exceeded anything that the Earth has experienced for millions of years, and the growth rate has been unprecedented. But such long-term views are sometimes hard to grasp. What is the time-scale relevant for society today? Perhaps it is more instructive to consider just the period over which civilization has developed, from the time when the first cities were established around 6000 years ago. If we consider this in terms of the minute hand on a clock, with time ticking away as we approach the present, each minute represents a century (Figure 3). 6000 years ago, CO_2 levels were around 270ppmv. When the first writing was developed, around 3800 years ago (20 minutes to the hour in terms of the "civilization clock") CO_2 levels were still close to 280ppmv … and they remained at this level throughout most of our history – throughout Egyptian and Chinese, Incan and Mayan dynasties, all through the Crusades, the Inquisition, the Renaissance and the period of European settlement of the New World. But things began to change significantly following James Watt's invention of the steam piston engine 250 years ago, and Karl Benz and Gustav Daimler's introduction of the first petrol-driven internal combustion engines in 1886 – a little over 100 years ago and only 2 or 3 minutes ago on our clock of civilization. As we began this process of industrialization, CO_2 levels were 275ppmv … but today they have reached 360ppmv and are rising rapidly. Thus, on the time-scale of this clock of civilization it's the last 2 minutes where things have gone badly wrong on a global scale … and it's in the "next minute" – that is, within this century – that we must fix the problem. We cannot mindlessly hand it off to our children, and to future generations as yet unborn, with the hope that something will turn up – some technological fix, some magic solution that may relieve us of this burden. We cannot ruthlessly pin our hopes in unsupported speculation that feedbacks will bring these unprecedented and incredibly rapid changes into balance. And we cannot rely on alternative energy systems which produce waste products that need to be isolated from living things for a hundred thousand years – 15 times longer than the entire history of our civilization. What an appalling legacy that would be. What right do we have to burden future generations with this responsibility?

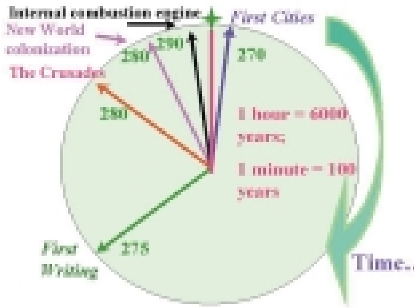
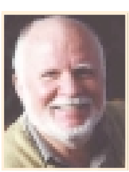


Figure 3. The "clock of civilization"; assuming the first cities (around 6000 years ago) mark the start of modern civilization, each minute represents hundred years. CO_2 levels at various times are shown in green (based on ice core measurements).

This is not merely an issue of scientific importance – it's an ethical and moral issue. We who are the inheritors of all that civilization has provided, of all the wisdom accumulated in our literature and science, all the beauty in art and music handed down for generations – *we* have to fix this problem. And we must act quickly, within the next "one minute" on the time-scale of our civilization's development.

Civilization implies civility – the development of a society that is caring and respectful of its citizens *and* its environment. Sadly, we have diverted from such a trajectory. The abuses our civilization has heaped on the world in "the last couple of minutes" will require a major effort to resolve, particularly given the expected further growth in world population. There will be 50 per cent more people on Earth within this century. Morally, ethically and scientifically we have no choice but to act boldly, and quickly, *as a global community*, to resolve these global-scale problems – our heritage from civilizations in the past, and our obligations to civilizations in the future require that we deal with these issues now.

Land-Use and Land-Cover Change: Advances in 1.5 Decades of Sustained International Research[1)]



Billie L. Turner II
Graduate School of Geography
& George Perkins Marsh Institute
Clark University, Worcester MA (USA)
E-Mail: bturner@clarku.edu
www.clarku.edu/departments/geography/faculty/

Land change – changes in the terrestrial surface of the Earth – is likely the most ancient of all human-induced environmental impacts on the biosphere and the first to obtain a magnitude to warrant the title "global". Evidence mounts that *Homo sapiens* was instrumental in the worldwide destruction of megafauna before the Last Glacial Maximum[2)], and by the 17th century humankind had restructured global biota by the transcontinental movement of domesticates and ornamental flora, complete with the unintentional transport of vermin, pests, weeds, and diseases, that affected ecosystems globally.[3)]

Today, virtually no land surface remains untouched in some way by humankind and about 50 per cent of the ice-free surface of Earth is considered significantly modified by human action. Land uses usurp as much as 40 per cent of the net

1) This contribution is based on the paper that was presented at the Global Change Open Science Conference: Challenges of a Changing Earth held in Amsterdam in July 2001. The complete proceedings of the conference will be published in 2002 by Springer-Verlag, Heidelberg, in a book entitled *Challenges of a Changing Earth*, edited by Will Steffen, Jill Jäger, David Carson and Clare Bradshaw.

2) J. Alroy: "A Multispecies Overkill Simulation of the End-Pleistocene Megafaunal Mass Extinction", *Science 292* (2001) 1893–1896; R.G. Roberts, T.F. Flannery, L.K. Ayliffe, H. Yoshida, J.M. Olley, G.J. Prideaux, G.M. Laslett, A. Baynes, M.A. Smith, R. Jones, B.L. Smith: "New Ages for the Last Australian Megafauna: Continent-Wide Extinction about 46 000 Years Ago", *Science 292* (2001) 1888–1892.

3) A.W. Crosby: *Ecological Imperialism – The Biological Expansion of Europe, 900–1900*, Cambridge University Press, Cambridge (1986).

primary productivity of the Earth.[4] About 35 300 dams have been constructed since 1950 fragmenting habitats within 60 per cent of the major river basins worldwide. Water diversion for irrigation, consuming about 70 per cent of all water withdrawals, is sufficiently significant to stop flow of such large rivers as the Colorado, Huang Ho, and Amu Darya from reaching the sea during the dry season.[5] Land-cover changes, largely deforestation, have accounted for 33 per cent of the increase in atmospheric CO_2 since 1850 [6], and recent assessments suggest that heretofore unaccounted parts of forests, including large areas of regrowth, constitute much of the missing carbon sink.[7] These and other land changes alter ecosystem services locally and globally [8], and account for most of the current "mass extinction" of biota. That the human impress on the terrestrial Earth is vast is no surprise; that land change was one of the last of the subjects to be formally entertained by global environmental change science is surprising.

This relatively late start notwithstanding, major headway has been made internationally toward the development of systematic and integrated land science that is consistent with the emerging research agendas variously labeled "sustainability science", including activities falling within the auspices of the IGBP, IHDP, and IPCC, especially the joint IGBP-IHDP LUCC (Land Use/Cover Change) program and various parts of the IGBP's GCTE (Global Change and the Terrestrial Ecosystem) program. The LUCC program seeks to assist the various research communities globally in (i) documenting the magnitude and pace of land changes and identifying the critical locations of these changes, (ii) understanding and explaining these changes sufficiently (iii) to produce robust near-term models of change at various spatial scales, and (iv) to apply this knowledge to various linked issues, such as the vulnerability of coupled human-environment systems to climate change and other perturbations and stresses. Oddly, given its significance, systematically generated and readily comparable documentation of land-use and land-cover change has been woefully sparse, and much of the work to date has focused on methodological and technological issues and software and hardware development, dramatically improving the documentation and monitoring land changes [9], as well as the means of modeling and projecting the observed changes. The state-of-the-art in "integrated land science" is rapidly improving, however, permitting assessments of major trends, causes, and model-method developments.

Forest Trends

The search for the missing carbon sink and the concern for tropical deforestation has drawn considerable attention to forest-cover change, the trends of which are better known than any other land cover, save agriculture. Since the advent of domestication, about 47 per cent of the world's forests have been lost [10], yet they continue to occupy some 3.5 million hectares, 55 per cent of which are located in the tropics. It is precisely this geographical realm, however, where the pace of deforestation is rapid. About 10 per cent of the world's tropical forests (or 200 million hectares) were lost between 1980 and 1995 alone [11], with hot spots of deforestation occurring in every region [12] and some, such as those of Sunda Shelf of Indonesia, at alarmingly high rates [13]. Most of the areas of deforestation involve "clear cutting" on the assumption that once cut, the lands will remain "open". Careful observations, however, demonstrate that much of the area that is desforested is permitted to regrow (for undetermined periods), reducing the estimates noted above. These reductions, however, appear to be significantly offset by "cryptic deforestation", that generated by selective logging and linked burning of logged lands.

Temperate and boreal forests, with one prominent exception, display trends contrary to those in the tropics. Tree cover in much of the developed economies of the world has increased over the past 15 years. About 20 million hectares were gained between 1980 and 1995 alone [11], be it transitioning of farmlands to suburban and recreational uses in service sector economies or deliberate tree planting in command economies, such as China.[7] Indeed, the Northern Hemisphere constitutes a considerable terrestrial carbon sink. Theoretically, this forestation is related to the movement of the former land-uses elsewhere (deforestation displacement), although efficiencies in modern production may lead to a reduce hectarage in the replacement activities compared to the hectarage of regrowth. The major exception to temperate and boreal forestation trends is found in Siberia, the looming deforestation giant. Here the demise of the Soviet command economy has given way to socio-economic conditions akin to those in the tropics, and international logging has taken advantage of the vast stocks of Siberian forests.

Agricultural Trends

Various projections foresee a future in which cultivation intensifies worldwide [14], focused on prime agricultural lands and with marginal lands increasingly taken out of production. This process has already begun in the developed economies, in some cases related to the depletion of critical resources, usually water drawn down in aquifers, which renders the land marginal for cultivation.[15] Where marginal agricultural production continues in these economies, it is supported by policies designed to protect the enterprise for political

[4] P.M. Vitousek, H.A. Mooney, J. Lubchenco, J.M. Melillo: "Human Domination of Earth's Ecosystems", *Science 277* (1997) 494–500.

[5] N. Johnson, C. Revenga, J. Echeverria: "Managing Water for People and Nature", *Science 292* (2001) 1071–1072.

[6] R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, D.J. Dokken (Ed.): *Land Use, Land-Use Change and Forestry*, Special Report of the Intergovernmental Panel of Climate Change (IPCC), Cambridge University Press, Cambridge (2000).

[7] J. Fang, A. Chen, C. Peng, S. Zhao, L. Ci: "Changes in Forest Biomass Carbon Storage in China between 1949 and 1998", *Science 292* (2001) 2320–2322.

[8] G.C. Daily, T. Söderqvist, S. Aniyar, K. Arrow, P. Dasgupta, P. R. Ehrlich, C. Folke, A. Hansson, B.-O. Jansson, N. Kautsky, S. Levin, J. Lubchenco, K.-G. Mäler, D. Simpson, D. Starrett, D. Tilman, B. Walker: "The Value of Nature and Nature of Value", *Science 289* (2000) 395–396.

[9] A. Di Gregorio, L.J.M. Jansen: *Land Cover Classification Systems – Classification Concepts and User Manual for Software Version 1.0*, Food and Agricultural Organization of the United Nations, Rome (2000).

[10] WRI: *World Resources 1998–1999. A Guide to the Global Environment*, World Resources Institute, Washington DC (1998).

[11] FAO: *State of the World's Forests*, Food and Agricultural Organization of the United Nations, Rome (1999).

[12] F. Achard, H. Eva, A. Glinni, P. Mayaux, T. Richards, H.J. Stibig (Ed.): *Identification of Deforestation Hot Spot Areas in the Humid Tropics*, Trees Publication Series B, Research Report No. 4, Space Application Institute, Global Vegetation Monitoring Unit, Joint Research Centre, European Commission, Brussels (1998).

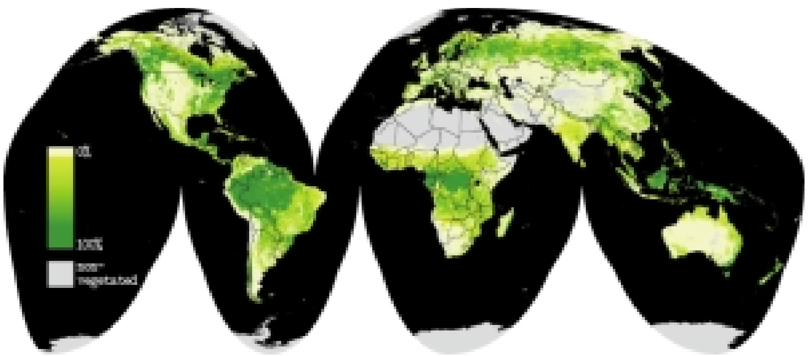
[13] P. Jepson, J.K. Jarvie, K. MacKinnon, K.A. Monk: "The End of Indonesia's Lowland Forest", *Science 292* (2001) 859–861.

[14] J.H. Ausubel: "Can Technology Spare the Earth?", *American Scientist 84* (1996) 166–178.

[15] E. Brooks, J. Emel: *The Llano Estacado of the US Southern High Plains – Environmental Transformation and the Prospect for Sustainability*, United Nations University Press, Tokyo (2000).

and other reasons. Intensified production, on the other hand, relies on significant chemical and fossil fuel inputs as well as irrigation, in some cases stressing catchment hydrology and leading to significant releases of N_2O to the atmosphere. Such problems promise to be substantially reduced by satellite-led "smart farming" and other advanced techniques.

The overall reduction and intensification in cultivated lands is not necessarily replicated in the less developed economies, especially within the tropics. Here economically marginal, but life-sustaining cultivation continues to expand into the forest frontier, commonly following roads constructed for timber and other extractive activities, or corporate or large-holder investments seek to profit from inexpensive land.[16] Few, if any indicators suggest that this expansion will cease in the near future, although it will surely ebb and flow by region. Where cropping strategies remain low-input but cultivation frequencies increase, invasive species promise to become a significant problem with this expansion.[17, 18]



Urban-related Trends

Notwithstanding the impressions from satellites of the night-lights of Earth, urban or built-up settlement areas pale in area covered compared to other land-covers. Despite rapid urban expansion, the major impact of urban areas is through the urban "footprint" on resource uses and environmental impacts on other land-covers.[19] These footprints are many, but two noted here raise special concerns for global change and sustainability science. Urban, and by definition, industrial production contributes significantly to tropospheric ozone which undertakes various reactions to become a toxic pollutant, not only with implications for human health but for plant growth. There is enough evidence of the spatial correlation between urban-industrial complexes worldwide and the build up of ozone that spreads across vast tracts of prime agricultural lands.[20] Some of the more endangered regions include the major croplands of the American mid-west, eastern Europe, eastern China, and the Ganges Basin, which is the most ozone-polluted watershed in the world. Beyond this indirect impact, urbanization has begun to consume significant amounts of prime croplands in China, India, western Africa, and most everywhere that the "megacities" process is underway. Urban-industrial land uses simply outbid agriculture for these lands, shifting the need to increase production on lands elsewhere. For example, in the Pearl River delta of China 1 376 square kilometers of prime rice land was consumed by urban growth from 1988 to 1996.[21]

Grassland-Pasture Trends

The land-cover conversion trends of grass- and pasture-lands are poorly understood. Part of the problem lies in definitions of what is to be counted in this land-cover category and how, as attested through comparisons of "systematic" assessments of the long-term trends in grass- and pasture-lands, which range from losses of only 1 per cent to more than 45 per cent. Agreement exists, however, that grasslands and by extension, arid lands have been extensively modified worldwide, largely degraded in terms of standing biomass.[22] This recognition, however, does not lend support to various estimates by UNCOD (UN Convention on Desertification) indicating dramatic desertification worldwide; various land-change and environment-development communities have seriously challenged these estimates, suggesting that they are highly exaggerated.[23]

Causes

Explaining land change beyond several simple and broad lessons has proven difficult, and the problems are heightened by the need for spatially or geographically explicit explanations. It is not sufficient to know the human-environment dynamics that will expand, shrink, or intensify a particular land use; the global change community needs to know where these changes will take place. Beyond agriculture, however, the attention paid to general land-change explanations has been sparse, and that to spatially explicit explanations, even more sparse. These circumstances are changing, in part driven by various modeling needs [24, 25] and by several comparative assessments of explanations that have been undertaken recently.[26]

The most detailed work of this last kind has been directed to tropical deforestation by way of comparison of modeling results and case studies. These comparisons break down the causes of tropical deforestation (as with any land-cover change) into proximate (immediate action leading to change)

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16) H. Geist, E. Lambin: "What Drives Tropical Deforestation? A Meta-Analysis of Proximate and Underlying Causes of Deforestation Based on Subnational Case Study Evidence", *LUCC Report Series* No. 4, LUCC International Project Office, Louvain-la-Neuve (2001).

17) H.A. Mooney, R.J. Hobbs (Ed.): *Invasive Species in a Changing World*, Island Press, Washington DC (2000).

18) B.L. Turner II, S. Cortina Villar, D. Foster, J. Geoghegan, E. Keys, P. Klepeis, D. Lawrence, P. Macario Mendoza, S. Manson, Y. Ogneva-Himmelberger, A.B. Plotkin, D. Pérez Salicrup, R. Roy Chowdhury, B. Savitsky, L. Schneider, B. Schmook, C. Vance: "Deforestation in the Southern Yucatán Peninsular Region: An Integrative Approach", *Forest Ecology and Management* (2001), in press.

19) C. Folke, A. Jansson, J. Larsson, R. Costanza: "Ecosystem Appropriation by Cities", *Ambio 26* (1997) 167–172.

20) W. Chameides, P.S. Kasibhatla, J. Yienger, H. Levy II: "Growth in Continental-Scale Metro-agroplexes: Regional Ozone Pollution and World Food Production", *Science 264* (1994) 74–77.

21) K.C.Seto, R.K. Kaufmann, C.E. Woodcock: "Agricultural Land Conversion in Southern China", *Nature 406* (2000) 121.

22) G.P. Chapman (Ed.): *Desertified Grasslands – Their Biology and Management*, Linnean Society Symposium Series No. 13, Academic Press, London (1992).

23) D.S.G. Thomas: "Science and the Desertification Debate", *Journal of Arid Environments 37* (1997) 599–608.

24) N.E. Bockstael: "Modeling Economics and Ecology – The Importance of a Spatial Perspective", *American Journal of Agricultural Economics 78* (1996) 1168–1180.

25) A. Veldkamp, E. Lambin (guest Ed.): "Predicting Land-Use Change", Special Issue, *Agriculture, Ecosystems and Environment 85* (2001).

26) E.F. Lambin, H. Geist, S. Agbola, A. Angelsen, J.W. Bruce, O. Coomes, R. Dirzo, G. Fischer, C. Folke, P.S. George, K. Homewood, J. Imbernon, R. Leemans, X. Li, E.F. Moran, M. Mortimore, P.S. Ramakrishnan, J.F. Richards, H. Skånes, W. Steffen, G.D. Stone, U. Svedin, T. Veldkamp, C. Vogel, J. Xu: "Our Emerging Understanding of the Causes of Land-Use and -Cover Change", *Global Environmental Change 4* (2001), in press.

and distal (forces precipitating the action) kinds. They demonstrate recurrent factors generating deforestation, but these factors come together in highly diverse ways and play out on the landscape similarly. In short, precise explanations – those on which modeling projections can be based – are highly place-specific and change by scale of aggregation addressed. Thus, a recent study finds that various models of tropical deforestation recurrently indicate the proximate causes to be some set of increasing agricultural prices, increasing roads, and a shortage of off-farm employment opportunities, while the distal causes involve market and policy failures, and debt and terms of trade. The authors conclude with the simple lessons that tropical deforestation takes place when and where these forests or the lands on which they grow becomes profitable to someone or by the ability of some groups to influence policy (for example, forest access) to enlarge their economic self-interests.[27)] Likewise, others identify the proximate causes of agricultural, timber, and/or infrastructure expansion into tropical forests, but enlarge the distal factors from economic and policy shifts to population increases driven by in-migration. Significantly, they suggest that the dominant combinations of proximate and distal drivers vary by locations (Sub-Saharan Africa, Southeast Asia, and Latin America).[16, 26)]

Methods and Models

Surely the most advances to date in land-change and land-cover studies have focused on new or improved methods of detection and observations of land change and models of this change. Worldwide systematic data sets have been developed [28)], reducing the need to rely so heavily on the FAO self-reported country data. In addition, various compilations of heterogeneous data (historical maps, aerial photography, remote sensing imagery) are being combined to create local and regional land-change assessments.[29)] These efforts not only enrich the total data pool, but serve as critical checks on one another.

Various detection and assessment methods have strongly improved our ability to address a variety of land changes underway. For example, detailed studies of grassland burning in portions of the Sahel demonstrate the over- and under-estimations of the area annually burned based on the pixel threshold levels used in analysis as well as the seasons in which the imagery is taken. Satellite data serve more generally as "checks" on ground-based calculations of land change, in some cases seriously challenging the latter, as in the case for cropland coverage in southern China.[21)] In another example, fine-tuned observations of forest fragmentation and the concomitant enlargement of edge effects increases our ability to address biomass and species losses in this space. Detailed ground studies permit various stages of successional growth to be observed and mapped, providing critical insights for land-change models in which rotational (crop-fallow) cultivation is followed as well as for carbon sequestration calculations.[6, 18, 30)] And, on the vulnerability front, new techniques and assessment have proven highly robust in projecting the direction of ENSO droughts in southern Africa, providing up to 6–8 weeks lead time in identifying the places to be affected.[31)]

Finally, major advances are underway in spatially explicit modeling of land changes of various kinds and form various approaches, be they econometric, explanatory, agent-based, or scenario-driven.[18, 24, 27)] Increasingly, these models are bringing together heretofore disparate communities in the human and remote sensing sciences.[25)] The modeling community no longer needs to rely on time series generated change rates projected into the future or on theoretically based but aspatial models. Rather, the various approaches are joined, linking the robust understanding of behavioral and structural models of decision making with the spatial trends found in time series data, using the two to understand local and regional based land-use/cover changes and to project them into the near-term future. Such efforts require new measures of calibration and validation suited for spatial modeling, and various developments include the modification of the Kappa statistic and Relative Operating Characteristic (ROC) to apply to land change.[32)]

Summary and Observations

The advances underway point to the emergence of an "integrated land science" in which the environmental, human, and remote sensing/GIS sciences unite to solve various questions about land-use and land-cover changes and the impacts of these changes on humankind and the environment. This kind of land science is consistent with the integrative restructuring of the IGBP, emerging programs such as the Millennium Ecosystem Assessment, and the move toward sustainability science by the IGBP, IHDP, and various national-level global environmental change programs around the world. The integrated character of this science is such that it invariably requires team-based approaches with high labor and fiscal costs, especially in those cases starting from "ground zero" in terms of teams and data.

The advances outlined in this brief review are substantial and flow from various communities with different ties to global environmental change programs, illustrating the centrality of land change to the large problems of global change, environment-development, and the transition towards sustainability. It is noteworthy, however, the land change science lags its counterparts in terms of base detection and firm calculations of use and cover change. The data and estimates underlying the highly studied topic of tropical deforestation, let alone grassland change, are far less rigorous than those employed in studies of the carbon or nitrogen cycles. While perhaps less interesting for much of the land-change community, it is essential that our base understanding of what is changing where and how rapidly improves.

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27) A. Angelsen, D. Kaimowitz: "Rethinking the Causes of Deforestation: Lessons from Economic Models", *The World Bank Research Observer 14* (1999) 73–98.

28) R.S. DeFries, M.C. Hansen, J.R.G. Townshend, A.C. Janetos, T.R. Loveland: "A new global 1km dataset of percentage tree cover derived from remote sensing", *Global Change Biology 6* (2000) 247–254;
K. Klein Goldewijk: "Estimating global land use change over the past 300 years – the HYDE 2.0 database", *Global Biogeochemical Cycles 15* (2000) 417–433;
N. Ramankutty, J.A. Foley: "Characterizing Patterns of Global Land Use – An Analysis of Global Croplands Data", *Global Biogeochemical Cycles 12* (1998) 667–685.

29) C. Petit, E.F. Lambin: "Impact of data integration technique on historical land-use/land-cover change – Comparing historical maps with remote sensing data in the Belgian Ardennes", *Landscape Ecology*, in press.

30) E.F. Moran, E.S. Brondizio, J.M. Tucker, M.C. da Silva-Forsberg, S. McCracken, I. Falesi: "Effects of Soil Fertility and Land-Use on Forest Succession in Amazonia", *Forest Ecology and Management 139* (2000) 93–108.

31) J.R. Eastman, A. Anyamba: "Prototypical Patterns of ENSO-drought and Drought Precursors in Southern Africa", *The 13th PECORA Symposium Proceedings*, Sioux Falls, South Dakota (20–22 August 1996).

32) R. Pontius, Jr.: "Quantification Error versus Location Error in Comparison of Categorical Maps", *Photogrammetry, Engineering, and Remote Sensing 66* (2000) 1011–1016.