A Synthesis of Information on Rapid Land-cover Change for the Period 1981–2000

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This article presents a synthesis of what is known about areas of rapid land-cover change around the world over the past two decades, based on data compiled from remote sensing and censuses, as well as expert opinion. Asia currently has the greatest concentration of areas of rapid land-cover changes, and dryland degradation in particular. The Amazon basin remains a major hotspot of tropical deforestation. Rapid cropland increase, often associated with large-scale deforestation, is prominent in Southeast Asia. Forest degradation in Siberia, mostly related to logging activities, is increasing rapidly. The southeastern United States and eastern China are experiencing rapid cropland decrease. Existing data do not support the claim that the African Sahel is a desertification hotspot. Many of the most populated and rapidly changing cities are found in the tropics.

Keywords: land use, cropland, deforestation, desertification, urbanization

Changes in land cover and in the way people use the land have become recognized over the last 15 years as important global environmental changes in their own right (Turner 2002). They are also intertwined in many ways with other environmental issues, such as climate change and carbon cycle, loss of biodiversity, sustainability of agriculture, and provision of safe drinking water. The international scientific community has created new interdisciplinary research programs to understand the multiple causes and consequences of land-cover and land-use change (Lambin et al. 2003). There has been a concomitant rapid expansion in the availability of data and information. However, there has not yet been a systematic examination, using global and regional observations, of the status and trends in terrestrial and coastal land-cover or related important ecosystem processes.

The information needs for such a synthesis are diverse. Remote sensing has an important contribution to make in documenting the actual change in land cover on regional and global spatial scales from the mid-1970s (Achard et al. 2002, DeFries et al. 2002, Lambin et al. 2003). It also has a role to play in evaluating indices of change in ecological processes, such as net primary production and rainfall use efficiency (Prince et al. 1998). Remote sensing information is found in a widely scattered literature, some of it refereed, some in the gray literature, and some unpublished as yet. There is also an obvious need for good inventory data and statistics about land cover and land-cover change at subnational, national, and international scales, augmented by a need for subnational and national indicators of condition, status, and trends of the global environment. Finally, there is a need to determine the interrelationships of remotely sensed and statistical inventory data, to integrate heterogenous data sources.

The tremendous investment in scientific analysis of remote sensing data over the last decade, and the profusion of studies based on other data sources, provides a basis for a synthesis. Although information is not complete globally, several products are now available that depict the land cover of Earth globally in the 1990s and in 2000–2001. The same is true for snapshots of many important regions with substantial land-

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cover change: European Russia, South America and Africa, parts of East Asia and Southeast Asia, and the continental United States and Canada, for example. There are multiple examples of studies and resultant databases of rapid land-cover change and ecosystem disturbances in important regions of the world: deforestation in the pantropical forest belt; fire frequency globally and regionally in South America, Southern Africa, and parts of Russia; and the influence of urbanization in selected cities around the world.

In addition to the scientific needs for a systematic documentation of changes in land cover over the past several decades, there is a pressing need to understand these changes from the standpoint of their consequences for human welfare. The Millennium Ecosystem Assessment has been initiated to evaluate the degree to which ecosystem services, on which human societies depend, are sustainable, given the many environmental stresses they face (*www.millenniumassessment.org*). A wide variety of stakeholders have identified the Millennium Ecosystem Assessment as a critical activity for understanding the current state and potential futures of ecosystem goods and services: individual countries, international nongovernmental organizations, government agencies and ministries, international governmental organizations, and international multilateral environmental agreements, such as the Biodiversity Convention, the Desertification Convention, and the Wetlands Convention. Early in its planning process, the Millennium Ecosystem Assessment identified the need to synthesize what is known about areas of rapid land-cover change around the world as critical to its ability to evaluate how the provision of ecosystem goods and services has changed over the past few decades.

Process

To address this need, a group of researchers agreed to share data and produce the most reliable current synthesis of documented change over the period 1981–2000. The first stage in producing the synthesis included the following:

- A compilation of existing global, regional, and subregional studies based on remote sensing and other data sources with georeferenced results (including census data)
- Extraction of spatial data on land-cover change and conversion to a common format
- Evaluation of the validation of different remote-sensing products
- An assessment of the degree of certainty of our knowledge of the areas of documented land-cover change in the synthetic global data sets

Subsequent to a workshop to evaluate preliminary results, there has been an extensive review and consultation process throughout the scientific community to review the judgments of the participants. This consultation led to the addition (or exclusion) of input data, modification of a few areas of rapid change, and refinement of the methodology and terminology. Most important, it helped to corroborate and document reported areas of rapid change. In addition, we have attempted to use this process to elicit judgments about priorities for future observations and research so that the next attempt to synthesize such data can make even more progress.

The approach for synthesizing data sets on recent land-cover change

The types of change (or proxy variables for change) included in the analysis are (a) forest-cover changes; (b) degraded lands in the dry and hyperarid zones of the world (often referred to as desertification, even though most definitions of desertification do not include hyperarid zones); (c) cropland expansion and abandonment; and (d) urban settlements. Some types of change were not included because of data constraints, even though they are important for ecosystem services. For instance, no spatially explicit data sets of reliable quality on afforestation and reforestation or on changes in pastoral lands are available at a regional-to-global scale. We did not attempt to address a large range of other questions for which data sources are even more limited, including where land-cover change is likely to occur, where ecosystem services are particularly vulnerable to future change, or which locations are experiencing a severe impact on ecosystem services even though the extent of land-cover change might be small.

Challenges in synthesizing data sets on land-cover change. Different data sources are not based on standard definitions, even though some definitions are more commonly accepted. For example, more than 90 different definitions of forest are in use throughout the world, complicating the effort to measure and evaluate data on forest-cover change. The most commonly accepted definition of forest is the one from the United Nations Food and Agriculture Organization (FAO), which includes natural forests and forest plantations (FAO 2001). According to most definitions, deforestation occurs when forest is converted to another land cover or when the tree canopy cover falls below a minimum percentage threshold (10% for the FAO definition). Forest degradation is defined as a process leading to a temporary or permanent deterioration in the density or structure of vegetation cover or its species composition, and thus to a lower productive capacity of the forest. The definition of cropland in this study follows the FAO definition of arable land: land under temporary crops, temporary meadows for mowing or pasture, land under market and kitchen gardens, land temporarily fallow (less than 5 years, thus excluding abandoned land resulting from shifting cultivation), and permanent crops (land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee and rubber; this category includes land under flowering shrubs, fruit trees, nut trees and vines, but excludes land under trees grown for wood or timber). Croplands do not include planted pastures or natural grazing lands.

The most commonly accepted definition of desertification is provided in the United Nations Convention to Combat Desertification: "land degradation in arid, semi-arid and dry subhumid areas resulting from various factors, including climatic variations and human activities," land degradation being defined as the decrease or destruction of the biological productivity of the land. Hyperarid zones are generally not part of the definition of desertification because they are presumed to be so dry that human degradation is severely limited unless irrigation is practiced, even though the United Nations Environment Programme's *World Atlas of Desertification* includes "true deserts" in the definition of drylands (Middleton and Thomas 1997).

For this synthesis, we addressed these definitional problems by identifying the areas with the highest rate of land-cover change given the definition adopted for a particular data set, rather than attempting to harmonize the definitions among data sets. The individual maps representing areas of rapid land-cover change for a particular process of land-cover change were then combined into a synthesis map for each process of change.

A second challenge is the varying spatial resolution of the data sources, the finest one being the data based on remote sensing (on the order of 1 square kilometer [km^2]) and the coarsest one being the national or subnational statistics (on the order of 10^2 to 10^3 km^2). Therefore, some areas identified as main areas of land-cover change are much larger than the actual land-cover change they represent, leading to commission errors around areas where actual change is detected. On the other hand, omission errors occur because not all the areas that experienced actual land-cover change are represented on the map, as some of these areas may be too small to be detected by the coarse resolution data. We chose a 10-km by 10-km grid for the spatial resolution of the maps combining the data sources. Areas of land-cover change much smaller than 100 km^2 are unlikely to be represented on the map, but 100-km^2 grid cells labeled as experiencing land-cover change are unlikely to be entirely affected by change in reality.

Yet a third challenge is the varying temporal and spatial coverage of the data sets included in the synthesis. Not all data sets include the 1980–2000 time period chosen for the synthesis. Therefore, the final maps provide no detailed information on the time period during which a particular area experienced rapid land-cover change, nor on the frequency of disturbances. Moreover, the varying spatial coverage of the available data sets introduces a bias. Some parts of the world were covered by several data sets, whereas for others only national statistics were available. Consequently, some areas appear to be more affected by rapid land-cover change simply because they have been studied more intensively. To account for this bias, we produced a second map for each type of change that provides information on the number of data sets covering an area.

Method for synthesis. We synthesized 49 data sets available in early 2003 at the national and global scale to identify locations of rapid land-cover change (described in detail at *www.geo.ucl.ac.be/LUCC/lucc.html* under "Rapid land-cover change product"). Some of these data sets identified hotspots of land-cover change, and others provided estimates of rates of change. For the latter, we identified areas with the highest rates of change by applying a threshold percentile value. Threshold values were determined for each of these data sets to identify the areas having a high percentile in terms of rates of change. Details of the data sources and procedure vary for each type of land-cover change.

Forest-cover changes. The map of the main areas of forest-cover changes is based on three types of data sources: expert opinion gathered through formal procedures (Achard et al. 1998, Hoffman 1999, AGO 2000, NRCS 2001, SEMARNAT 2003), remote sensing–based products (Isaev 1990, Skole and Tucker 1993, Barson et al. 2000, Sierra 2000, Aksenov et al. 2002, Alves 2002, DeFries et al. 2002, Bartalev et al. 2003), and national statistics (Hongchang 1995, Eurostat 2000, FAO 2001, Smith et al. 2002, Fundação SOS Mata Atlântica 2002, INPE 2002). Most of these data directly measure deforestation and forest degradation. However, we refer to the map as showing "forest-cover changes," given the paucity of data on reforestation and, therefore, our inability to assess consistently whether the forest conversion is temporary or permanent. To avoid the coarse scale of national statistics, priority was given to the remote sensing and expert opinion data. The information based on national and subnational statistics was used only when no other data were available. Statistical data were used only for the forested areas of the world, as represented by the forest classes of global land-cover classifications produced for the early 1990s (IGBP DISCover map, found in Loveland et al. 2000) and for 2000 (Global Land Cover 2000 map, found in Bartholomé et al. 2002). Grid cells lying outside the forest classes on either of these two maps were not considered in the mapping of the main areas of forest-cover changes.

The final map (figure 1) identifies, for each "forested" grid cell, whether it was considered as a main area of forest-cover changes by the input data sets. The color code represents the reliability (estimated in terms of convergence of evidence) of the information (i.e., the frequency of detection as a hotspot relative to the number of data sets covering the area). A second map identifies how many input data sets covered the area (figure 1b). The information based on national or subnational statistics provides average annual rates of deforestation, and should be considered as secondary to the other sources because it is not at a fine resolution. When that rate is higher than 3% per year, the area is considered as undergoing rapid change. Myers (1993) previously defined tropical deforestation hotspots as areas undergoing deforestation rates of 4% or more per year by comparison with the biomewide average rate of less than 0.5%. Given that this threshold was applied here to large administrative units (countries or provinces), it had to be lowered to identify regions undergoing

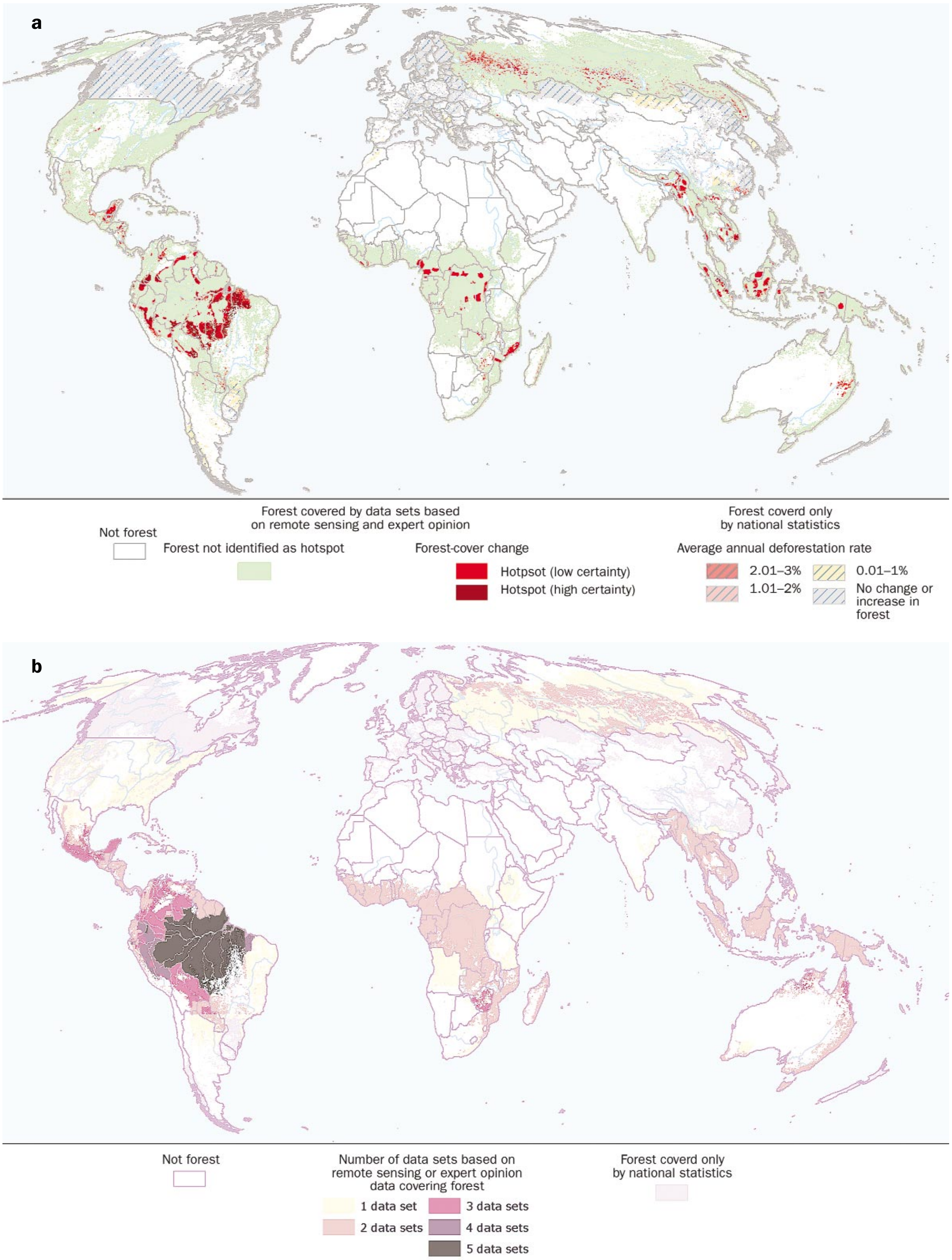

Figure 1. (a) Main areas of forest-cover changes over 20 years (1980–2000); (b) number of data sets covering the area.

rapid deforestation. If the statistics indicate no deforestation at a national scale, it is nevertheless possible that new tree plantations elsewhere in the country balance deforestation in some locations (e.g., China and India, with 1.1 million hectares [ha] and 1.5 million ha, respectively, of new forest plantations in the year 2000; FAO 2001). Some countries, such as European countries and Canada, experienced an overall increase in forest cover at the national level.

Dryland degradation. The map of the main areas of degraded land is constrained by a lack of reliable data, compared

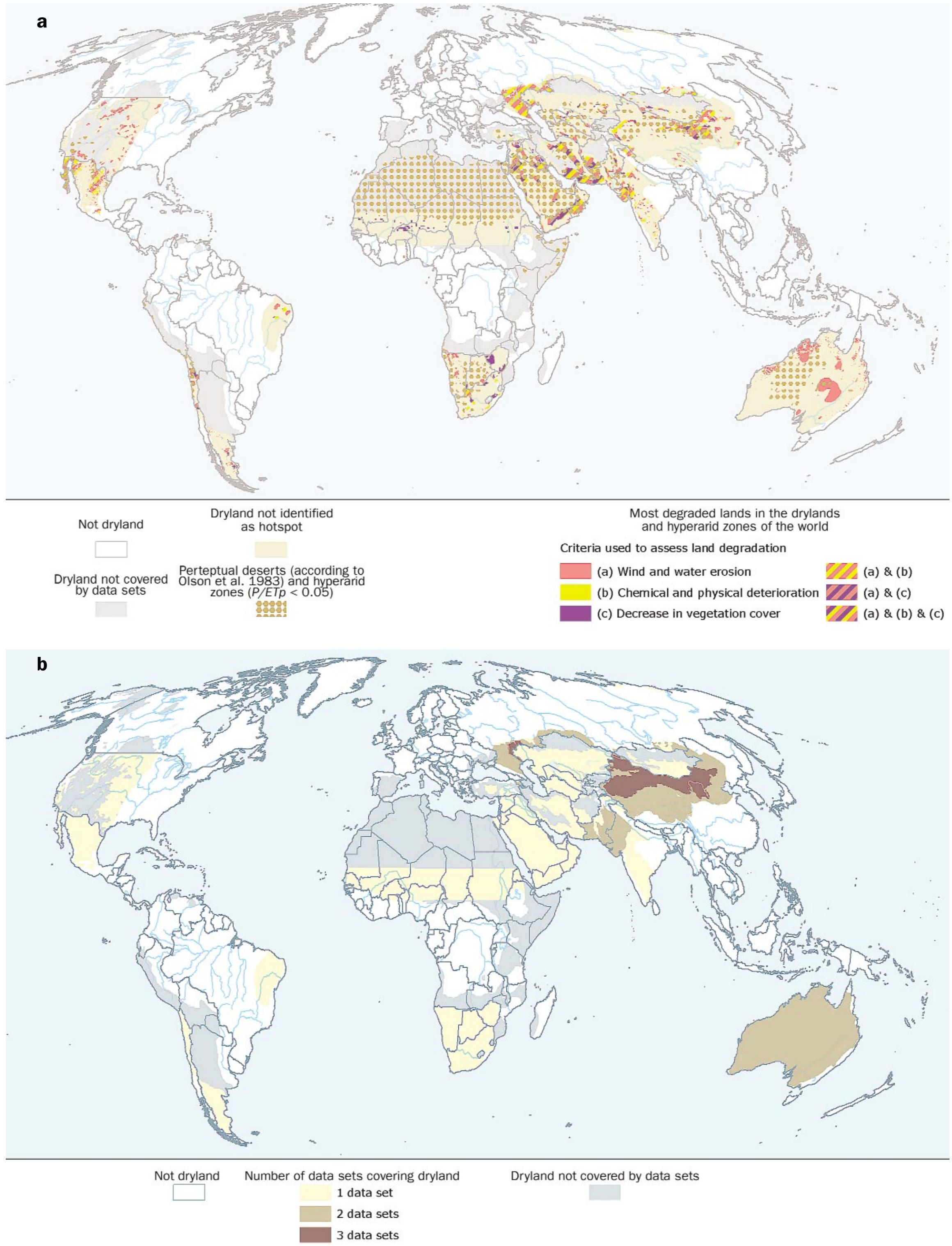

Figure 2. (a) Main areas of degraded land over 20 years (1980–2000); (b) number of data sets covering the area.

with the maps on forest-cover changes and cropland extent. A few data sets were retained for Africa (Prince et al. 1998, Hoffman 1999, Klintenberg and Gustad 2002, Prince 2002), Asia (Stolbovoi and Fischer 1997, Van Lynden and Oldeman 1997, Kharin et al. 1999, Kust et al. 2002), Australia (McTainsh 1998, Lu et al. 2003), and the Americas (NRCS 1997, Del Valle et al. 1998, Ministerio do Meio Ambiente 2000, SEMARNAT 2003). Most available data are quite heterogeneous in terms of monitoring methods or indicators used. We identify hyper-arid zones, which have experienced desertlike conditions for

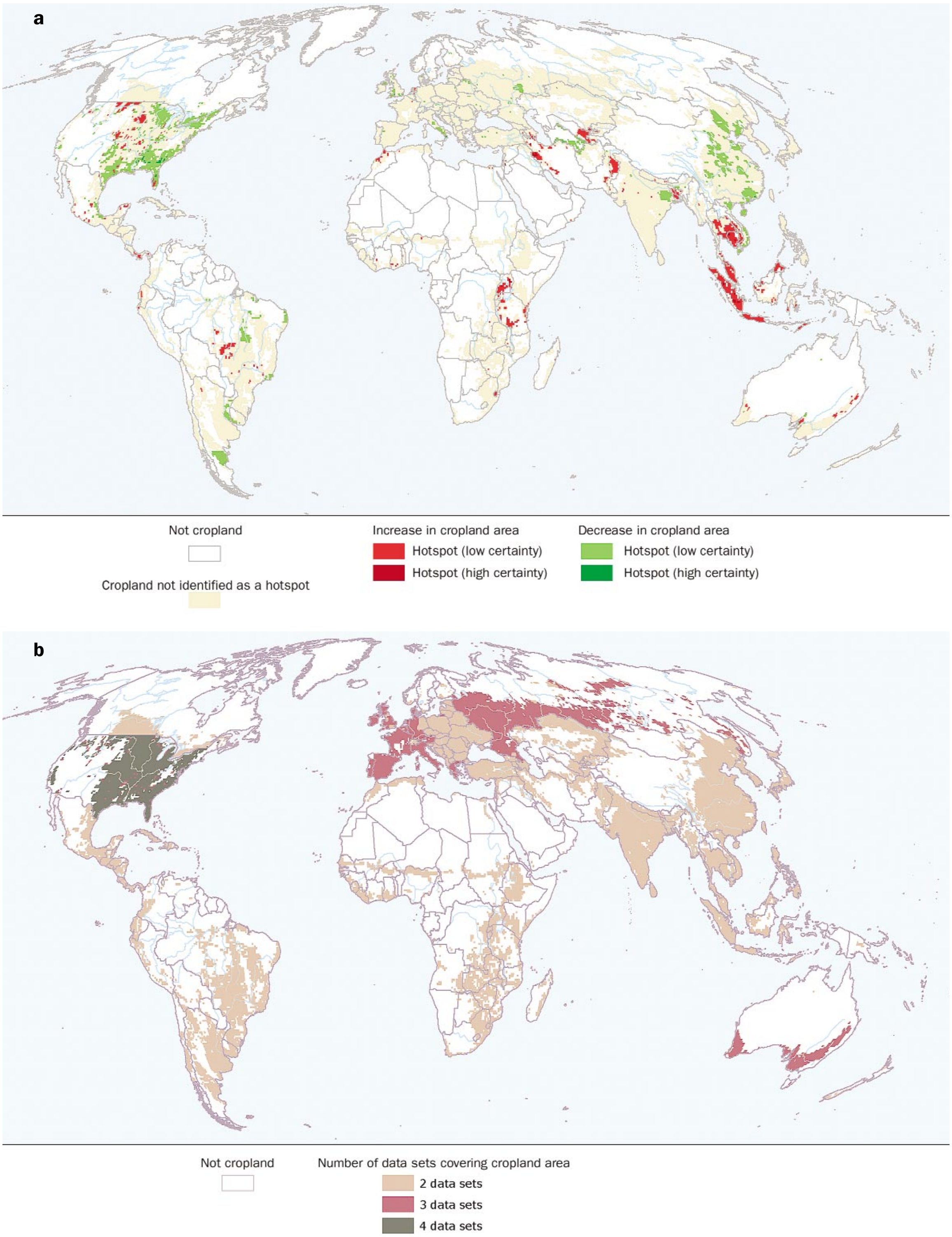

Figure 3. (a) Main areas of change in cropland extent over 10 years (1980–1990); (b) number of data sets covering the area.

centuries, on the basis of Olson and colleagues (1983). Figure 2 indicates the dryland degradation processes identified in the source data, including vegetation degradation, water and wind erosion, and chemical and physical deterioration. Some locations are affected by a combination of these processes. Note, however, that the data do not allow separation of "decrease" from "destruction" of biological productivity of the land, representing different degrees in the definition of land degradation. A second map identifies how many input data sets covered the area (figure 2b).

Changes in cropland extent. Most of the existing data sets related to changes in agricultural land focus on arable land

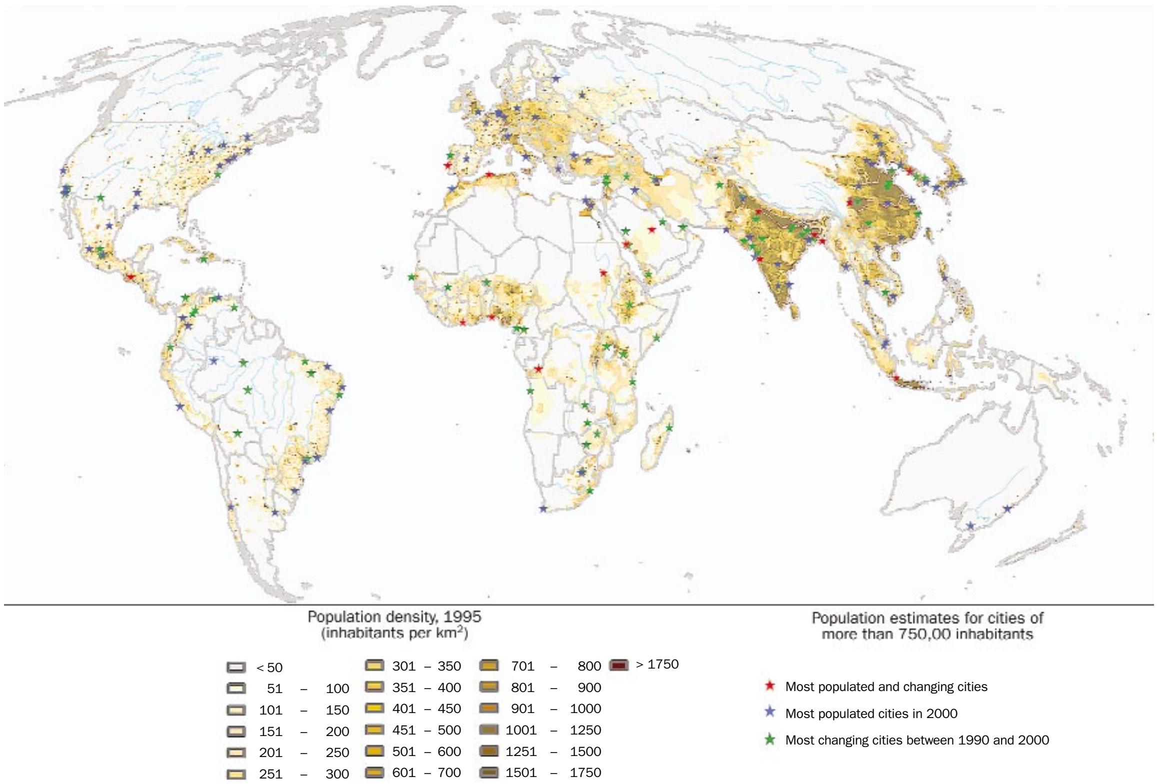

Figure 4. Population density in 1995 and most populated and changing cities over 750,000 inhabitants between 1980 and 2000.

and permanent crops (Rossiiskoi Federatsii po Statistike 1995, Ramankutty and Foley 1999, Eurostat 2000, Goldewijk 2000, BRS 2001, NRCS 2001, Waisanen and Bliss 2002). The map of the main areas of change in cropland extent identifies both increase and decrease in cropland extent. All the pixels characterized by more than 10% cropland in 1990 within a 0.5° × 0.5° cell from the Ramankutty and Foley (1999) data set were selected to develop the cropland mask. Grid cells lying outside this cropland mask were not considered in the identification of the main areas of change in cropland extent. The final map represents the areas experiencing major increases or decreases in cropland extent (figure 3a). A second map identifies how many input datasets covered the area (figure 3b).

Changes in urban extent. While an urban area is defined as any region with population density greater than a threshold, the impact of urbanization on land cover is better measured by the change in built-up area. As very few data exist on changes in the extent and shape of built-up areas, only indirect indicators such as human population could be used as a proxy. The relationship between the number of inhabitants and built-up area is positive, monotonic, but probably nonlinear. We used two complementary global population data sets. First, the 2001 revision of *World Urbanization Prospects*, prepared by the United Nations Population Division (UN 2002), focuses on "mega-cities" and provides population estimates and projections of urban agglomerations with 750,000 or more inhabitants in 2000 and all capital cities in 2001 for the period 1950–2015. Second, the "Gridded Population of the World" (Deichmann et al. 2001) focuses on less heavily populated areas and provides population counts and densities in 1990 and 1995. The final map, combining both data sets, shows the spatial distribution of the population density in 1995 and identifies the most populated and most rapidly changing cities of more than 750,000 inhabitants (figure 4). In the future, with a common definition of urban areas and a consistent data set on the actual extent of urban areas, changes in urban extent could be mapped based on time series of nighttime light maps derived from the Defense Meteorological Satellite Program satellite imagery (Elvidge et al. 2001).

Results

The broad geographic patterns of land-cover change can be inferred from the four global maps. All maps are presented in the pseudocylindrical, equal-area Molleweide projection. Deforestation is the most measured process of land-cover change at a regional scale (FAO 2001, Achard et al. 2002, DeFries et al. 2002). During the 1990s, forest-cover changes were much more frequent in the tropics than in the other parts of the world. In particular, the Amazon basin and Southeast Asia contain a concentration of deforestation hotspots. More data sets covered the tropics than the boreal zones; therefore, areas of forest-cover change in the boreal or temperate regions (e.g., in Canada or Siberia) may be less meaningful. However, forest degradation in Eurasia, mostly related to unsustainable logging activities or increase in fire frequency, has been growing in recent years. The frequency of fires, a natural disturbance factor in boreal ecosystems, has increased in recent years in Siberia in particular. Over 7.5 million ha per year for Russia alone were burnt over a 6-year period in the late 1990s (Sukhinin et al. 2004). Even though deforestation is one of the most intensively studied processes of land-cover change, regional gaps in spatially explicit data persist.

The Asian continent includes most of the main areas of degraded dryland. Not all the drylands and hyperarid zones of the world are well covered by desertification studies. Major gaps occur around the Mediterranean basin, in eastern Africa, in parts of South America (northern Argentina, Paraguay, Bolivia, Peru, and Ecuador), and in the United States. If all the continents were evenly covered by dryland degradation data, the global distribution of the most degraded land could be different, but the patterns observed in Asia would most likely remain the same. The available data do not support the claim that the African Sahel is a desertification hotspot at present.

The main areas of recent cropland increase are spread across all continents. They are principally located in Southeast Asia, which had the largest expansion of croplands recently; in Bangladesh; along the Indus Valley; in parts of the Middle East and Central Asia; in the region of the Great Lakes of eastern Africa; along the southern border of the Amazon basin in Latin America; and in the Great Plains region of the United States. North America accounts for most of the main areas of decrease in cropland (lowlands of the southeastern United States), followed by Asia (eastern China) and South America (parts of Brazil and Argentina). Some areas of decrease in cropland extent are located in the other continents, except for Africa, where no decrease in cropland was identified. All the cropland areas of the world were covered by at least two global data sets (Ramankutty and Foley 1999, Goldewijk 2000).

The most populated areas of the world are located in the Indo-Gangetic Plain of northern India, on the plain and north plateau of China, and on the island of Java in Indonesia. The most populated cities of more than 750,000 inhabitants are located mainly on the East Coast of the United States, in western Europe, in India, and in East Asia, whereas the most changing cities are located throughout the tropical belt.

Conclusion

This project produced a synthesis of available information on land-cover changes at the regional to global scale from 1981 to 2000. It was based exclusively on existing data sets. The patterns of rapid land-cover change observed in this study serve as a hypothesis that must be confirmed with additional fine-resolution data and ground-truthing in a subset of areas. As for any global map, one should look at the broadscale patterns. Local-scale scrutiny of the maps is likely to reveal anomalies caused by heterogenous data sources. For example, the sharp boundary in cropland change along the US–Canada boundary is probably an artifact of the different scales of the data used for the two countries. Finer-resolution data (for the United States, in this case) show more change than do coarse-resolution data.

Despite limitations in the data, the four synthesis maps help focus attention on the areas experiencing the most rapid land-cover changes. They also reveal the global geographic patterns of land-cover change. Most notably, this project revealed the following:

- Many parts of the world are not adequately represented in the available data sets, so it is possible that rapid change is occurring in locations that are not identified in the maps. It is also possible that ecological impacts of change are large even though observable land-cover changes were not identified as rapid in this study.
- Rapid land-cover change is not randomly or uniformly distributed but is clustered in some locations. For example, deforestation mostly takes place at the edge of large forest areas and along major transportation networks (e.g., along the southern Amazon basin).
- There are different trajectories of land-cover change in different parts of the world (e.g., decrease in cropland in temperate areas and increase in the tropics).
- Data on changes in drylands are less complete than data on other types of land-cover change, owing to the difficulties of satellite interpretation in these regions and to an inability to distinguish human-induced trends from large, climate-driven interannual variability in vegetation cover.
- Asia currently has the greatest concentration of areas of rapid land-cover changes, and in particular dryland degradation. The Amazon basin remains a major hotspot of tropical deforestation. Rapid cropland increase, often associated with large-scale deforestation, is prominent in Southeast Asia. Forest degradation in Siberia, mostly related to logging activities, is increasing rapidly. The southeastern United States and eastern China experience rapid cropland decrease. Existing data do not support the claim that the African Sahel is a desertification hotspot. Many of the most populated and rapidly changing cities are found in the tropics.
- Much of our information on tropical land-cover change comes from remotely sensed land-cover data, while information on change in the extratropical regions comes predominantly from census data. Systematic analysis to identify land-cover change has been done predominantly in the tropics because of the interest in tropical deforestation, and possibly because of the lower availability and reliability of census data in the tropics.

This project identified geographic areas and land-cover change issues with surprisingly poor information and data. There are other forms of rapid land-cover change that are thought to be widespread but are still poorly documented at the global scale. Local- to national-scale studies, however, demonstrate their importance and ecological significance. Prominent among these are changes in the tropical and subtropical dry forests (e.g., Miombo forests in southern Africa and Chaco forests in South America); forest-cover changes caused by selective logging, fires, and insect damage; drainage or other forms of alteration of wetlands; soil degradation in croplands; and changes in the extent and productive capacity of pastoral lands (Lambin et al. 2003).

We should ensure that the next attempt to synthesize land-cover data at a global scale avoids the shortcomings and pitfalls identified in the current exercise. For this, some of the priorities for future observations and research are as follows:

- A quantitative accuracy assessment of the coarse-scale data presented here should be performed with finer-resolution satellite imagery of a subset of locations integrated with ground-truth data on actual land-use conversions (i.e., were harvested forests reforested? were forests converted to cropland or pastures?).
- Data producers should use a hierarchical, standardized land-cover classification system to be applied to validated land-cover data at a fine spatial resolution and to time series of data integrated at the appropriate scale. We recommend wide adoption of the classification system proposed by the FAO (Di Gregorio and Jansen 2000).
- As an alternative or a complement to categorical land-cover representations, a continuous description of the land cover (e.g., in terms of fraction of tree cover or crop cover) should be more widely adopted whenever possible, as it offers greater ease for comparison of different databases (Ramankutty and Foley 1999, DeFries et al. 2002).
- Operational monitoring of land cover should be extended to regions that are not known as hotspots but where rapid changes may still take place and catch the scientific community by surprise.
- Systematic, consistent measurements of soil properties should be undertaken at a global scale, at a relatively fine resolution, since soil attributes are an important component of land cover.
- New empirical work is required based on conceptual advances in dealing with definitions of desertification (Stafford Smith and Reynolds 2002) and urbanization.
- There is an urgent need for systematic observations on the still poorly measured processes of land-cover change.

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