Frontier Land Use Change: Synthesis, Challenges, and Next Steps

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Profound social, economic, and environmental changes that include new land management practices are often associated with advancing agricultural frontiers. We argue that existing approaches to case studies do not allow for clear generalization or the systematic testing of hypotheses. As an alternative, our study uses Mill’s method of agreement approach to synthesize results from seven long-term case studies of land cover change in frontier areas. We identify a number of generalizations that hold across the specific case studies. We also identify changes in the spatial organization of land use in agricultural frontier areas, which are typically characterized by agricultural expansion, growing population, and transportation improvements. We then evaluate the methodological strengths and weaknesses of Mill’s method of agreement based on use in this study. Finally, we argue that agent-based models, using virtual landscapes and the logic of demographic standardization, are an important next step to facilitate methodologically defensible comparisons across case studies.

Key Words: agent-based models, case comparisons, frontier, land use change, population dynamics.

Research on the causes of land cover and land use change has accelerated in response to concern about negative effects of such change (Watson et al. 2000; Homewood et al. 2001; National Research Council 2001; Glass et al. 2002; Kalnay and Cai 2003; Steffen et al. 2003; Turner, Matson, et al. 2003). There is now essentially universal agreement across the disciplines involved in the emerging land change science that to understand the causes of land cover and use change, it is essential to incorporate human behavior in our theories, models, data, and analyses (for recent assessments of the field see Gutman et al. 2004; Lambin and Geist 2006). Doing so, however, is complicated by profound cultural differences between social science and natural science disciplines. The research approach that most consistently has been able to blend human behavioral elements with biophysical and other elements is the place-based case study approach (e.g., see the papers in the following edited volumes: Liverman et al. 1998; Millington, Walsh, and Osborne 2001; Walsh and Crews-Meyer 2002; Fox et al. 2003; Entwisle and Stern 2005). Case studies have been important because they integrate data describing people, place, and environment with land cover and land use data as well as data on land use decision makers (e.g., individuals, households, communities, local governments, corporations, non-governmental organizations, and various volunteer organizations). By linking land change data with data from decision makers, case studies are well positioned to move beyond description toward an understanding of land cover and land use change (Entwisle and Stern 2005).

Case studies, however, have two principal drawbacks (Cook and Campbell 1979; King, Keohane, and Verba 1994; Ragin 2000). First, published reports typically do not contain sufficient detail for the reader to (a) know all relevant aspects of the place, (b) evaluate the quality of the data collected on the case, and (c) evaluate the appropriateness of the analytical methods used. Indeed, the land change field itself does not have agreement on what should be reported (Rindfuss et al. 2004; Entwisle and Stern 2005). The second drawback of case studies is uncertainty regarding generalizability: To what extent can the relationships found in one place be extended to other places? Both of these drawbacks have negative implications for the use of meta-analytic techniques in land change science. Although we have learned much from recent meta-analyses (Angelsen and Kaimowitz 1999; Geist and Lambin 2001, 2002; Lambin et al. 2001; McConnell and Keys 2005; Rudel 2005), the lack of detailed information to allow the meta-analyst to evaluate special and unique aspects of the case study’s place, data quality, and analytical defensibility means that the conclusions from meta-analyses need to be treated tentatively.

This article has three main purposes. First, going beyond meta-analyses, we use the logic of Mill’s method of agreement as it has been used in the macrocomparative...
literature (Ragin 1987) to synthesize results from seven excellent and diverse case studies of agricultural frontiers. Agricultural frontiers are places undergoing relatively rapid transformation in land management practices. This transformational phase is an ideal time to study land cover and land use change (Gutmann et al. 2004). We ask: What are the social and biophysical factors driving the patterns of land use change? Among our findings is that land use conversion is affected more by whether in-migrants are organized into a larger number of households with relatively few members (as opposed to a smaller number of households with more members per household) than by a simple count of the number of in-migrants or a simple population size measure. Agricultural expansion, fueled by a growing population and, typically, transportation improvements, changes the spatial organization of the landscape. Settlement patterns and land cover organization are constrained by biophysical aspects of the environment, national and local policies, and institutional arrangements. The second purpose of the article is to assess the strengths and weaknesses of Mill's method of agreement as well as other approaches to cross-site comparisons for the purpose of making broad inferences about the drivers of land use and land cover change. Given the present availability of detailed case studies, we find severe limitations in all of the case comparison approaches. Finally, building upon and extending recent literature on agent-based models (ABMs; e.g., Parker et al. 2003; Verburg and Veldkamp 2005), we argue that ABMs, using stylized or virtual landscapes and the logic of demographic standardization, can potentially facilitate methodologically defensible comparisons across case studies.

Case Studies of Agricultural Frontiers

“Frontier” is a concept with multiple definitions and connotations. A frontier may be defined as a political boundary (e.g., a border between countries). It may also be defined as a region of new settlement. F. J. Turner’s (1893) descriptions of the frontier suggest fluidity and movement, “a continually advancing frontier line.” In this article, we consider an agricultural frontier to be the front or leading edge associated with people moving into a geographic area, bringing with them land management practices that differ from the land management schemes already in place. It is a process that, by definition, involves land use change. In most cases, the frontier transformation is not just a change in land cover, but also a change in the way of life. Not infrequently, social, economic, and cultural conflicts arise between the newcomers and the indigenous populations, as well as among different groups of newcomers. As such, “frontier,” as an organizing principle, focuses on transformative processes seen in numerous places and times around the world.

Agricultural frontiers are abundant in space and natural resources from the perspective of in-migrants (Lithwick, Gradus, and Lithwick 1996). Agricultural activities and the extraction of natural resources (e.g., oil, wood) can lead to extensification and then intensification of land use, altering native vegetation. As the frontier is settled, there can be reorganization of land or space (Elazar 1996). When all land available for settlement has been spoken for, the external frontier is considered closed. In those locations where settlers claim relatively large plots (e.g., Amazonia), land might be cleared in phases as the household grows and ages. Such clearing of land within a plot after the external frontier has closed can be considered an “internal frontier” (Carr 2002). As internal frontiers close, some in the next generation may use the landscape more intensively, may out-migrate, or may respond in a variety of other ways (Davis 1963; Bilsborrow 1987), and reforestation may occur (Walker 1993; Moran and Brondizio 1998; Rudel, Bates, and Machiguashi 2002).

To describe transformative processes in agricultural frontiers, we draw on case studies of the U.S. Great Plains, Southern Yucatán of Mexico, the Brazilian Amazon, the Ecuadorian Amazon, Montane Southeast Asia, the Wolong Nature Preserve in China, and Nang Rong district in Northeast Thailand. All seven are detailed, in-depth, quantitative, longitudinal studies that integrate spatial, social, and biophysical data, are directed by multidisciplinary research teams, have been funded by multiple, peer-reviewed sources, and have been published in numerous peer-reviewed journals. By studying relatively small, unified areas, our case studies focus in depth on many aspects of the setting (Yin 2003), using a variety of data sources (e.g., remotely sensed data, socioeconomic surveys, historical documents, interviews with key informants, maps, and policy documents), a variety of analytical methods (e.g., descriptive approaches, statistical analysis, and spatial modeling techniques), and guidance from multiple theories (e.g., Life Course Theory, Hierarchy Theory, and Complexity Theory). We follow the logic of Mill’s method of agreement as it is applied in the macrocomparative literature (Ragin 1987), focusing on an in-depth assessment of seven case studies. We use our examination of the cases to extract common results and construct a combined account of population dynamics and land use change in agricultural frontier settings.
The fact that the sites and the studies based on them are diverse strengthens inference. Had the studies under evaluation shared a disciplinary starting point, focused on a particular region of the world, all been from the same time period, examined relationships at a limited range of scales, all been originally forested, or used the same set of tools, these commonalities might be partly or fully responsible for any similarities observed. This is not the situation, however. Rather, the seven case studies represent multiple disciplinary starting points, cover study sites around the world, span varying spatial, temporal, and social scales, and draw on various combinations of data sources and analytic tools. Whatever is common across the studies is thus likely to represent a more general “story,” with potential application to other sites and studies.

The seven study sites are shown in Figure 1 and some of their characteristics are shown in Table 1. The first criterion in selecting these studies was that all the sites be agricultural frontiers during the time period examined by the studies. Second, since land change science is inherently interdisciplinary (Turner 2002; Turner, Geoghegan, and Foster 2003; Rindfuss et al. 2004), the research teams involved needed to be interdisciplinary. Third, we focused on inland sites because of the potentially strong effect of coasts on land use change. We expect that coastal factors and inland relationships would differ. Fourth, since land use change is inherently about change over time, we focused on case studies that had temporal depth in their social and biophysical components. Finally, we selected sites with long-term commitments on the part of research teams so that the synthesis reported here could influence ongoing work. Further, we need to be clear that there was no attempt to coordinate across the case studies. Each was begun for its own set of idiosyncratic reasons and was conducted independently of the others. Many of the investigators from the various studies knew one another so there was some informal influence from one to the other, but there was no formal coordination.

Commonalities and Differences across Cases

In varying degrees, the historical experiences of the seven study sites represent a version of the following “story.” First, there is an influx of new people into an already occupied but relatively “natural” landscape, who bring with them new technology and social organization. Second, population pressure is exacerbated by both natural increase and in-migration. Third, as the newcomers settle and populations expand, how they organize into villages and households matters for their impact on the land. Fourth, settlement coincides with, and indeed is facilitated by, linkage of frontier areas into national
transportation systems. Fifth, agriculture expands and intensifies to support a growing population. In addition, cash crops are frequently introduced. The introduction of cash crops contributes to the marketization of agriculture, the changing face of the landscape, and integration into regional, national, or global markets. Sixth, the consequence of these activities is loss and fragmentation of the native vegetation and a change in spatial organization. Seventh, settlement patterns and changes in land use respond also to environmental constraints, state policy and intervention, and institutional arrangements including land tenure. With the exception of the first point, which has to be the case given our definition of frontier, the rest can be considered hypotheses that hold across our seven sites. The remainder of this section elaborates the elements of this “story.”

In the popular imagination, frontiers are sometimes seen as first encounters with “natural environments.” This is not the case for any of the seven study sites. All involve landscapes that, though dominated by native vegetation, were already occupied. In two cases, the residents were remnants of former civilizations, with the imprint of this history still visible in patterns of land cover a millennium after their collapse. One is the Yucatán site where construction materials used during Mayan times had consequences for forest composition that prevail today (Klepeis and Turner 2001; Turner et al. 2001). The other is Nang Rong, Thailand, where two former civilizations existed, one approximately two millennia ago and the other one millennium ago (Coedes 1963; Murray 1996; Higham and Thosaret 1998; Higham 2001). The evidence that these civilizations existed is still readily discernable on the landscape and visible in contemporary aerial photographs. At the other sites, indigenous populations were already in residence: ethnic minorities in the Wolong and Yunnan, China, sites; hill tribes in Northern Thailand; Native Americans in the Great Plains; and a variety of Amerindian and mixed race groups in Brazil and Ecuador. How the people already living in frontier areas are treated and considered depends on the governments representing the influx of new people. For example, Thailand treated the lowland paddy rice farmers already present in the Nang Rong area as citizens but the mountainous hill tribes in the North as noncitizens (Sturgeon 2004). In the Ecuadorian Amazon and in Yunnan, China, local indigenous peoples were displaced and marginalized by frontier settlement (Holt, Bilsborrow, and Ona 2004; Jianchu et al. 2005).

In most study sites, new people came from other places within the country. International as well as internal migration was the source of new settlers in the historical Great Plains, an exception to the more general picture. Modern nation states provide a regulatory context in all instances. Population movements into frontier areas were specifically sponsored by national

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**Table 1. Characteristics of the frontier case study areas**

<table>
<thead>
<tr>
<th>Study area</th>
<th>Size (km²)</th>
<th>Temporal scope</th>
<th>Web site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazilian Amazon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ingá, Pará</td>
<td>165.90</td>
<td>1986–1997</td>
<td></td>
</tr>
<tr>
<td>Rondônia</td>
<td>30.00</td>
<td>1988–1998</td>
<td></td>
</tr>
<tr>
<td>N. Ecuadorian Amazon</td>
<td>17,000.00</td>
<td>1974–2002</td>
<td><a href="http://www.cpc.unc.edu/projects/ecuador">http://www.cpc.unc.edu/projects/ecuador</a></td>
</tr>
<tr>
<td>Southern Yucatán</td>
<td>1,870.00</td>
<td>1969–1998</td>
<td><a href="http://earth.clarku.edu/lcluc/">http://earth.clarku.edu/lcluc/</a></td>
</tr>
<tr>
<td>Wolong Nature Reserve</td>
<td>2,000.00</td>
<td>1965–1997</td>
<td><a href="http://www.csis.msu.edu/home.htm">http://www.csis.msu.edu/home.htm</a></td>
</tr>
<tr>
<td>Yunnan, China</td>
<td>700.00</td>
<td>1951–1999</td>
<td></td>
</tr>
<tr>
<td>Xishuangbanna, China</td>
<td>108.35</td>
<td>1965–1992</td>
<td></td>
</tr>
<tr>
<td>Baka, China</td>
<td>88.00</td>
<td>1965–1992</td>
<td></td>
</tr>
<tr>
<td>Mengsong, China</td>
<td>100.00</td>
<td>1965–1993</td>
<td></td>
</tr>
<tr>
<td>Menglong, China</td>
<td>108.25</td>
<td>1962–1992</td>
<td></td>
</tr>
<tr>
<td>Ang Nhai, Laos</td>
<td>26.90</td>
<td>1950–2000</td>
<td></td>
</tr>
<tr>
<td>Ban Lung, Cambodia</td>
<td>185.00</td>
<td>1953–1996</td>
<td></td>
</tr>
<tr>
<td>Ban Khun, Thailand</td>
<td>95.00</td>
<td>1959–1983</td>
<td></td>
</tr>
<tr>
<td>Mae Tho, Thailand</td>
<td>100.00</td>
<td>1954–1995</td>
<td></td>
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</tbody>
</table>

*Upland area of Cambodia, Laos, Myanmar, Thailand, Vietnam, and Yunnan Province, China.
governments in Brazil, China, and Mexico, and were implicitly encouraged elsewhere. In the northern Ecuadorean Amazon, the region was perceived as an area with almost infinite space and resources, providing an “escape valve” to relieve socioeconomic imbalances in other regions of Ecuador (Oberai 1988; Pichón and Bilsborrow 1999).

It is worth noting that not all of the original settlers stay. For example, a survey of 402 farming households in Altamira, in the Brazilian Amazon, showed that only 30 percent of the original colonists remained on their plots (Siqueira et al. 2003). Timing of arrival may be an important part of the selectivity of those who remain in the area when the site ceases to be a frontier. Early arrivals, if knowledgeable, select the best land (Moran et al. 2000; Sylvester and Gutmann, forthcoming). The implications of turnover and selective retention of settlers have not yet been fully examined.

The migrants brought their own land use practices, which influenced where they settled as well as what they did with the land. Gutmann and his colleagues (2004) argue that within the environmental constraints of climate, topography, and soils, ethnicity made a difference in land use on the Great Plains. As the percentage of county residents who were German increased, the proportion of land devoted to wheat, rye, and oats increased. In the Yucatán, most of the ejidatarios migrated from the Gulf Coast lowlands of Mexico where chili production for a national market had been common. Chili is now a principal market crop in the Yucatán (Turner et al. 2001). The Yunnan, China, site provides another example. There was a significant expansion of rubber cultivation led by state-owned farms inhabited by resettled Han Chinese (Jianchu et al. 2005). Some of the local minority groups (Dai, Hani, and Bulang) participated in the expanded rubber cultivation, but others were displaced by it. There are instances where the knowledge and practices brought by the settlers contributed to failure rather than success. In the Brazilian Amazon, many settlers lacked the necessary agricultural knowledge and skills, and therefore yielded higher failure rates than indigenous peoples did (Moran 1981).

As newcomers settle and populations expand, organization into villages and households affects patterns of land use and land cover change. The number of households given the size of the overall population is crucially important (Liu et al. 2003). Even when rates of population growth are not high, the number of households can continue to grow rapidly, with household fissures resulting in more households with fewer members (Entwisle et al. 2005). Land use conversion appears to be more closely tied to household formation than to growth in population size. As the number of households grows, there may be pressures to create new plots to support them.

Household size and characteristics (such as the ratio of children to working age adults) influence land cover and land use in settings where agriculture is neither very mechanized nor market-oriented (Walker et al. 2002; Vance and Geoghegan 2004; VanWey, Brondizio, et al. 2004). Moran and colleagues (Moran, Siqueira, and Brondizio 2003) have hypothesized an effect of household life cycle (e.g., the progression from a young couple just starting to have children to an older couple with most or all of their children out of the household) in conjunction with time since initial settlement that recognizes changes in size, age, and sex composition (McCracken et al. 1999). Initially, households plant annual crops; a little later, annuals, perennials, or perhaps, some pasture clearing; then they maintain pasture, perennials, and potentially reduce the amount of land in use. Over time, through the aggregation of these patterns, there are predictable shifts in the amount of land in use and also in the composition of land use. Support for these interrelated hypotheses is mixed (e.g., VanWey, Brondizio, et al. 2004). Either way, it is worth noting that smallholders are the primary settlers in all the sites studied.

The spatial arrangements of dwelling units vary from site to site in important ways. Households in the Asian sites tend to be organized into village clusters. When this is so, land use change radiates out from the center of settlement (Entwisle, Rindfuss, et al. forthcoming). Settler dwelling units in the North and South American sites are distributed on the landscape, typically in the classic “fishbone” pattern with long, thin land parcels extending from either side of the road. The form and pattern of settlement have important implications for the rapidity and shape of land cover change. For example, a “fishbone” pattern of deforestation tends to result when households occupy the land they farm and this land is oriented toward a transportation grid. The composition of the landscape may be more sensitive to household size and composition when households are distributed (as in the Brazilian Amazon; McCracken et al. 1999) than when they are clustered (as in Nang Rong, Thailand; Entwisle et al. 2005), but the evidence on this point is not conclusive.

Expansion of the transportation system is important to land use change. In the Yucatán, a major highway was built during the 1960s linking the region to central Mexico (Klepeis and Turner 2001). In Thailand, Nang Rong was linked into the national highway system at about the same time (Entwisle et al. 1998). The initial impetus for the Brazilian study was a desire to study the
Montane Southeast Asia is interesting from the standpoint of road construction because of a planned road linking China, Laos, and Vietnam, thereby providing a prospective look at transnational road impacts. As Vance and Geoghegan (2004) observe, roads subsidize the costs of encroachment and clearance. There is more deforestation in areas closer to roads (Turner et al. 2001; Pan and Bilsborrow 2005). Patterns of road building (e.g., traditional orthogonal road network) when combined with certain policies of land allocation (such as smaller plot sizes) encourage forest fragmentation (Rudel and Roper 1997; Batistella, Robeson, and Moran 2003). Railroads were instrumental in opening up the Great Plains (Hudson 1985) and areas such as southeastern Brazil (Dean 1995). A deep water port was recently built adjacent to a study site in Santérem, the Brazilian Amazon, which opened the area to large-scale, mechanized agriculture, specifically soybeans (VanWey, Brondizio, et al. 2004).

Agriculture expanded in all of the study sites, in part to support a growing population and frequently with new crops in response to expanding markets. The introduction of new crops coincided with a commercialization of agriculture and the shift from a subsistence economy. As the transition from subsistence to market agriculture occurs, those who use the land choose to or are forced to specialize in crops where they have a comparative advantage—a competitive edge—typically leading to intensification (a decrease in fallow times and an increase in the use of inputs) and simplification (a reduction in the number of crop varieties). The competitive advantage is related to biophysical factors (such as soil type, availability of water for irrigation, and climatic factors) and social factors (such as distance to market, transportation costs, and help available for agricultural tasks).

The consequence of agricultural expansion was loss of forest, or, in the case of the Great Plains, loss of prairie. Loss of forest has direct consequences for species habitat (Vitousek et al. 1997; Liu et al. 2003) and therefore for biodiversity. The spatial structure of landscapes was also altered (e.g., Walsh et al. 2001; Batistella, Robeson, and Moran 2003), although this is not as well documented across the study sites as are crop compositional changes. For the northern Ecuadorian Amazon, rapid population growth was associated with substantial subdivision of plots, which in turn created a more complex pattern of forest and agricultural crop land (Pan et al. 2004). Key factors predicting landscape complexity are population size and composition, expansion of the road and electricity network, size and age of plots, and topography. On the other hand, swidden cultivation involves forest fragmentation (e.g., Jianchu and Wilkes 2003). If swidden agriculture is the point of comparison, then the introduction of more permanent cultivation may lead first to an increase in forest fragmentation, until a threshold is reached. Once this threshold is reached, agricultural use dominates the landscape and fragmentation declines.

How the “story” of settlement and changes in land use unfolds in any given study site depends on environmental constraints, state policy, and institutional arrangements. The sites vary in climate, soils, topography, elevation, native vegetation, and disturbance regimes—conditions that place fundamental constraints on settlement patterns and agricultural systems. For instance, given an undulating topography, the need for low-lying lands for paddy rice cultivation combined with the need for more elevated sites to locate houses helps explain the clustering of dwelling units into villages in Nang Rong, Thailand (Entwisle, Edmeades, et al. forthcoming). Environmental constraints also affect how the land is used, as is evident in the Great Plains where water availability is the major control of cropland feasibility (Burke et al. 1994). Settlement also responds to differences in ecological disturbance regimes; recurrent droughts and related dust storms contributed to population declines in the Great Plains (Deane and Gutmann 2003). In Brazilian and Ecuadorian Amazonia, soil characteristics are important factors in regional land use variability (Pichón and Bilsborrow 1999; Moran et al. 2000). Environmental constraints also condition impact (Batistella, Robeson, and Moran 2003; Pan et al. 2004). Within sites, deforestation is less likely at higher elevations (Turner et al. 2001) and more likely at sites with flat topography (Pan and Bilsborrow 2005).

Differences in state policy have influenced development of the seven agricultural frontier sites. Settlement programs, road construction, and tax incentives have encouraged frontier advancement in some instances, whereas national parks and conservation programs have discouraged it in others (Messina et al. 2006). These effects are evident in the contrast between Wolong, China, and the Brazilian Amazon. In the former case, settlement and in-migration are controlled, a national park protects some of the native vegetation, and out-migration is encouraged. In the latter case, the Brazilian government participated directly in the settling of the Amazon through the recruitment of settlers, plot assignments, and the provision of loans and technical assistance, as well as the construction of the TransAmazon Highway and tax incentives for cattle ranching.

Governments can intervene to discourage settlement, as through state-claimed forests in Yunnan, China
(Chun-Lin et al. 1999), and through restrictions on immigration to the Wolong Panda Reserve, the Culakmul Biosphere Reserve in the Yucatán, and the formation of the Cuyabeno Wildlife Reserve in the northern Ecuadorian Amazon. The evidentiary base for these seven case studies is not yet sufficient to know if the creation of reserves and protected forests retards rates of land use and land cover change, but it is consistent with results reported by Nepstad and colleagues (2006) suggesting that reserves have a protective effect.

Settlement patterns are also shaped by institutional arrangements, especially those regarding land tenure. Communal arrangements are present in many of the sites. In the Brazilian Amazon, for instance, land in the lower Amazon that had been given to selected individuals in large parcels by the Portuguese government in the nineteenth century was expropriated by the Brazilian government in 1987, subdivided, and given to local (“indigenous”) families who were allowed to occupy and use the land, but not sell it (Futemma and Brondizio 2003). Some evidence suggests that communally held land helps maintain lower levels of forest fragmentation (Batistella, Robeson, and Moran 2003). Land in China is held communally as well: households have “use rights” to land which they lease to others. Land tenure arrangements are undergoing change in some sites, and the implications are not yet known. For example, in Mexico, after a constitutional change in 1992, ejido lands could be bought and sold, although with this change it is not yet clear that an active land market has emerged.

We began this section with a list of common findings across the seven sites; we end with uncertainties in our understanding of the causes of land use change. These uncertainties emerged as a result of our review of the seven case studies. First, the extent to which environmental conditions influence some settlers to leave, and the feedback implications for subsequent land use change are not known. Across the case studies, there are examples of matches and mismatches between settlers' premigration land use practices and the frontier biophysical conditions postmigration, but the range of examples is too small to permit meaningful generalization. Second, it is unclear the extent to which having a fish-bone versus nucleated village pattern of settlement affects the trajectories of land use change. Third, how do initial conditions in the frontier area, including indigenous land tenure and management, affect subsequent land use by newcomers, and to what extent would alternative land use policies have influenced land use change? Finally, under what circumstances will land-holding consolidation and agribusiness emerge? For many of these issues, the crucial variables are constant within a given site. We now turn to a discussion of the limitations of case studies in “seeing” the effects of variables that are a constant within a site.

### Site Constants, Statistical Modeling, and Inference

Even though there are common stories across the seven sites, in order to push forward our understanding of population and land use change in frontier areas, it will be important to extend and add dimensions to such narratives, to express them more formally, and to statistically evaluate their generalizability. Understanding the causes and consequences of land cover and land use change in and across our seven frontier sites is constrained by two factors: (a) some important variables are constant across individual sites and (b) some important changes affect entire sites. We discuss each in turn, but both lead to the same problem, namely, the effects of these kinds of variables are neither statistically detectable nor methodologically provable unless a relatively large number of study sites with comparable data are available for analysis.

Consider first the constants throughout individual sites, using biophysical aspects for discussion purposes. The Nang Rong, Brazil, Ecuador, and Southern Yucatán sites are all tropical climates. This means that a variety of plants/crops will not grow there. So if world demand for a crop that only grows in temperate regions increases, or if some kind of temperate climate tree is found to be especially efficient at sequestering carbon, none of these tropical sites could respond. Further, if residents of these tropical sites want to incorporate crops from temperate areas into their diet, they need to buy them from temperate sites.

Now, contrast this situation with variables within each of the sites, again using biophysical variables as examples. Within the Wolong site, Liu and his colleagues (Liu et al. 1999) estimate that without human interference, 41 percent of the reserve would have a forest/bamboo mix suitable for panda habitat. Only part of the Nang Rong site is suitable for growing cassava. The Great Plains site has considerable intra-annual to decadal variation in temperature and precipitation, allowing analysis of biophysical causes of the 1930s dust storms (Cunfer 2002; Sylvester and Gutmann, forthcoming). For each of these three examples, variability within the site on some factor, say factor X, allows the researcher to examine the relationship between factor X and land cover/land use.

The second issue is change that affects the dynamics of the entire site. For example, in Santarém, Pará, Brazil,
a deep water port was completed in April 2003 that allowed agricultural products grown there to more easily enter national and global markets (VanWey, D’Antona, and Adams 2004). It is argued that in anticipation of and subsequent to its completion, farmers, many from outside Santarém, moved to consolidate land holdings so that mechanized soybean production was possible (VanWey, D’Antona, and Adams 2004). In Montane Southeast Asia, there are plans to construct a road that links southwest China, northeast Burma, northern Thailand, and northwest Laos. It is anticipated that crops now grown for the Thai market in northern Thailand, such as cabbage, will be grown in southwest China, where the climate is better suited to growing cabbage; in turn, northern Thailand will likely convert to growing semitropical crops for the Chinese market. The major hurricanes that hit southern Yucatán in 1955, 1987, and 1995 are reported to have had an impact on the structure of the forest as a consequence of damaging winds and secondary effects caused by landslides and other disturbance agents (Klepeis and Turner 2001).

Various government policies provide other examples. The formation of the Cuyabeno Wildlife Reserve in the northern Ecuadorian Amazon in 1979 was designed to protect a region of critically important ecological and cultural diversity. Despite its status as a protected area afforded by the Ecuadorian government, there have been land cover and land use changes and related conflicts in the Cuyabeno and its periphery associated with road development, colonization, and the direct and indirect effects of urbanization (Mena et al. 2006; Messina et al. 2006).

Consider the establishment of the Wolong Reserve in 1975 as an illustration of the problem of establishing causal links between a change that affects an entire site and land cover and land use change. Measures of the proportion of the Reserve in panda-suitable land cover are available for well before the establishment of the Reserve (1965), at the time of its establishment (1975), and well after (1997). The temporal ordering of the data and the proportion of the Reserve that has panda-suitable land cover suggests that establishing the Reserve did not meet its stated goal of preserving panda habitat (Liu et al., “Ecological Degradation,” 2001). But this logic assumes that the establishment of the Reserve is the only thing that changed over the thirty-two years, which, of course, is a highly unlikely scenario. What else might have changed? Possibilities include change in the size, structure, and distribution of the human population in the Reserve (e.g., Liu et al. 2003), the advent of tourism, an increase in the size of the domestic pig population,6 changes in the cost and availability of agricultural technology, and various government policies, including land reform in 1979.7 The general point, and a point that applies to all seven sites, is that when one change affects the entire site there are likely to be numerous other changes, including many that are unmeasured. Attributing land use change to just one of them is a risky bet.

What is needed is a way to understand the implications of macro forces and their consequences. A standard social-demographic approach is to use multilevel statistical modeling, where the first level consists of microlevel units (i.e., households, pixels, or farm plots) and the second level consists of macrolevel units (in the case of the present discussion, agricultural frontier sites). With this setup, it is possible to explore differences across sites associated with designated site characteristics as well as possible interactions or cross-scale effects. A variation is to use an approach that merges time series analysis with multilevel models (Deane and Gutmann 2003). Either way, a sufficient number of units at both levels are needed to support estimation. If the interest is in differences across sites, the number of sites constrains the variables that can be considered. With seven sites, there are six degrees of freedom and therefore the possibility of considering six contextual variables in a multilevel design. However, few would have much confidence in results based on such a design. A moderately large number of macro units (study sites) are necessary to be in a position to tease out the effects of variables that characterize them. (How many sites would be needed? There is no simple answer to this question, but most would agree that the more the better.)

An alternative approach, not constrained by small numbers of sites, would apply the principles of qualitative case comparison to make inferences about macro forces and their consequences in frontier settings. Indeed, extracting commonalities among the case studies as we have done follows the logic of one qualitative approach: Mill’s method of agreement. According to the method of agreement, when all cases share an outcome (in our case, a rapid conversion of forest/grasslands to agricultural use), causal conditions that are shared among the cases are the likely cause(s) of that outcome. The fact that the cases themselves are so diverse (from the historical U.S. Great Plains to a giant panda reserve in China) strengthens inference in this design. Inference would be strengthened even further if conditions shared among the positive cases are demonstrably not present in a set of negative cases, an application of Mill’s indirect method of difference. The identification of negative cases is a major challenge, however. The success of the method depends on selecting negative cases that are as similar as possible to the posi-
ative ones—for example, the same site before a rapid conversion of forest/grasslands to agricultural uses. This is difficult because data are not usually collected until there is something interesting to study. A more recent approach that incorporates the logic of Mill’s methods and allows for uncertainty of classification and measurement is qualitative case analysis (QCA), also known as fuzzy-set social science (Ragin 2000). All of these approaches claim to handle small numbers of cases or sites. However, as of yet, there is no way to incorporate the full quantitative richness of the microlevel detail within sites in the macrolevel qualitative case comparisons. This is a major drawback as the processes we are trying to understand fully involve both levels (and more).

In the face of these challenges, we turn to microsimulation approaches, especially ABMs or multiagent models (Parker et al. 2003; Deadman et al. 2004; Evans and Kelley 2004). Simulations can be constructed for a variety of purposes, such as to predict the course of future change, to advise policymakers, or to explain the past. Our use of these models is a little different. In our application, the focus is explanation, but the simulation operates as a kind of “laboratory” within which various “experiments” can be run. As we explain in the next section, of interest are experiments exploring the consequences of differences and changes in site conditions in frontier environments for land use and land cover. Microsimulations take full advantage of the richness of the microlevel detail within sites without being hampered by a small number of sites.

Agent-Based Models of Land Use and Land Cover Change

So far, we have argued that understanding the determinants of land use change is critical for a variety of scientific and policy reasons, including global climate change, human health and vulnerability more broadly defined, and biodiversity. Human behaviors are fundamental to land use change, and the case study approach is currently the most feasible way to bring empirical data on human behavior to bear in integrated studies of land use change. Mill’s method of agreement approach showed a variety of commonalities across the seven sites. But our review of these seven also points to the limitations of using only case studies to generalize. Some factors thought to be important in a given case are constant for that case and hence it is impossible to demonstrate that they had a causative effect.

As a further complication, measurement standardization does not exist across studies. Case studies of land use change collect quite different data depending on the characteristics of the study site and the disciplinary composition of the research team (Rindfuss et al. 2004; Moran and Ostrom 2005). There are relatively few longitudinal case studies of land use change, and attempts to standardize protocols across case study sites have not yet been successful. Without a massive infusion of funding, following a centralized approach like the World Fertility Survey in the 1970s and 1980s (e.g., Cleland and Scott 1987), multilevel modeling approaches to understand the effects of variables that are relatively constant across a site (like climate) or that change in such a manner that the change affects the entire site (such as a new and efficient transportation link to the outside world) are not feasible. Even if there were standard protocols, the small number of case studies would produce a degrees of freedom problem. Finally, running true experiments is unthinkable. So the question is: How should the field capitalize on the rich and detailed case studies that exist and move toward generalization?

We argue that spatially explicit, multiagent systems models offer a promising way to incorporate results from case studies in such a manner that simulations, essentially spatial-statistical experiments, can be run. The advantages of spatially explicit, multiagent systems models have been discussed in a number of places (e.g., Parker et al. 2003; Verburg and Veldkamp 2005). Here we discuss their potential for comparative research across a limited number of dissimilar sites.

Spatially-explicit modeling methods are well suited to the exploration of spatial factors in land cover and land use systems within the concepts of complexity (Messina and Walsh 2001, 2005; Parker et al. 2003; Walsh et al., forthcoming), and here we consider ABMs. ABMs are defined by a set of autonomous decision-making entities or agents (e.g., individuals, households, corporations), an environment that agents share, rules that define relationships between agents and their environment, and rules defining the sequence of actions in the model (Berger 2001; Ligtenberg, Bregt, and Van Lammeren 2001; Berry, Keil, and Elliott 2002). In our case, agricultural frontiers constitute the shared landscape where the actions of one agent can affect those of others. Agents can differ in fundamental ways. Their interactions are dynamic. As their characteristics change, agents adapt and evolve to a changing environment, learn from their experiences through feedback, or “die” as they fail to alter behavior relative to new conditions or factors. A key characteristic of agents is autonomy, which implies that agents have control over their actions to achieve their goals using some degree of cognition that ranges from a simple stimulus-response to the point...
where agents are proactive, take initiative, and have larger intentions (Parker et al. 2003).

The Wolong Nature Reserve case study provides an example of agent-based modeling (An et al. 2005). The types of agents considered are individuals, households, pixels, and management agents. Wood is the dominant fuel used for cooking and heating in Wolong, and the areas where pandas prefer to feed are also the areas where the population prefers to gather fuel wood. Among the findings is that a modest electricity subsidy of 0.05 Yuan would cut panda habitat loss by 50 percent over a twenty-year period.

The potential of multiagent models to support meaningful comparative analysis and generalization from a limited set of detailed cases can be understood in terms of standardization logic familiar in social demography (Shryock and Siegel 1976; Preston, Heuveline, and Guillen 2001). According to this approach, if results for two or more sites differ, it is because of differences in the characteristics of agents and the land, differences in the relationships or rules encoded in the model, or both. For instance, according to some studies, land use decisions by households depend on stage in the family cycle (e.g., McCracken et al. 1999). If this is generally true, then differences between sites in the size and demographic makeup of households could lead to different patterns of land use even if everything else about the sites and the models were the same. In the language of social demography, this is a “composition effect.” If, however, the effect of family cycle on land use decisions varies between sites (i.e., the “rules” of the model differ), this is a “rates effect.” Differences between the land use and land cover dynamics of different sites thus reflect various combinations of composition effects, rates effects, and interactions between them.

The logic of standardization helps organize our thinking about why patterns might differ and provides a starting point for building scenarios to explore these differences. It is possible to include actual geographic data from the different sites, as well as actual sociodemographic characteristics of agents, as long as the variability is within the limits imposed by the verification process. The inclusion of different geographic settings and population distributions allows a direct contrast across sites to explore their relevance. Agent-based simulations are a means for exploring a myriad of differences across sites. The degrees of freedom problem that arises in a comparative statistical analysis of seven sites is not a problem with this agent-based modeling approach using varying scenarios.

To illustrate how ABMs could help improve our understanding of the causes, correlates, and consequences of land cover and land use change we consider an example related to differences in social organization—specifically, whether households live in dwelling units clustered in nucleated villages, or occupy dwelling units on the parcels of land they work. A priori, we anticipate that nucleated settlement patterns may lead to a more homogenous pattern of land cover change radiating out from the village. On the other hand, when households live on the parcels of land they own or control, the overall pattern of land cover change may be patchier and more linear. When households live in nucleated villages they may be more willing to pool resources to build connector roads or other infrastructure elements, which in turn could affect further in-migration as well as the retention of previous migrants. Households living in nucleated villages probably interact with one another more frequently than households that are dispersed across the landscape. Hence, agricultural innovations probably diffuse more rapidly in settings where nucleated villages predominate.

The standardization approach can be adapted to running ABM scenarios—that is, model experiments using runs of ABMs where agents, rules, or environments are perturbed. Consider first using virtual landscapes, which are landscapes that have been abstracted and simplified to capture the essence of place. Models within a virtual landscape allow investigators to explore the conditions in which functional integration may occur and to estimate conditional probabilities (Lansing 2002). Virtual landscapes can be developed to mimic “real” landscapes by retaining key elements of geographic settings that capture the spatial and compositional character of places within a simplified representation. Fractal patterns may be used to describe the spatial organization of real versus virtual landscapes, and percentages of land use and land cover types of real landscapes can be used to define virtual landscapes. Agent characteristics and agent interactions can be simplified so that a limited and well-specified set of pattern-process relationships can be addressed. Joining virtual landscapes to those calibrated empirically for individual case studies offers a means of generalizing across cases and generating theoretical insights. Developing a set of scenarios to operate within a virtual and ABM environment serves to test likely propositions, discern theoretical implications, examine underlying causal mechanisms, test the sensitivity of relations to various perturbations, and consider the types and direction of feedbacks (Henrickson and McElvee 2002).

Imagine a virtual landscape that captured the essence of one site, including households living in nucleated villages. For the sake of discussion, let this site be the
Wolong site. This virtual landscape would include a few primary land cover types, a typical road and river network, basic topographic configuration, characteristic attributes and behavior of agents (households, primarily), and the nature of interactions. For some scenarios, households could be dispersed such that they are living on their land parcels. Further, in some scenarios, for both nucleated and dispersed settlement possibilities, the rules could be perturbed regarding the amount of interaction and imitation across households. One could repeat the exercise using an Amazonian virtual landscape. Comparing the results, it might be that the expectation of more land cover homogeneity in nucleated village areas is found; but it also may be that biophysical factors trump variations in settlement type.

One potential outcome from such ABM experimentation is that the results are sufficiently clear and illuminating that the investigators simply need to write about them. Alternatively, and perhaps more likely, the results are suggestive rather than conclusive. Then, it is possible to draw on expert knowledge from the project team, do additional fieldwork, and/or conduct additional analyses of existing data to adjudicate among the suggestive ABM results. And it may be that the results suggest promising lines for additional research, including new data collection.

A virtual landscape also offers the opportunity to directly model other factors potentially influencing land use and land cover change. Policies are a good example. The inclusion of constraints on activities, such as the restricted migration to the Wolong Reserve in China, or changes in land tenure regimes as in the case of the Southern Yucatán, offers the possibility to answer questions that are relevant to policy and natural resource management. Further comparisons can be modeled, such as case studies that illustrate different land use practices that migrants bring to the frontier. In the virtual frontier, these practices and their impacts on the landscape can be contrasted, maintaining a range of relevant factors as constant to create simulations where policy interventions can also be tested.

A significant lesson of complexity theory for land use and land cover change research is that complex systems contain more possibilities than can be actualized, and their descriptions are not constrained by an a priori definition (Luhman 1985). In agricultural frontier settings, multiple stakeholders interact to create a dynamic land use system that is space and time dependent (Walsh et al. 1999), where feedbacks between human activities, land use change, and ecological dynamics produce nonlinearity (Malanson, Zeng, and Walsh 2006a, 2006b). A complex system not only evolves through time, but its past is co-responsible for its present behavior through mechanisms such as path dependence and state cycling (Cilliers 1998). Experiments involving the use of ABMs and virtual landscapes make it possible to consider a wide range of alternative futures.

Conclusion

This article’s synthesis of seven agricultural frontier case studies highlights commonalities across them, including the importance of new crops, technologies, and types of social organization. The roles of environmental constraints, state policies, and institutional arrangements such as land tenure are evident everywhere, but the specifics vary across sites. The frontier period also marks closer linkages to regional, national, and global markets, with resulting impacts on land cover and land use as decision makers attempt to maximize their results relative to the opportunities in these broader markets.

From the perspective of emerging land change science, the existence of these commonalities is important—indeed comparability, commonalities, and synthesis are the grist of science. Yet this review drives home the limitations of relying on in-depth, quantitative (or qualitative), longitudinal case studies that incorporate spatial, biophysical, and social data. Sites often have unique biophysical and social features that need to be addressed in data collection and analysis, yet doing so makes generalization difficult. To minimize such problems, we restricted our review to cases studies of frontier sites away from coastal areas and conducted by interdisciplinary research teams. Despite employing these restrictions to make the sites more comparable, their contextual diversity is evident, limiting our ability to generalize.

The current situation represents a type of “the cup is half full” situation. On the one hand, our understanding of the forces of land change processes in frontier situations has benefited enormously from these seven ongoing case studies. On the other hand, it is clear that the branch of land change science that is concerned with fine-grained relationships that exist between individual social actors and individual land plots, influenced and constrained by environmental conditions, policy, institutions, and the like, needs to add methodologies that will permit and foster hypothesis testing and generalizability across sites. It seems self-evident that true experimentation is not a fiscally or morally acceptable option. The field will, of course, take advantage of natural experiments as they arise. The Montane Mainland Southeast Asia projects that capitalize on the planned
road construction linking China, Laos, Burma, and Thailand are an example. But even with additional case studies and taking advantage of natural experiments, additional strategies are needed if the field is to be able to generalize and perhaps move toward prediction.

In our view, the next logical step for the field is to bring the details and results from the case studies into an agent-based modeling approach. The creation of a “laboratory” where the essence or abstraction of sites is used to create a virtual environment allowing ABMs to run, altering agents, rules, or environment to “experimentally” test hypotheses and generalize across place. Doing so will require closer cooperation between those on the one hand who have specialized in collecting and analyzing case study data, and those on the other hand who have specialized in constructing ABMs but have not had access to linked, fine-grained spatial, biophysical, and social data. The challenges are many, but the opportunities for obtaining fresh insight on critical pattern-process relations at frontier settings and beyond, for conducting synthesis across multiple sites, and for testing “what if” scenarios of land change offer considerable motivation for continued study.

Importantly, ABMs are based on the precepts of complex systems, which allow exploration of issues of stability and resilience to perturbations in coupled human-natural systems. Across disciplinary perspectives (Lansing 2002) and through the use of scenarios generated by simulations (Henrickson and McKelvey 2002), ABMs are philosophically armed for the development of a model-centered science (Henrickson and McKelvey 2002). Simulation is useful for understanding frontier environments—commonalities and differences in their structure, function, and evolution across space and time as well the conflicts that frontiers generate. ABMs can be used to model survival strategies such as cooperation and self-interest behavior among agents (Danielson 2002), which in practice avoid or generate conflicts related to resource use. Agent-based simulations also provide flexibility and considerable analytical power to examine pattern and process relations within the context of theory and practice, including policymaking.

Acknowledgments

The development of this article was supported in part by a National Institutes of Health (NIH) Roadmap Initiative grant (HD051643-01) to the Carolina Population Center (CPC), University of North Carolina at Chapel Hill. While this article was being written, Christine M. Erlien was supported by a NSF IGERT grant (DGE-0333193) and a NASA grant (NCC5-699); Clark Gray was supported by a NSF IGERT grant (DGE-0333193) and a NSF graduate fellowship (DGE-0202736); and Carlos F. Mena was supported by a NASA grant (NNG04GR12H). Ronald R. Rindfuss was supported by the Centre for Advanced Study at the Norwegian Academy of Science and Letters when work on this article was in its final stage. Helpful comments on an earlier version were received from Richard Bilisborough, Eduardo Brondizio, Jefferson Fox, Jacqueline Geoghegan, Steven Manson, George Malanson, Ken Sylvester, members of the CPC population-environment seminar, and five anonymous reviews. We are also grateful for general support from CPC and administrative support from Mary Williams.

Notes

1. Land cover refers to what can be seen remotely, from satellite data or aerial photographs. Land use refers to how the land is actually used. For example, satellite data might indicate the presence of a forest, but this forest could be an orchard or a pristine stand of hardwoods.
2. Mill's method of agreement involves using cases that share an outcome (in our article, a rapid conversion of forest/grassland to agricultural use), and the cases are diverse with respect to location and other attributes.
3. We focus on rural frontiers. There are, of course, urban frontiers as well, as cities and suburbs expand into their rural countryside, and as new cities are created.
4. For any specific site, there may be multiple overlapping and contested narratives about land use and land cover change and its causes, associated with multiple relevant stakeholders. Our aim is to extract from these site-specific accounts the elements that are common across sites and to construct from them a more general “story” that applies across the sites.
5. In Kunming, China, beginning with major land reform in 1978, farmers received twenty-year use rights to their agricultural land. Since then, they have had the right to lease the land out to others for periods shorter than their lease. These original leases were renewed starting in 1998 for periods of thirty years. Rights to forest lands were given to farmers starting in 1982/83. These rights were generally for fifty years, and again farmers have the right to lease land to others. The sale of land is illegal (Fox, private communication, 28 July 2005).
6. Fuelwood is needed to prepare feed for the pigs, and this fuelwood comes from the forest, leading to a loss of panda habitat.
8. The validity of inferences based on these qualitative designs has been questioned (Geddes 1990; Lieberson 1991; King, Keohane, and Verba 1994) and is still a matter of some controversy.
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