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Long-Term Ecological Changes in the Densely Populated Rural Landscapes of China

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Asia’s densely populated agricultural landscapes are undergoing unprecedented ecological changes caused by population growth and adoption of industrial technologies such as fossil fuel and chemical fertilizer. Covering nearly $6 \times 10^6 \text{ km}^2$, these landscapes now release more than half of global greenhouse gas emissions from agricultural land and biomass fuel. Measuring ecological processes and their changes in these highly heterogeneous “village landscapes” is made difficult by their very small scale of management, with households typically managing many small plots using a wide variety of inputs and methods. This chapter describes the global extent of village landscapes, characterizes their spatial heterogeneity, establishes appropriate scales for ecological change measurement, and demonstrates methods developed to measure long-term ecological changes across village landscapes in China. Reliable measurements of ecological change in village landscapes can be made by integrating high-resolution ($\leq 1 \text{ m}$) landscape change measurements with household-level resource management data. These methods link local land use practices with regional and local ecological change, potentially aiding land use decision-making, but require far greater research effort than conventional land use measurements based on 30–1000 m resolution imagery and county or provincial data. Therefore, a multi-scale sampling and analysis system was developed to integrate local and regional data for estimating regional change across village landscapes in China. The strengths and weaknesses of this approach in measuring and mediating the impacts of ecological changes in densely populated landscapes are discussed in light of preliminary results indicating that population increase and modernization are increasing carbon sequestration across these landscapes.

1. INTRODUCTION

Asia’s densely populated rural landscapes encompass some of the world’s most intensively managed ecosystems, including not only agroecosystems, but also settlements, forests and other semi-natural ecosystems managed by the populations of rural hamlets and villages. Though many of these landscapes have been densely populated and intensively managed for centuries or longer, recent population growth and the adoption of industrial technologies such as fossil fuel and synthetic nitrogen fertilizer are profoundly altering land use and ecosystem processes across large areas of Asia.

This chapter describes the extent and global importance of Asia’s densely populated rural landscapes and introduces a multi-scale approach to the measurement of long-term changes
in land use and biogeochemistry across these landscapes in China, with the dual purpose of demonstrating methods for measuring these changes at the very fine scales at which they occur and the scaling of local measurements to make regional and global estimates. By this approach, the global and local consequences of increasing populations and technological inputs can be investigated across densely populated landscapes, where changes in ecological processes such as carbon sequestration, primary productivity, and biodiversity are unlikely to follow trends observed for larger-scale processes such as tropical deforestation or urbanization. This chapter focuses primarily on changes in carbon and nitrogen biogeochemistry, but refers in general to changes in ecological processes when describing methods, as these should apply equally well to the measurement of changes in biodiversity, hydrology, and other local ecological variables.

1.1. The Global Importance of Asia’s Densely Populated Rural Landscapes

More than half of the world’s population lives in Asia, and more than half of this population is agricultural (Table 1). This is apparent when maps of population density and agricultural land cover are compared: dense populations are extensive in Asia and correspond well with agriculture, more so than in other regions of the world (Figure 1, a and b). These dense rural populations manage local landscapes for income, food, fuel, fiber, and shelter, creating “village landscapes” with the complex patterns of integrated landscape management needed to meet the diverse needs of local populations based on local resources.

1.1.1. An ecological definition of village landscapes. We define “village landscapes” as areas where dense human populations intensively manage local land and water resources for agriculture and other production based on natural resources, primarily in support of local demand and/or local income. High population densities in village landscapes drive ecological processes such as manure nutrient recycling, biomass combustion for fuel, and hydrologic alteration by human structures that are rarely significant when few people dwell in agricultural areas. For this reason, the ecology of village landscapes differs significantly from extensive agricultural landscapes such as rangelands, large-scale agriculture, plantations, swidden, and other low labor intensity agroecosystems.

Ecological processes in village landscapes are often strongly linked to population density and have completely different dynamics from those of extensive agriculture. For example, biomass burning is often positively correlated with population density and is evenly distributed across the year in villages because of its linkage with cooking, while biomass burning is primarily seasonal and is unrelated or even inversely related to population density in extensive agricultural landscapes because of its primary use as a labor saving technique where population densities are low [Netting, 1993]. It should also be recognized that while village landscapes are often dominated by agriculture, they often include significant areas of forested and fallow land or water that are interspersed with dwellings in highly heterogeneous patterns that contrast with the more homogeneous landscapes typical of extensive agriculture.

Our definition of village landscapes overlaps with the conventional definition of villages as “an administrative unit below that of the township,” but differs from this definition by requiring high population densities and direct linkage of local populations with productive management of local land. Though in some wealthier village landscapes the percentage of local income gained by managing local land and water resources is declining into insignificance, as long as the majority of the local population manages local land for agricultural and other

| Table 1. Global extent and impacts of village landscapes circa 2000. Numbers in parentheses are percent of global value. |
|-----------------------------|------------------|------------------|------------------|
|                             | Global | Asia* | China |
| Population (10^\(\text{b}\))^b |        |       |       |
| Total                       | 6.06   | 3.56 (59) | 1.29 (21)  |
| Agricultural                | 2.54   | 1.88 (74) | 0.85 (34)   |
| Village^c                    | 1.75   | 1.37 (78) | 0.52 (29)   |
| Area (10^6 km^2)^d           |        |       |       |
| Total                       | 125    | 39.7 (32) | 9.37 (7)    |
| Agricultural                | 46.5   | 11.6 (25) | 5.35 (12)   |
| Arable land                 | 13.6   | 5.49 (41) | 1.24 (9)    |
| Village^e                    | 8.90   | 5.93 (67) | 2.31 (26)   |
| Emissions (Tg)^f             |        |       |       |
| Biomass fuel CO₂             | 458    | 313 (68) | 101 (22)    |
| Agricultural CH₄             | 2816   | 1532 (54) | 479 (17)    |
| Agricultural NO₂             | 2.8    | 1.5 (54) | 0.48 (31)   |

* Includes nations of South, East, and Southeast Asia and the former Soviet Union.
b Total population for 2000 and agricultural population for 1999 [FAO, 2002].
c Village populations and area are preliminary estimates from village cells illustrated in Figure 1; North America and Australia excluded. These estimates contain uncertainties on the order of ±50%.
d Total areas calculated from Environmental Systems Research Institute Inc. [2003].
e Agriculture and Arable land areas for 1999 are from FAO [2002].
f Estimates based on national totals from EDGAR 3.2 by RIVM/TNO [Olivier and Berdowski, 2001] in Tg of CO₂ equivalent, except for NO₂, which is in Tg of NO₂. These estimates contain uncertainties on the order of 100%. 
productive use, these lands may be defined as village landscapes. This distinguishes village landscapes from suburban landscapes, even though suburban areas often have relatively dense populations and significant agricultural land cover (usually interspersed with developments in patches remaining from previous, more extensive agriculture), because suburban populations merely co-exist with local agricultural land, without managing it. Furthermore, the household energy demand of suburban areas is usually supplied from centralized fuel or power sources, strongly limiting the combustion of local biomass that is typical in village landscapes.

Village landscapes vary in population density, but for practical purposes, they may be defined as areas with significant agricultural cover and population densities between 100 and 2500 persons km$^{-2}$ where local populations manage local land and water resources. This is because population densities >2500 persons km$^{-2}$ generally cannot be supported by local agricultural production even under ideal conditions and agri-

![Figure 1](image_url). Map of global village landscapes. (a) Population density from Landscan 2002 [after Dobson et al., 2000]. (b) Percent cover by agriculture, 1992 [from Ramankutty and Foley, 1999]. (c) Village landscapes mapped as 5' cells with >25% agricultural and <25% urban cover [Friedl et al., 2002] and agricultural population density between 100 and 2500 persons km$^{-2}$ (Landscan 2002 [after Dobson et al., 2000]). All maps are in Plate Carrée projection.
cultural areas with population densities <100 persons km\(^{-2}\) agricultural land are usually dominated by non-intensive land management and ecological processes that are more typical of extensive agriculture [Netting, 1993].

At resolutions ≥1 km\(^2\) in most village landscapes, rural settlements and agricultural land are thoroughly mixed together, integrating local populations with agricultural land into a land use class that is best classified as “village landscapes.” At resolutions <1 km\(^2\), depending on population density and the degree of “clumping” of rural dwellings, settlements and agricultural land are more clearly distinguished as separate land use classes. Therefore, village landscapes should be mapped as a distinct land use class only when the minimum mapping resolution is large enough, usually above 1 km\(^2\), so that agricultural land and village settlements are well mixed within a single mapping unit.

1.1.2. Global extent of village landscapes. The density and distribution of agricultural populations in rural Asia is difficult to map by current methods [Dobson et al., 2000], and the mixed land cover typical of village landscapes can confuse land cover classifications [Frolking et al., 1999], making it hard to measure and map the global extent of village landscapes. The sum of the agricultural populations of developing nations, $2.4 \times 10^9$, provides a plausible rough global estimate of village populations [calculated from FAO, 2002], and Ellis et al. [2000b] estimated a global village area of $8 \times 10^6$ km\(^2\) based on the subsistence agriculture map of Whittlesey [1936].

To make a more detailed and accurate global map and population estimate for village landscapes, we use recent global 1 km resolution MODIS IGBP landcover data [Friedl et al., 2002] and 30" resolution (30 arc second) global population density maps [Landscan 2002, after Dobson et al., 2000] to make estimates at 5' resolution (5 arc minute). Prior to analysis, landcover data were simplified using a 3 × 3 nearest neighbor majority analysis to eliminate speckle noise and highlight larger areas of each cover class. Potential village 5' cells were selected as those with >25% agricultural cover and <25% urban cover. Agricultural population density (persons km\(^{-2}\) agricultural land) within potential village cells was calculated as the sum of 30" Landscan 2002 cells with population density <2500 persons km\(^{-2}\) divided by the agricultural area within 5' cells. Probable village landscape cells (Figure 1, c) were then chosen as the potential village cells with agricultural population density between 100 and 2500 persons km\(^{-2}\). Global areas and populations of village landscapes (Table 1) were calculated from probable village landscape cells within all nations excluding North America and Australia.

Global village area is likely overestimated by our methods because significant areas of suburban and rural town landscapes are included, especially in Europe. However, village populations are likely underestimated, because Landscan usually underestimates rural populations in Asia. Given our remaining uncertainty, we propose that $8 ± 4 \times 10^6$ km\(^2\) and $1.8 ± 0.9 \times 10^9$ are reliable estimates of global village area and population, respectively. Based on this analysis, the greatest extent and population of village landscapes is clearly in Asia. Outside Asia, estimates of village landscape area and population are suspect, as more developed nations have greater suburban populations, adding a positive bias to estimates in these areas.

1.1.3. Global impacts of village landscapes. Based on our estimates, villages are the most extensive densely populated landscapes on Earth, with more than 30 times the global area of urban and builtup landscapes ($0.25 \times 10^6$ km\(^2\) [United Nations Development Programme et al., 2003]. Village populations are also about 60% as large as global urban populations ($2.8 \times 10^9$ [FAO, 2002].

The large extent and population of village landscapes indicates that they should play a significant role in global biogeochemical processes. Asian nations, where most agricultural population and land are in villages, are responsible for the majority of global anthropogenic greenhouse gas emissions driven by agriculture and rural population, including the majority of CO\(_2\) from biomass fuel burning together with agricultural emissions of methane and nitrous oxide (Table 1). However, uncertainties in these estimates from national statistics based methods are in the 100% range [Olivier and Berdowski, 2001]. Current fossil fuel emissions from villages are also significant, as these have displaced traditional biomass burning in wealthier areas, but the true extent of these emissions are difficult to estimate based on national data.

Village landscapes cover more than 60% of global crop-land area (Table 1) and have an area nearly 80% as large as that of tropical rainforests ($11 \times 10^6$ km\(^2\) [Achard et al., 2002]. It therefore seems appropriate that global land use/landcover maps at 1 km resolution and above should recognize “Village Landscapes” as a separate class from “Agriculture” (the classification of most village landscapes in current systems). This would serve a similar purpose as the IGBP “Cropland/Natural Vegetation Mosaics” class [Hansen et al., 2000], which also characterizes fragmented landscapes with mixed cover, but would recognize the powerful role of ecological processes driven by human populations in the densely populated village landscapes of the world.

1.2. China’s Village Landscapes

Given its large extent and population size, it is not surprising that China has a greater village area and population than
any other nation (Table 1). China has a major role in anthropogenic greenhouse gas emissions as well, with ~30% of global agricultural nitrous oxide emissions resulting from the application of ~25% of the world’s annual N fertilizer production in 1990 [Constant and Sheldrick, 1992]. With its number one status in village area and population, together with environmental variation from subarctic to tropical and from floodplains to mountains, China is an ideal locale for the investigation of linkages between land use change and ecological processes in villages.

In most of China, densely populated villages evolved under labor-intensive traditional agricultural methods that limited the amount of land a person could cultivate year after year. For this reason, traditional village populations tend to range between the minimum needed to sustain intensive cultivation (~100 persons km⁻² agricultural land) and the maximum supportable using the most intensive methods (up to 2500 persons km⁻² agricultural land) [Ellis and Wang, 1997; Netting, 1993].

There is no doubt that the ecology of China’s village landscapes has changed dramatically in the past 50 years. China’s rural populations have nearly doubled, growing from 485 million in 1950 to 866 million in 2000 [FAO, 2002], and at the same time have adopted industrial technologies such as synthetic fertilizers and fossil fuels, along with other modernizations that have mostly displaced long-term traditional practices of land and resource management. Though China’s villages were collectivized for nearly 30 years, in most cases, collectives merely reallocated the same resources that village households had previously managed [Xu and Peel, 1991]. The household responsibility system restored land management to households in 1982, returning village landscapes to small-scale land management patterns remarkably similar to those of the past, though with more equitable distribution of land. As an indicator of continuity, in many cases, individual village boundaries have survived the transition from imperial China through revolution, collectivization, and reform, up until the current time.

Most of the land use transformations associated with China’s village landscapes have occurred not by increasing the total extent of village landscapes but by small-scale transformations within village landscapes. For the most part, the total extent of China’s village landscapes has not changed since the 1940s, even though China’s total agricultural area expanded significantly after 1950. This is because much of this expansion was driven by increases in extensive agriculture by state farms and the rest by transforming non-agricultural village lands, such as hilly areas, into agricultural use [Xu and Peel, 1991]. Extensive, mechanized, commodity based agriculture managed by state farms and newly formed collectives was introduced only where villages did not already claim agricultural land [Xu and Peel, 1991], and their extensive agriculture landscapes do not resemble the complex integrated use patterns of village landscapes from which they are readily distinguished using 30 m resolution landcover data.

1.3. Challenges in Measuring Ecological Changes Across Village Landscapes

Though great changes have certainly occurred in the ecology of village landscapes as a result of increased population and application of industrial technologies, the very small spatial scale and diverse pathways of these changes presents serious challenges to those who would measure and mediate their local and global impacts. In village landscapes, large regional changes are the cumulative result of a vast number of very small changes. This is quite a different situation from the more widely investigated land use change phenomena, such as large-scale deforestation and urban expansion, where change processes are readily observed at even 1 km or greater resolution. Moreover, fine scale land transformations from one use to another are often combined with changes in management practices within each land use type, especially when changes are considered over long periods of time. For these reasons, the regional and local ecological impacts of land use change in village landscapes will only be understood by investigating the diverse practices of small scale farmers as they manage and transform their local landscapes.

1.3.1. Scales of ecological change in villages. Two scales must be considered when investigating long-term ecological changes across village landscapes. The first is the scale at which land use changes occur, and the second is the scale of variability in practices applied within specific land use types. In village landscapes, land use changes occur at the plot scale, while land management varies both from plot to plot and within and between households.

Across history, with the possible exception of the collective period, most of China’s village land has been finely divided into small plots managed by different households. Prior to the revolution, land management was fairly evenly divided between households, mostly due to labor requirements for agricultural production, even though landlords and larger farm households often controlled a much greater share of the actual land ownership and harvests [Buck, 1930]. Even during the collective period (1950s to 1970s), much land management was still more or less controlled by households arranged in production teams, and households in most areas retained small private plots for household vegetable production. Since 1982, the household responsibility system has guaranteed almost every village household a set of plots divided out of the total village lands according to the quality and types of land available within each village, assuring the equitable distribution of
all village land among households. Though changing now, this system has maintained a finely fragmented landscape, as different households with different plans and practices usually control numerous noncontiguous small plots of each land type within each village.

The scale of agricultural plots varies tremendously across China. In the 1930s, North China Plain households averaged about 9 plots of land with a mean area of ~0.4 ha per plot, while households in Sichuan’s rice areas averaged 23 plots of about 0.08 ha each [Buck, 1937a]. We have observed remarkably similar patterns in current household surveys from China, though average plot sizes are generally smaller now. Even though agricultural plots are sometimes part of larger fields, in many areas, especially the rice growing regions, agricultural land is a mosaic of plots smaller than 30 × 30 m laced with small berms, paths, and/or ditches ranging in width from 0.1 m up to 5 m, sometimes including trees or other semi-managed vegetation (Plates 1b, 1c, and 1d) [Ellis et al., 2000b].

The size of housing and associated vegetation features is often even smaller than for agricultural plots, depending on the region. Houses in the North China Plain are usually grouped together into very large “natural villages” with hundreds of dwellings, and into groups of tens of dwellings in the Yangtze Plains, but in other regions of China, housing is nearly always dispersed in clusters of <10 dwellings, and often as individual dwellings. The average size of farm buildings, including dwellings, ranged between 60 and 25 m² in the 1930s (estimated from Buck [1937a]), though they are often significantly larger now. Then and now, dwellings are usually surrounded and even covered by trees or bamboo, making their detection by remote sensing a challenge (Plate 1, d and e).

Plate 1, a and b, illustrate landcover classification of a sample of village land in Sichuan from orthorectified 28.5 m Landsat ETM+ imagery, along with an IKONOS 1 m resolution image displaying the many small patches of trees, houses, and paddy and upland agriculture plots laced with paths and ditches that are typical of this region’s village landscapes. Though it may be possible to classify land cover more precisely from Landsat imagery, in general, most landscape features in densely populated hilly regions are much smaller than 28.5 m Landsat pixels, and are therefore difficult to detect, let alone measure, using this resolution of imagery. Clearly, the mapping and measurement of long-term changes in village landscapes will benefit from the use of high resolution imagery (≤1 m) from satellites such as IKONOS and Quickbird that can readily detect small features, on the order of a few meters, that are common across village landscapes.

The scale of variability in village land management practices is as fine as that of land transformation. Plate 1, g, illustrates the typical method for spreading most of the chemical fertilizer in China, while Plate 1, f, demonstrates the high level of variability between household N fertilizer applications. Even though the average fertilizer application of a village may optimize yield without major environmental harm, a significant group of households, mostly animal managers in this case, may still apply large, saturating, amounts of N without any yield benefit, causing most of the nitrous oxide emissions and nitrate leaching from N fertilizer across an entire village landscape (Plate 1, f) [Ellis et al., 2000c]. Plate 1, i and h, illustrate typical use of crop residues for fuel and fuel wood gathered by a single household, respectively, exemplifying the small scale and diversity of biomass burning for fuel.

Just as no U.S. citizen actually eats the average U.S. diet, the resource management practices of different households within a single village usually differ far from any regional, county or even village average. This can cause unforeseen ecological impacts from practices such as nitrogen fertilizer application and biomass harvest for fuel that cannot be identified or measured when only averaged or typical practices are considered. This is because ecosystem responses to disturbance are usually non-linear, with insignificant effects at lower levels giving way to major changes when thresholds are exceeded, so that a few households with extreme practices may cause most of the ecological impacts of a specific practice [Ellis et al., 2000c]. For this reason, data describing the diversity of resource management practices between managers are critical to understanding and anticipating the ecological impacts of land transformation and management in village landscapes.

1.3.2. Integrating land use, households, and ecological processes. Given the fine scale of land and resource management within village landscapes, reliable measurements of land use changes and ecosystem impacts across village landscapes requires the integration of high resolution land use change measurements with household level data for land and resource management. This integration is challenging, because resource management data are best collected directly from the managers themselves, while measurements of land use change and ecosystem processes are best made using remote sensing, field measurements, and models. The disciplines involved in obtaining these data usually do not use the same units, let alone the same measurements.

The critical link between land use change, land management practices, and ecosystem processes is land. By developing mapping and classification systems that stratify landscapes into ecologically distinct units useful for ecosystem measurements and also approximating those of local resource managers, data from household surveys and field measurements can be linked with precise measurements of land use change to make estimates across village landscapes.
1.3.3. Estimating regional change from local data. Just as there is no such thing as a typical year or a typical person, there is no such thing as a “typical representative site” encompassing all of the variability within a region. Nevertheless, by using regional analysis to select sites that contain a major share of the ecological variability within a region at a practical scale for village-scale measurements, measurements within a site or sites may be used to represent ecological processes across a region. This is especially true for village landscapes, where land management and ecological processes interact at very small scales.

The success of this procedure depends on the selection of sites that contain enough variability in environment, population density, and development to represent variability across the region. Prior to site selection, it is essential to define regions according to criteria that are stable over time and that limit environmental variability within each region, making it easier to select sites that can encompass most of a region’s environmental variability. After choosing sites with good samples of the range of critical environmental variation across a region, village-scale measurements of land use and ecosystem processes made across each site can be linked to the environmental variability shared between sites and regions, to “upscale” local data to estimate the regional impacts of local changes.

2. MEASURING CHANGE ACROSS CHINA’S VILLAGE LANDSCAPES

To measure long-term changes, we compare the state of village landscapes at the current time with their state in the 1940s, prior to the introduction of industrial technologies. We meet the challenge of measuring local changes across China’s >2 × 10⁶ km² of village landscapes by combining a top-down approach to sampling with a bottom-up approach to the estimation of regional change. First, China’s densely populated rural landscapes were stratified into five biophysically distinct regions by Peter Verburg using a k-means cluster analysis based on terrain, climate, and soil fertility variables in a 32 km resolution gridded dataset [Verburg et al., 1999] as illustrated in Figure 2 and Table 2. Relatively static biophysical variables were used for clustering to ensure the long-term stability of regional definitions, facilitating long term comparisons between and within regions.

It is notable that the regions derived by this analysis accounted for >90% of China’s agricultural population but <80% of its arable land; the remaining areas and populations are a combination of remote pockets of village landscapes and extensive agricultural areas with lower population densities. Data in Figure 2 and Table 2 include all cells with population density >150 persons km⁻², regardless of similarity to regional cluster means. When only cells with high resemblance to regional definitions were included (Euclidean distance from cluster means <2), the total area incorporated within the five regions is reduced to ~65% of China’s agricultural population and ~50% of its arable land, indicating that only this extent and population are reliably included within the regional analysis of this study.

We chose to stratify into five regions based on resource availability for our project. Fortunately, five regions generated nearly the same total area with high resemblance to regional means as did regionalizations with higher numbers of

<table>
<thead>
<tr>
<th>Region</th>
<th>Arable land (10⁴ km²)</th>
<th>Arable land (%)</th>
<th>Agricultural population (10⁶)</th>
<th>Agricultural population density (pers km⁻²)</th>
<th>Flat land (%)</th>
<th>Poor soils (%)</th>
<th>Annual precipitation (mm)</th>
<th>Annual mean temperature (°C)</th>
</tr>
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<tr>
<td>North China Plain</td>
<td>486</td>
<td>51</td>
<td>307</td>
<td>321</td>
<td>61</td>
<td>6</td>
<td>645</td>
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<td>75</td>
<td>44</td>
<td>80</td>
<td>464</td>
<td>70</td>
<td>17</td>
<td>1312</td>
<td>16</td>
</tr>
<tr>
<td>Sichuan Hilly</td>
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<td>162</td>
<td>248</td>
<td>4</td>
<td>5</td>
<td>950</td>
<td>11</td>
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<tr>
<td>Subtropical Hilly</td>
<td>172</td>
<td>18</td>
<td>175</td>
<td>188</td>
<td>5</td>
<td>85</td>
<td>1426</td>
<td>14</td>
</tr>
<tr>
<td>Tropical Hilly</td>
<td>71</td>
<td>20</td>
<td>83</td>
<td>233</td>
<td>16</td>
<td>78</td>
<td>1651</td>
<td>20</td>
</tr>
<tr>
<td>Outside</td>
<td>286</td>
<td>5</td>
<td>79</td>
<td>12</td>
<td>30</td>
<td>20</td>
<td>384</td>
<td>2</td>
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</table>
Figure 2. Regional stratification and site selection. (a) Population density from Landscan 2002 [Dobson et al., 2000]. (b) Terrain clusters from analysis of 32 km resolution data for % steep slopes (PHYSS), % hilly/mountainous (GEOMOR1), and % plain (GEOMOR5) [Verburg et al., 1999]. (c) Climate clusters from 32 km resolution analysis of variables for long-term average temperature (TMP_AVG), long-term total annual precipitation (PRC_TOT), and number of months with average monthly temperature above 10°C (TMP_10C) [Verburg et al., 1999]. (d) Soil fertility defined as “fertile” <40% poor soil cover (FERT1) and “poor” >40% poor soil cover from 32 km resolution data [Verburg et al., 1999]. (e) Five biophysical regions determined by cluster analysis on clustered variables in (b), (c), and (d). Blank areas were excluded from the analysis due to low population density (<150 persons km⁻²). (f) Local site selection criteria, including areas excluded due to urbanization (<10 km from cities with area >25 km²), areas of interest for 1940s aerial photographs (AOI degree cells), footprints of existing 1940s aerials, and the locations of farm household surveys from the 1930s [Buck, 1937b]. All maps are in Albers Equal Area Conic projection optimized for China (Albers China: central meridian = 105°, standard parallel 1 = 25°, standard parallel 2 = 47° and latitude of origin = 0°).
regions. Still, the low resolution of the current analysis suggests that a regional stratification based on higher resolution data would significantly improve the reliability of regional estimates based on upscaling site data, though likely with a more limited prediction extent and population.

2.2. Site Selection

A single site was selected within each of the five regions based on the criteria below. Each site was limited to a single 100 km$^2$ rectangular area based on the size of IKONOS scenes affordable by the project ($7 \times 14.25$ km, except for Gaoyi site = $9 \times 11.1$ km). To avoid areas where urban influence on land use change processes would be greater than typical for rural regions, we excluded from consideration areas within 10 km of cities $>25$ km$^2$ in size (Figure 2, f; urban areas from 1990s 250 m landcover data from the Chinese Academy of Sciences, Institute of Geography). Potential areas of interest (AOI) within each region were then delimited at the county and 1° grid cell level, based on the availability of 1940s aerial pho-

![Figure 3. Sample selection, Tropical Hilly Region, Dianbai Site, Guangdong Province. (a) Location of region and site. (b) Location of Landsat imagery used for landcover classification. (c) Classified land cover from supervised, maximum likelihood classification of 28.5 m resolution orthorectified Landsat ETM+ (Geocover) data (Table 3). (d) Regional map of landcover clusters from 500 × 500 m cell land cover; cells with >75% water or >25% urban cover removed prior to cluster analysis. Clusters are Typical = similar to regional means for each landcover class, +Paddy = greater paddy than typical, +Builtup = greater builtup and water cover, +Other = greater other class cover (mostly shrubby vegetation and young orchards). (e) Dianbai site map of landcover clusters; IKONOS = IKONOS image cover, 1940s = 1940s aerial photograph cover, Samples = 12 500 × 500 m cells sampled for high-resolution analysis, clusters same as (d), with black arrow pointing to cell mapped in Plate 2. All maps are in Albers China projection (see Figure 2 caption).
tographs, and the locations of farm household surveys conducted in the 1930s [Buck, 1937b] (Figure 2f). After field visits to at least two potential sites per region and discussions with regional and local experts, we chose sites representing the North China Plain (Gaoyi County, Hebei Province), Yangtze Plain (Yixing County, Jiangsu Province), Sichuan Hilly Region (Jintang County, Sichuan Province), Subtropical Hilly Region (Yiyang County, Hunan Province), and Tropical Hilly Region (Dianbai County, Guangdong Province) (Figure 2).

Though there was some incentive to select sites with strong local collaboration and convenient transport, the primary constraint in selecting sites was locating areas with typical terrain and levels of development that were also covered by 1940s aerial photos in the collections of the U.S. National Archives and Records Administration (www.archives.gov); apparently, 1940s photography focused on the more developed areas. Initially, we planned to include villages within each site that were surveyed in the 1930s [Buck, 1937b], but these overlapped so rarely with 1940s photos that we settled for sites where surveys were available for villages with similar environments in nearby counties.

### 2.3. Landscape Sample Selection

To maximize the regional representativeness of the small sample area (3 km²) we were able to map within each site using our high resolution ecological mapping methods, we distributed this sample among twelve 500 × 500 m landscape sample cells selected across each site. Sample cells were chosen to represent the three to four most important clusters of regional landcover patterns determined using a k-means cluster analysis of 28.5 m landcover data aggregated into 500 × 500 m cells across two Landsat scenes per site.

Landcover data for the analysis were obtained using supervised, maximum likelihood classification of 28.5 m resolution orthorectified Landsat ETM+ (Geocover) data. Prior to cluster analysis, we removed 500 m cells with >75% water or >25% urban builtup cover (urban was distinguished from village builtup cover by visual interpretation of the builtup cover class from supervised classification). This process is illustrated in Figure 3 for the Dianbai Site in the Tropical Hilly Region, with landcover results for the region, site, and sample in Table 3. By this method, regional variation in landcover patterns at 500 m resolution was stratified into 4 clusters that were mapped both regionally and across each site.

We selected the twelve 500 m cells per site from among those with 100% coverage by both IKONOS imagery and 1940s aerals. First, four cells were selected in a 1 km² square pattern based on expert appraisal of their regional representativeness. The remaining eight cells were selected to give a site sample with the number of cells selected from each cluster proportional to the clusters’ regional abundance, by selecting cells in order of greatest regional abundance and with greatest resemblance to cluster means, while attempting to include at least 3 replicate cells per cluster that were not adjacent to previously selected cells.

This process gave different spatial patterns and numbers of cells per cluster at each site, with the Dianbai Site representing a more limited distribution of cells between clusters and across the site than at the other four sites (note the spatial clustering of cells and the single cell selected from the Builtup cluster in Figure 3, e). In all sites, cells were selected from clusters representing >90% of regional area and in 3 of 5 sites, all clusters were sampled with replication. Table 3 illustrates the effectiveness of the sample selection process, as the % landcover pattern of the sample of 12 cells is significantly more similar to regional land over patterns than that of the entire site.

### 2.4. High-Resolution Land Use Change Measurement

To map and measure land use changes at the scale at which they occur in village landscapes, we have developed a feature-based approach to ecological mapping that combines the direct interpretation of high resolution (≤1 m) imagery with groundtruthing. Though these methods are labor intensive, they are applicable no matter what type of imagery is used, as long as the resolution is adequate. This is critical when measuring long-term changes, as aerial photographs are the only

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**Table 3. Example of scaling regional, site, and sample data based on regional landcover data for the Tropical Hilly Region (Figure 3).** Percent land cover is estimated from the same 28.5 m classified landcover dataset averaged across the region (two Landsat scenes), the site (100 km² scene), the sample (twelve 500 × 500 m sample cells), and for the sample cells corrected using regional weights (equation 2).

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Region</th>
<th>Site</th>
<th>Sample</th>
<th>Corrected sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>76.3%</td>
<td>49.9%</td>
<td>58.6%</td>
<td>76.4%</td>
</tr>
<tr>
<td>Rice paddy</td>
<td>15.2%</td>
<td>41.6%</td>
<td>29.9%</td>
<td>17.6%</td>
</tr>
<tr>
<td>Otherb</td>
<td>4.9%</td>
<td>5.0%</td>
<td>9.1%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Water</td>
<td>1.3%</td>
<td>0.3%</td>
<td>0.8%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Builtupa</td>
<td>1.1%</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Barren</td>
<td>1.1%</td>
<td>1.4%</td>
<td>1.1%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

---

*aLandcover classes from supervised, maximum likelihood classification of two 28.5 m resolution orthorectified Landsat ETM+ (Geocover) scenes illustrated in Figure 3; overall accuracy = 90.6%, Kappa = 0.890.

*bOther class is primarily a mix of shrubby vegetation and younger tropical fruit orchards.

+Non-urban/village builtup cover; urban cover excluded.
Plate 1. Examples of village land use and resource management. (a) Classified land cover from orthorectified 28.5 m Landsat imagery of a 1 × 1 km area in Jintang County, Sichuan Province, draped over a 2 m resolution digital elevation model (DEM) generated from 1:50K topographic lines; 1.5× vertical exaggeration. (b) IKONOS 1 m orthorectified imagery draped over same area as (a), red arrow points out housing and trees missing from (a). (c) View near (a) showing typical fragmented patterns of hilly village landscapes. (d) Housing near (a), displaying association of perennial cover with housing. (e) Typical village house, Yiyang site, Hunan Province. (f) Fertilizer inputs by 50 farm households in Xiejia Village, Jiangsu Province, 1994 [Ellis et al., 2000c]. (g) Typical fertilizer application method, Xiejia Village, 1994. (h) Branches collected for cooking fuel, Dianbai site, Guangdong Province, 2002. (i) Using crop residues as cooking fuel, Jintang site, Sichuan Province, 2002.
sources of imagery prior to the 1960s. Before mapping, IKONOS imagery and 1940s aerials were obtained and orthorectified for each site [Wang and Ellis, in review].

We stratify village landscapes into ecologically distinct landscape features, or ecotopes, using the four level classification hierarchy: FORM→USE→COVER→GROUP+TYPE; an expanded version of methods in Ellis et al. [2000b]. All four classification levels are combined to classify each eco-
tope feature fully, but every level can also be used separately or in any useful combination for analysis once mapping and classification are complete.

In order to measure local changes using classes that fully describe the consistent long-term land use systems of local land managers, past and present, the ecotope classification system is designed for flexibility, using the hierarchical combination of detailed standardized classification terms. Though this system potentially yields a nearly unlimited number of possible classes, only a relatively small number of ecotope classes, usually <100, are usually observed at any one site. Moreover, the criteria for determining the appropriate classification for each feature in imagery or in the field are essentially the same as those used in interviews with land managers. For this reason, area measurements from classified ecotope maps are readily linked with management data. A complete description of the ecotope classification and mapping methods is beyond the scope of this paper and is planned for a subsequent publication by this author. A brief overview of the methods is given below.

The sequence and scale of ecotope feature mapping follows the relative ease of detecting different types of features in ~1 m resolution imagery. First, all linear features ≥2 m in width with area ≥25 m² are mapped (linear features have length ≥4 × width). This is followed by hard areal features with ≥5 m minimum dimension (hard features have clear edges and relatively homogenous interiors; examples are buildings and water bodies). Finally, larger soft features with dimensions ≥10 m or ≥5 m with area ≥100 m² are mapped (soft features have fuzzy edges and variable centers, such as crop plots and patches of trees).

The mapping and classification process begins with collaborative training of site researchers in the methods, based on the preparation of test maps of the same sample area that are repeatedly tested for conformance with the standard mapping and classification rules. First, after reviewing site imagery and locating confusing areas, the mapper makes an initial visit to the AOI to be mapped equipped with 1:1,200 image maps, to investigate general conditions and confusing areas. The mapper then prepares an initial classified ecotope map of the AOI using vector editing in a Geographic Information System (GIS) based on direct image interpretation, field maps, and field notes. After completing the initial map, the mapper returns to the AOI with 1:1,200 map prints to check for agreement between the initial map and what is observed across the AOI in the field, again focusing on the remaining confusing areas. The mapper then corrects the initial map using the GIS to create a draft map that is then checked one more time in the field to create the final map.

The process above is altered slightly when ecotope maps for the 1940s are groundtruthed using 1940s aerials. To accomplish this, two village elders, aged ≥74 in 2003 (≥16 in 1945), with a lifelong history of managing land ≤500 m from the AOI are selected to aid in groundtruthing each AOI. After initial interpretation by a trained mapper, elders are interviewed to identify unknown features and ecotope classes in the AOI with the aid of large-format 1:1,200 historical and current image maps, and by visiting all confusing areas in the field with the elders. Plate 2 illustrates the results of this mapping system applied to a single 500 m sample cell in the Dianbai Site.

2.5. Household-Level Resource Management

Contemporary household land and resource management data were obtained by random structured household surveys using standardized forms developed to accommodate local practices based on test surveys at each site, but also designed to facilitate cross-site analysis. Data were collected for each plot of land (coded to ecotope code), and for household animals, food, feed, fuels, fertilizer, crop residues, and other major material inputs and outputs. Household samples were obtained by random selection of 100 households from correction village household lists from five villages at all sites except for Dianbai. At Dianbai, 50 households were selected based on a randomized spatial sample of dwellings within the 12 landscape AOIs, because these villages were too extensive to facilitate useful random sampling from household lists. Random sampling from lists generated a spatially random sample of households across the five selected village areas. Survey response rate for list-sampled households was 100%, based on repeated visits and strong village support; response rate for the spatial sample (Dianbai site) will be determined when surveys are complete at this site.

Data on 1940s resource management were obtained by interviews with 5 pairs of elders at each site, chosen from among those selected to aid in historical groundtruthing, according to the relative regional importance of their AOIs. Elder interviews were designed to elicit not only the typical resource management practices of the 1940s, but also to capture the full variability of these practices in the past. Additional data on traditional resource management were derived from 1930s household surveys by Buck [1937b], and other historical sources.
Plate 2. High-resolution landscape change measurement for a 500 × 500 m sample cell, Dianbai site, Guangdong Province (arrow in Figure 3e points to this cell). All layers are draped over a 2 m resolution DEM generated from 1:50K topographic lines; no vertical exaggeration. (a) Orthorectified May 14, 1944, aerial photograph; green line delineates sample cell. (b) Orthorectified October 27, 2001, IKONOS 1 m pan-sharpened GEO image. (c) Circa 1940s ecotope land use map based on elder groundtruthing in 2003; use classes are indicated in lower right. (d) 2002 ecotope land use map based on groundtruthing in 2002 and 2003; same use classes as (c). (e) Changes in ecotope land use between 1940s and 2002 highlighted in red.
2.6. Integrating Land Use With Resource Management

Land and resource management data collected from interviews are readily combined with area measurements from ecotope maps, as both types of data are collected using the same landscape units. For example, 

\[
\text{N loading rates for the rice paddy ecotope from a sample of 100 households can be characterized statistically and used to estimate nitrogen emissions and leaching using models designed specifically for this component of the landscape, and the results can be used to estimate emissions both per ecotope and per unit area of village landscape.}
\]

Village ecosystem processes that are not linked directly to land, such as combustion of biomass for fuel, may still be linked to household count or population within an area. Using population estimates for landscape sample cells by counting houses and expert interviews, net emissions from biomass fuel combustion are readily estimated on a landscape basis from household-level combustion data.

The end result of integrating land use and resource management data are estimates of land use areas, ecological processes and their changes at the scale of ecotopes and 500 m landscape sample cells. Using measurements of land use and ecological processes from the 1940s and 2002, changes are estimated simply by subtracting estimates for each time period, yielding the change by difference. This may be done at the scale of each ecotope, or each process, or per unit area of village landscapes, depending on the goal of the analysis. Furthermore, the relative amount of change caused by land transformation versus changes in ecosystem processes can be estimated across a given area of village landscape by holding either ecotope areas or ecosystem processes constant between the two periods when calculating differences [Ellis et al., 2000b].

2.7. Upscaling Local to Regional

Once site-based estimates of ecological change have been made at representative sites within a region, three different methods are useful in upscaling these data to make regional estimates of changes in land use and ecosystem processes. All of these methods are based on relationships derived by comparing regional data at the site and regional scale; the scaling methods do not depend on local scale data which are merely used as an input once the regional analysis is complete.

The first method uses estimates for the twelve 500 m landscape sample cells at each site, by calculating the relative proportion of the entire region that should be represented by each sample cell (the cell’s “regional weight”). This is calculated based on the relative area represented by each regional cluster, corrected for the relative similarity of each cell to the regional cluster mean using inverse squared cluster distance weights ($CDW$) from the equation

\[
CDW_i = \left( \frac{1}{CDW_i} \right) \left( \frac{1}{\sum_j CDW_j} \right) \times \frac{N_k}{N_j}
\]

where $CDW_i$ is the inverse squared cluster distance weight for sample cell $i$, $CD_j$ is the cluster distance for sample $i$ within cluster $k$, $n_k$ is the number of sample cells in cluster $k$, $N_k$ is the number of regional cells in cluster $k$, and $N_j$ is the total number of regional cells. Sample cell based measurements ($CE_i$) are then scaled to make regional estimates ($RE$) by correcting for their regional weight ($CDW$) using the equation

\[
RE = \sum_i CE_i \times CDW_i
\]

where $I$ is the total number of sample cells in the analysis.

Results of this correction for the Tropical Hilly Region are presented in the “Corrected Sample” column of Table 3. By correcting not only for the relative area of each cluster, but also for its relative distance from the cluster mean, estimates of regional land cover from corrected samples of just twelve cells can produce landcover estimates that are remarkably similar to the regional values (Table 3). By weighting land-use and ecosystem process change measurements for each sample cell as described above, regional estimates can be made from local change measurements.

Another method for regional estimation is to calculate relationships between specific ecotopes or clusters of ecotopes and ~30 m resolution regional landcover data. When there are strong relationships between these data, regional estimates of ecotope-level processes can be calculated based on the relative proportions of the relevant ecotopes across the region based on their relative association with regional 30 m landcover data. Though this may seem to allow a more precise set of estimates across a region, it is likely that relationships between 30 m landcover classes and local environmental patterns may vary more across a region than would those of 500 m cells, which are aggregates of regional patterns and contain more information about associations between landcover classes caused by environmental variation.

The third method facilitates regional estimation of ecological processes that depend on population, such as biomass fuel combustion. Based on local estimates of these processes per capita or per household, regional estimates can be made either using existing regional data for agricultural populations, or if this is unreliable, by estimating regional village populations from the population data for landscape sample cells as described in method one.
By combining regional estimates made by these different methods and comparing them with each other and existing regional data, the relative strengths of each method can be determined. The reliability of regional estimates can then be improved by incorporating groundtruthed data from high resolution ecological mapping, household surveys, elder interviews, and other sources of local data that can resolve ecological processes within village landscapes at the resolution at which they are managed by people.

3. LESSONS LEARNED

3.1. Tradeoffs in Scales of Measurement

3.1.1. Local management, regional response. Even though local managers are highly adapted to local conditions, and their management varies from household to household, their collective actions can have major regional impacts, even without any obvious changes at the regional scale. For example, the regional areas of vegetable fields and rice paddies and the regional use of human manure for fertilizer may remain constant, yet total N leaching to groundwater may increase dramatically when synthetic N is introduced, displacing manure applications from the larger paddy fields to the very small area of vegetable gardens, where aerobic soils may cause high levels of nitrate leaching [Ellis et al., 2000c]. This is but one example of a regional ecological change that would be unanticipated without local measurements of land management practices. In regions of the world where land management is partitioned among numerous intensive small scale managers, the only reliable way to understand relationships between land use and ecosystem processes is to measure these at the scale at which land and other resources are managed.

3.1.2. Regional differences in local management. This study stratified village landscapes into five biophysically distinct regions, and it was clear immediately that this was a good idea. Each region had almost completely different land and resource management practices in response to local conditions, not to mention a different language, cuisine, regional identity, and culture. No doubt, the more sites used in regional estimation, the more reliable the national estimates obtained would be. For practical purposes though, stratifying a large area such as China’s densely populated village landscapes into just five regions limited the variability within each region to a level that was manageable for site level research. From extensive travel across each region during the site selection process, it was readily apparent that there was a far greater similarity in practices within regions than between regions. For example, the landscape position of housing was always consistent within regions, with clumped housing in the flattest, most uniform areas and more and more dispersed housing as terrain became more heterogeneous. Another example is the burning of wheat but not rice straw for cooking in the Sichuan Hilly Region, while only rice straw was used for cooking in the Yangtze Plain, despite the fact that both regions are dominated by a rice/wheat crop rotation and that farmers in both areas insisted that their choice of straw provided the best quality fuel.

3.1.3. Scales of regionalization and prediction. Five 100 km² sites are a very limited basis for estimating long-term ecological changes across China’s village landscapes. By stratifying landscape sample data within sites using regional criteria, it was possible to greatly improve the regional representativeness of local site data. However, the degree to which a set of sample cells from a site can represent an entire region also differs between regions, depending on the degree of large-scale variability across the region and the degree to which relationships between regional data remain constant across the region (i.e. the degree of spatial stationarity). This is more of a problem in some regions than in others. On the one hand, most land use and ecosystem variability in the North China Plain is determined by proximity to settlements and drainages, with a remarkably limited amount of variability across the region. On the other hand, the Tropical Hilly Region retained so much variability within its regional extent that one might say it is not a region at all, but a large set of sub-regions that should be divided according to their degree of proximity to the coast, elevation, soils, economic development and other variables.

When estimating the uncertainty of regional estimates made by upsampling local data, it is extremely important to estimate the amount of uncertainty caused by the failure of site variability to capture regional variability. Interestingly, differences in the degree of internal variability between regions were as apparent on the ground as they were in the 32 km cluster data used to derive the regions in the first place. Using a higher resolution regional analysis, we anticipate that the strength of regional prediction based on site sample data can be improved significantly.

3.1.4. Strengths and weaknesses of high-resolution measurements. High resolution ecotope mapping provides data on land use at scales appropriate for integration of local management practices with land use measurements, facilitating local and regional assessment of the impacts of specific practices. This is useful not only for reliable measurements of small scale management’s impacts at different scales, but also provides a practical basis for decision-making toward the remediation of harmful practices or introduction of improved practices.
On the other hand, high resolution feature-based mapping using groundtruthing and direct image interpretation is extremely time consuming, greatly limiting the total area that can ever be mapped. Automated feature extraction software may speed this up in the future, but the correct classification and mapping of land use classes will always require some degree of fieldwork, so that ecotope mapping will remain a method for use with smaller areas and samples. This is no less true for the collection of household-level land and resource management data.

Different regions gain different benefits from ecotope mapping and household surveys. For example, the very large patch patterns of settlements and agriculture in the North China Plain make the measurement of changes in the most important land-use classes relatively straightforward even with relatively low resolution mapping methods. Another example is in very hilly and mountainous areas where villages are tucked into smaller pockets of productive land within valleys, and land managers make relatively small impacts on the vegetation of hillsides. In these areas, the high resolution methods used for intensively managed parts of the landscape are complemented by lower resolution mapping using Landsat or other sensors with more extensive reach. Depending on the scales of land-use variation within a region, the accuracy of change measurements at both local and regional scales may be enhanced by integrating high resolution data for the highly fragmented parts of landscapes with more extensive lower resolution data for areas with larger scale variation in land use and cover.

3.2. Tradeoffs in Land Use Change

Based on extensive observations across sites, preliminary results demonstrate that land use changes in village landscapes often incorporate tradeoffs between enhanced ecosystem services and environmental harm. The first observation is that dwellings are invariably associated with trees, bamboo, and other perennial vegetation, so that increases in dwelling area generally translate into more trees and other perennials within village landscapes. This was evident even though the most common types of housing-associated vegetation ranged from deciduous tree plantings in the North China Plain, to bamboo plantings in Sichuan, to evergreen plantings in the Subtropical Hilly Region, along with various forms of regrowth vegetation at all sites. As every site has more dwellings now than in the past, we anticipate that our measurements, once complete, will demonstrate a general increase in tree and other perennial cover since the 1940s. On the other hand, large trees were far more common in the past according to elder respondents at every site, mostly due to the harvest of all large timber in villages during the “Great Leap Forward” in 1958, and to the intensification of forestry since that time.

Another consistent observation across sites was that the area of orchards, grapes, and other perennial fruit crops has increased as areas have become wealthier over time and space. In all villages surveyed, the only perennial crops with a significant extent in the 1940s were tea and mulberry (for silk production), and fruit trees were so rare in most villages that elders could remember the locations of individual bearing trees after 50 years.

At all sites, many of the less productive crop lands have been abandoned in response to changes in land policy, increased wealth, and as populations leave village landscapes for the city, either temporarily or for good. Outside of the Tropical Hilly Region, where much abandoned land is now covered by tropical grasses, most of these lands have reverted to various stages of woody perennial regrowth, often with full tree canopy cover.

Though preliminary, general trends observed across sites indicate that carbon sequestration in soils and vegetation has increased across village landscapes due to a combination of decreased tillage and increased perennial vegetation cover. Land abandonment and perennial regrowth have also likely increased the biodiversity of both plants and wildlife [Lugo and Helmer, 2004]. It therefore appears that, contrary to expectations, land transformations associated with population growth and the adoption of modern technologies are driving substantial improvements in ecosystem services across village landscapes.

These improvements appear to contrast with the ecological impacts of chemical fertilizer adoption, which has vastly increased nitrogen and phosphorus loading to agricultural land, thereby increasing nitrous oxide emissions, nitrate leaching, and phosphorus loading of surface waters [Smil, 1993]. However, there is evidence that these inputs have also improved soil nutrient balance in agricultural lands, increasing crop yields dramatically [Sheldrick et al., 2003; Smil, 1993], and even increasing carbon and nitrogen sequestration in intensively managed anthropogenic soils [Ellis et al., 2000a]. Taken as a whole, these preliminary observations indicate that population increase and adoption of modern technologies have had both positive and negative impacts on ecological processes across China’s village landscapes. Precise measurement of the relative balance of these impacts at local, regional and global scales is therefore essential for understanding and mediating the long-term consequences of land use and ecosystem changes across China’s village landscapes.

3.3. Future Opportunities

Though village landscapes are clearly the most extensive densely populated ecosystems of the world, it is likely that village populations in most areas are now declining, after more than half a century of rapid growth, as rural people move...
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