activities associated with the development of a global spatial data infrastructure (e.g., Digital Earth, ISCGM, and the United Nations Permanent Committees on Geographic Information Systems).

What have we proven through the DISCover project? We have shown that, through cooperation and collaboration, the international remote sensing science and applications community can pull together to achieve a significant goal, the creation of a validated global land-cover data set. We no longer should be satisfied using global maps of unknown accuracy whose thematic representations are, in essence, the "expert testimony" of their creators. In common with other global data sets, the DISCover product is already dated, yet the need for current global terrestrial information continues to grow. The importance of the global perspective now has new significance as environmental information input to the policy making, policy development, and policy implementation processes grows (e.g., the Kyoto Protocol to the UN framework convention on climate change, and the UN Convention on Biological Diversity).

It is important to remember that the DISCover product was not generated in a truly independent fashion. DISCover was generated from a database of seasonal land-cover clusters. These clusters can be, and have been, aggregated in many ways based on particular needs for global data sets. Specifically, five other global land-cover maps have been derived from this database. A question for future validation efforts, that an approach such as this poses, can be formulated as follows: Should we concentrate more on the validation of legends designed in support of more specific user needs (i.e., albedo or surface roughness); or on validation of more general, multipurpose land-cover systems (e.g., Olsen or Anderson) in use today? Our conclusion is that we should do both.

Because global land-cover data will inevitably be used for smaller geographic regions, methods for sub-global validation are needed. If the database strategy used in this initiative is determined to provide useful and flexible land-cover products, there will also be a need to develop validation strategies that permit case-by-case application-specific assessments of the products derived from the database.

Land-cover mapping at any scale yields imperfect results. At the global level, the tradition and experience base is brief and there are no comparable validated data against which the DISCover results can be compared. It is important to view this effort as a step in the evolution of the science of global land-cover mapping. The result of the DISCover initiative establishes one standard for global land-cover data. That standard and the utility of the database, as judged by users, provides a basis for future progress in global land-cover mapping.

Perhaps the challenge to improving the quality of land-cover maps relates as much to the data used in the classification as it does to algorithms or methods. Simply put, the problem may be the data. The relationship between land-cover and temporal-spectral data is too frequently ambiguous. While broad patterns of general land-cover types can be mapped with some degree of accuracy, mapping fine-scale complex patterns of land cover can result in problematic accuracy. Different land-cover types often have similar spatial, temporal, and spectral characteristics. Mapping land cover is further complicated by the fact that land-cover characteristics in many parts of the world, and certainly in the tropics, are affected by atmospheric and other environmental contaminants (Loveland *et al.*, 1999, in this issue). Better methods or algorithms may not be the answer to solving these problems. Remotely sensed data with improved geometric and radiometric quality, increased use of microwave acquisitions, and more effective use of ancillary data, are essential to improving classification.

The overall cost of the critical project elements needed to continue this work is not that great. The cost is well within reason when one considers the wide variety of modeling efforts currently being funded which have, up until now, depended upon unverified data of questionable accuracy.

We should remember, however, that DISCover is only a first step towards the development of procedures to operationally validate global-scale land-cover products at regular intervals. An important point is that this effort should be built upon as we look to the future. Now, as in the past, it is more difficult to get a funding agency to pay for the validation of a data set. Funding must cover the range of global data set issues, from mapping to validation, as well as basic and applied research.

Considering our experience with this project, we are certain that another effort such as this could and should be mounted. A loose infrastructure of dedicated organizations all gave unselfishly to achieve the results presented in this volume. The new CEOS WGCV sub-group will be able to profit from the experience gained in this effort and may be able to promote the establishment of similar informal infrastructures for future projects.

Finally, with respect to all these organizations and individuals, we cannot close this issue without again extending our thanks to them all. The logistics of this effort were complex, and the spirit of collaboration demonstrated in the production and validation of DISCover was significant. A detailed acknowledgment of project participation is found in Belward *et al.* (1999, in this issue).

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