Remote Sensing for Modelling Socio-Environmental Change in the Tropics at Large Geographic and Temporal Scales

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Introduction

In this brief discussion paper I cast the net widely to touch on the following seminar questions:

1. What are the branches of population-environment (PE) research using remote sensing (RS) data?
2. What are the barriers to greater use of RS data in PE research?
3. How do indicators constructed from RS data compare with those collected through field research or surveys?
4. What are the societal benefits of using RS in PE research?

In addressing these questions, I focus on recent research concerning tropical forest-cover change due to socio-economic transitions over large areas and long periods. The aim of this discussion paper is not to answer the aforementioned questions so much as it is to raise relevant research and issues for further discussion.

Branches and Evolution of PE Research Using RS Data

The obvious utility of RS data to PE research is reflected in its long history of use. With the passage of time and the advancement of computer technology as well as RS data archives, new research opportunities and capabilities have arisen that have in turn yielded new streams of PE enquiry. In this section I will address two broad fields of PE research that use RS data: are urban ecology and tropical forest-cover change, an important sub-set of land use/cover science.

Jensen’s (1979) use of early Landsat MSS imagery to map the extent and nature of urban sprawl is a good, if applied, early example of an urban ecology application. More recent examples include observations of urban smog due to vehicular congestion and similar factors, and Bauer and Wilson’s (2005) use of Landsat TM data to measure the permeability of the urban surfaces to rainfall, this being a function of vegetation cover and thus social factors such as population density. More recently still, and indicative of current trends, Sloan and Hall (Forthcoming) spatially integrate SPOT5 imagery and fine-scale census data to explain the aerial decline of urban vegetation over Brisbane , Australia as a function of a preference for bigger homes over bigger yards. The research by Sloan and Hall is similar to that of Heynen (2006), Heynen and Lindsey (2003) and others who have used aerial photography and census data to explore how socio-economic conditions influence the distribution of urban vegetation cover. But whereas the geographic coverage of these later studies is often limited by the labour intensity of air-photo analysis, which in turn limits the generality and scope of their findings, the use of fine-scale (e.g., < 2.5 m pixels) satellite imagery has permitted ‘global’ observations (i.e., for an entire city). Thus, broadly speaking, with the advancement of RS data and particularly GIS, urban-ecological enquiry using RS has moved away from making environmental and social observations separately at the small scale, and moved towards (i) observations of environmental change elusive to air-photo analysis (e.g., permeability of urban landscape) and (ii) modelling social and environmental processes in an integrated manner over larger areas.

Research on tropical forest-cover change has followed a similar track, albeit with forks and twists. As with urban ecology, early studies used RS to observe the extent and location of land cover change, which was then attributed to spatially coincident social processes observed separately. Fearnside's (1986) account of deforestation in Amazonia due to agricultural expansion is an archetypical example. However, unlike trends in urban ecology, the large scales of observation and poor availability of social data in the tropics has meant that this approach (namely, observing a coincidence of physical and social processes) is still prominent. This is seen in Hermann et al.'s (2005) speculation on the human dimension of the 'greening' of the African Sahel observed via AHVRR imagery with 8 km pixel resolution. Such studies may be categorised into a 'global environmental change' (GEC) branch of enquiry in recognition of their large scale and broad resolution.

At smaller scales, such as region or district, it has been possible to provide more integrated and detailed accounts of the social dynamics underlying tropical forest-cover change as well as the nature of this change (e.g., forest fragmentation, agro-forestry, etc) (Steininger et al., 2001, Moran et al., 1994, Sloan, Forthcoming-a, McCracken et al., 1999, Brondizio et al., 1996). Such studies use many of the same tools as the GEC branch, especially satellite imagery, but I set them aside in a separate 'human ecology' (HE) branch of enquiry in recognition of their richer social data, finer scale, case-study nature and attention to the social *responses* to environmental change.

One of the more exciting developments in recent PE research has been the gradual fusion of the GEC and HE branches with respect to the analysis of tropical reforestation. This merged branch, which I term here 'GEC-HE', observes transitions from tropical deforestation to reforestation at a national scale and over long periods, as per the GEC branch, but does so with sufficient richness of social data as to empirically model the human dimension of the transition in detail, as per the HE branch. Studies by Sloan (2010), which integrates RS and individual-scale census data for 400 Panamanian counties over 1980-2008, as well as Perz and Skole (2003a, , 2003b), Meyfroidt and Lambin (2008a, , 2008b), Hecht and Saatachi (2007) and Wright and Samaniego (2008) constitute the entirety of this nascent branch[1]. The remainder of this article focuses on these studies.

Barriers to Greater Use of RS Data

The barriers to greater use of RS data in PE research are various. An unfamiliarity with the technicalities of satellite-image analysis on the part of PE researchers cannot be discounted, but with more user friendly software packages this factor has diminished in importance (Moran and Brondizio, 1998). Indeed, the extensive workbooks / tutorials that now accompany image-analysis software such as IDRISI are sufficient for one to independently gain an intermediate level of technical and practical proficiency. In the context of GEC-HE research, more troublesome than unfamiliarity, I would argue, are the poor quality and availability of RS data and complementary social data.

For time-series analysis of tropical forest-cover change, only Landsat MSS or AVHRR imagery are available to define baseline conditions in the 1980s[2]. Neither is well suited to the task, however. Landsat

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[1] Various other studies explore the same dynamic as those cited here, but as they do not use RS data nor favour correlational analysis for multiple spatial units of analysis, I do not consider them here.

[2] Early baseline imagery for some regions is not doubt also available in the form of panchromatic or multispectral aerial photography and radar imagery. However, this discussion confines itself to publically available multispectral satellite imagery, as with few exceptions only such imagery can form a baseline for large-scale time-series analysis.

MSS imagery has a *relatively* fine spatial resolution (80 m pixels). But archived MSS images of tropical areas during the 1980s are so few, so infrequent and often so cloudy that that their utility to estimate forest-cover change over 1980-1990 for even for a small country is virtually nil. Indeed, Nezry et al. (1993) estimate that, in a given year in Sumatra, the probability of acquiring a single Landsat MSS, Landsat TM or a SPOT satellite image having <70% cloud cover (which is still *very* cloudy) is only 0.25. Similar conclusions have been reached by Asner (2001) for Brazil and Gastellu-Etchegorry (1988a, , 1988b) for Indonesia.

Composites of AVHRR imagery, in contrast, are relatively cloud free due to a daily overpass rate, an important feature for tropical-area studies. However, AVHRR imagery is spectrally and spatially coarse (min pixel 1.1 km at nadir), as it was originally intended for meteorological applications. Therefore, AHVRR-derived land-cover maps may have poor or uncertain accuracy (Sloan, Forthcoming-b) except at the largest of scales of observation, and will provide crude representations of landscape geometry (e.g. forest fragmentation). Nonetheless, many researchers use AVHRR imagery for large-area studies as a matter of necessity and convenience (Lucas et al., 2000a, Lucas et al., 2000b, Nelson et al., 1987, Meyfoidt and Lambin, 2008a, Meyfoidt and Lambin, 2008b). Many also report that land-cover estimates derived from AVHRR imagery compare favorably to those derived from Landsat imagery for homogenous land covers over large areas, e.g., mature tropical forest in Africa and Brazil (Gervin et al., 1985, Nelson and Holden, 1986, Paivinen and Witt, 1988, Mayaux et al., 1998, Iverson et al., 1989).

Nonetheless, within the context of GEC-HE research, using an AVHRR baseline within a national Landsat time-series, or indeed using AHVRR exclusively, makes me nervous for a number of reasons. First, AVHRR data is inappropriate for describing many 'anthropogenic', landscapes characterised by spatial fragmentation and heterogeneity, rare and dispersed land covers, and linear features (e.g., forest-penetration roads) (Iverson et al., 1989, Mayaux et al., 1998: 50, Nelson and Holden, 1986). Yet it is in such landscapes that forest regeneration and other interesting anthropogenic land-cover changes are most likely to occur. Second, if the spatial units of analysis (i.e., administrative areas) for GEC-HE analysis are very fine, say (somewhat arbitrarily) <100 km^2, then the 'chunky' AVHRR aerial estimates of environmental change may prove inaccurate unless first 'calibrated' with Landsat data to thus estimate the *proportion* of AVHRR pixels belonging to given land-cover class (Iverson et al., 1989). This 'spectral unmixing' approach, of course, presupposes the availability of the Landsat imagery, and is suitable only for simple land-cover classifications (e.g., forest/no forest). Still, even if thusly calibrated, I remain unsure of how well the AVHRR baseline estimates would compare with later Landsat estimates for such small spatial units. Poor comparisons between baseline and later estimates would lead not only to misleading estimates of land-cover change for smaller spatial units, but also to misleading correlations between social and forest-cover change for such units. Interested readers may consult Sader et al. (1990) and Grainger (1984) for thorough reviews of the use and limitations of RS data for tropical forest observation.

Given the above, it is unsurprising that of the seven GEC-HE studies cited earlier, none considers forest-cover change prior to 1990 (when the volume of Landsat imagery in the archives become more ample). This temporal limitation might not have proven be so severe were it not for the fact that GEC-HE studies derive their social data exclusively from national censuses, which in the tropics are usually decadal. Thus, if we exclude census data for 1980 because there is no contemporary RS data, we have, until now, social and RS data for only 1990 and 2000, a span of a mere 10 years by which to account for a national scale socio-environmental transition. Again, of the aforementioned GEC-HE studies, only one (Sloan, 2010) observes forest-cover change over a period greater than ~10 years. Worse still, considering that cloud cover necessitates that national Landsat-derived maps for "1990" and "2000" are often composites of imagery for 1988-1992 and 1998-2001, respectively, as is the case for Panama (ANAM, 2003), then correlations between ten years of social change and six-to-thirteen years of forest-cover change (depending on location within Panama) may give rise to misleading results.

Finally, it almost goes without saying that time-series census data for a tropical country are also fraught with problems. These problems do not relate to RS data directly, but they do bear on whether it is worthwhile pursuing the GEC-HE approach in a given country. Often, the only (published) time-series census data available to model forest-cover change are a handful of generic variables at coarse geographic scales (Wright and Samaniego, 2008, Perz and Skole, 2003a, Perz and Skole, 2003b). The paucity of social and agricultural data offers little incentive to process scores of satellite images into a national forest-cover change map, for the poor availability of the census data has already limited the ultimate power of the intended socio-environmental model[3].

The Comparability of Indicators

The distinctions between land-cover classifications derived from RS data versus field surveys are many. Apart from the obvious scale advantages of RS data (geographic and temporal), the distinctions usually reduce to what a field survey can measure but RS data cannot. In PE research, the principal distinction is the degree to which the land-cover classification reflects land use / intervention, as opposed to mere land cover. For example, while a field survey may distinguish unmanaged natural forest fallows from those managed to produce food and fibre by observing differences in tree species composition, to the satellite image, which ‘sees’ only the biophysical properties of the fallow (e.g., leafy vigour, shadow, texture), all such fallows may appear identical. Thus, the scale advantages and convenience of RS observations are offset by an inferior ability to discern subtle biophysical properties having implications for land use and human-environment interactions.

Whether this limitation affects the HE, GEC or indeed the GEC-HE branches of enquiry most severely is debatable. With respect to the HE branch, a limited ability to discern land usage clearly undermines the HE branch’s interest in anthropogenic landscapes, and in some instances it has limited certain lines of enquiry altogether (e.g., Moran and Brondizio, 1998 with respect to anthropogenic palm forests in Brazil). However, Moran and Brondizio (1998) also demonstrate that by linking extensive field surveys (including interviews) with RS data using a GPS, satellite imagery may be ‘trained’ to correctly classify elusive anthropogenic land covers (e.g., multiple stages of tropical forest succession). In addition, within small-scale study, the detailed examination of land-cover maps alongside contextual information and one’s own field experiences is often sufficient to reveal hidden patterns of land-use (Robbins, 2001).

With respect to the GEC-HE branch concerning national transitions from deforestation to reforestation, it is oft criticized for its homogenous treatment of “forest” (Perz, 2007), which gives little regard to the quality, variety or distribution of forest cover within a landscape. Unlike HE research, GEC-HE research cannot easily resolve such issues via field surveys, given the large area covered by its observations and aggregated spatial units of analysis. In the end, the GEC-HE approach “must fall to the complexity of the real world, which does not allow a facile representation of all the facts” (Walker, 2008: 138). Given the large scale and generalizing nature of the GEC-HE branch, it is unlikely to suffer so much as HE research should the later similarly ‘fall to the complexity of the real world’.

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[3] Published census data may also be available at less aggregate spatial scales over consecutive censuses. However, once it is considered that many such variables are also likely generic (e.g., population, age, sex, education) and that thousands of such data values must be manually entered into a computer – e.g., 5600 values for eight variables, 350 spatial units and two decades – the incentive to proceed may remain subdued. In this light, the only way forward for meaningful, fine-scale, time-series analysis is to use digital, raw, respondent-level census records. To the best of my knowledge, only my own study of Panama has done this (Sloan, 2010).

Societal Benefits

The potential societal benefits of GEC-HE research using remote sensing are immense, albeit largely unrealized. In my view, the principal benefit is that, for the first time, policy makers may draw upon a *rich, national-scale* empirical basis to develop social/agricultural/economic policy relevant to large-scale environmental issues, namely those concerning tropical forests. Here, by 'empirical basis' I refer to national, spatially-explicit statistical models integrating observations of socio-economic and environmental change; for example, Sloan (2010), described above. Such an empirical basis has not been available previously. In their absence, simplistic conceptualisations of large-scale interactions between social and tropical forest-cover change gained traction[4] (e.g., Wright and Muller-Landau, 2006, Izquierdo et al., 2008), as have more creditable but poorly substantiated conceptualisations, such as those concerning urban economic growth and forest recovery (Rudel et al., 2005). While researchers inevitably aligned with one camp or another, only recently has GEC-HE enquiry greatly qualified them all and indicated more clearly where and how governments might encourage agricultural transitions (e.g., towards intensification) or economic development (e.g., via increased education of rural females) to achieve desirable environmental outcomes (Meyfoidt and Lambin, 2008a, Sloan, 2010). In the text box below I present an example of such GEC-HE research and its utility to tropical forest conservation and climate-change mitigation.

REDD and Panama: National Scale Observations

The Reduced Emissions from Deforestation and Forest Degradation (REDD) mechanism of the post-2012 Kyoto Protocol would award tropical nations with carbon credits for 'avoiding' future deforestation, as via social policy which reduces pressure on forests, where future deforestation is anticipated by trends over a baseline period. Participating governments therefore assume that the relationship between social change (e.g., agricultural activity, economic growth, population growth) and forest-cover change over a baseline period reliably predicts future deforestation and, thus, is a sound basis on which to develop social policy to curb deforestation. The soundness of this assumption is, however, uncertain[5]. A validation of the constancy with which social change relates to forest-cover change is therefore required to inform REDD-implementation plans.

Sloan (2010) presents such a validation for Panama. He integrates RS data and respondent-scale census records to model deforestation over 1990-2000 as a function of various 'pathways' of social, agricultural and economic change prominent in Panama over 1990-2000, e.g., agricultural intensification, urbanization and afforestation, increased rural non-farm economic activity, etc. He then validates the model by testing how well it predicts deforestation over 2000-2008 as well as in alternative contexts[6] for 1990-2000. Findings indicate that the relationship between deforestation and the pathways of social change is moderately strong but prone to instability given slight contextual changes that may occur over time or that may exist between regions of a nation. Hence, on the basis of the model, the Panamanian government may confidently devise social policy to curb future deforestation by focusing on only on those pathways of change having stable relationships with deforestation, and may do so with an expectation of how effective such efforts may be. All this should lead to more effective REDD implementation and thus climate-change mitigation.

To summarize the example from the text box, the greatest utility of such PE research does not lie in its technical sophistication, but in its observation of change for an entire nation at a fine scale. It captures

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[4] Most such simplistic conceptualisations attribute undue importance to population as a determinant of forest-cover change.

[5] Uncertainty arises from the likelihood that social change and forest-cover change have an inconstant relationship. Hence, the interaction between social and forest-cover change during one period may not accurately predict the nature of subsequent interactions.

[6] The 'alternative contexts' for 1990-2000 are random samples of the 400 counties of the original dataset for 1990-2000. Each random sample is a social and geographic alternative to the original, and represents a potential reality that might have existed or that may exist in the future.

socio-environmental dynamics unique to this scale and resolution, observing those overarching relationships that are invisible from the field. Knowledge of these large-scale dynamics is required to inform policy tackling many current environmental crises that also operate at large scales and over long periods, e.g., climate change. This knowledge is not necessarily available from observations at lesser scales. Observations such as Sloan's (2010) would have been impossible without national coverage of RS data, but also useless without fine-scale social data and a 'PE orientation' through which to explain the environmental change.

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