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CHAPTER 6

Nitrogen and the Sustainable Village

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CONTENTS

6.1 INTRODUCTION

Use of synthetic nitrogen fertilizer has increased 15-fold over the past 50 years, helping triple world grain production in support of doubled human populations (Constant and Sheldrick, 1992). While synthetic N has boosted grain production in the past, the high yields of many modern N intensive cropping systems now appear unsustainable (Cassman et al., 1995). Moreover, N fertilizers are increasingly harming both local and global environments (Galloway et al., 1995; Ma, 1997).

Nearly half the people on Earth live in rural villages that depend on subsistence agriculture for food (Marsh and Grossa, 1996). Asia, home of most of these populations, now applies about half the global supply of N fertilizer. This proportion is increasing, along with nitrate pollution of groundwater, N saturation of aquatic and terrestrial ecosystems, and reactive N emissions to the atmosphere that are driving global warming and depleting stratospheric ozone (Galloway et al., 1995).

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China's subsistence agriculture population (>800 million) is greater than that of any other nation. China now applies more synthetic N than any other nation, about 25% of the world's supply in 1990 (Constant and Sheldrick, 1992; Galloway et al., 1996), and more than Africa and the Americas combined.

This chapter explores the long-term ecological impact of synthetic N use within a rural village in the Tai Lake Region of China (Xiejia Village, Wujin County, Jiangsu Province; Latitude 31.5°N, Longitude 120.1°E; Ellis and Wang, 1997; Ellis et al., 2000a; Ellis et al., 2000b). The broad and unexpected effects of synthetic N within this densely populated village landscape offer valuable lessons for developing agroecosystems that can maintain food security in subsistence agriculture regions with less harm to local and global ecosystems.

6.2 NITROGEN IN VILLAGE ECOSYSTEMS

To measure the impacts of synthetic N in village ecosystems, observations are needed across the many different land managers and land types within these systems. Intensive subsistence agriculture clusters large numbers of farmers within relatively small areas, generating highly heterogeneous anthropogenic landscapes with ecosystem processes that are controlled as much by social dynamics as by environmental factors. The interplay between management variability and landscape heterogeneity in village ecosystems generates emergent properties that can only be understood by a village scale approach that incorporates diversity across farmers and landscapes. Figure 6.1 illustrates this situation: farming households with differing management styles, represented by shades of gray, may manage similar and/or neighboring land types, while differing types of land are often managed by the same farmers.

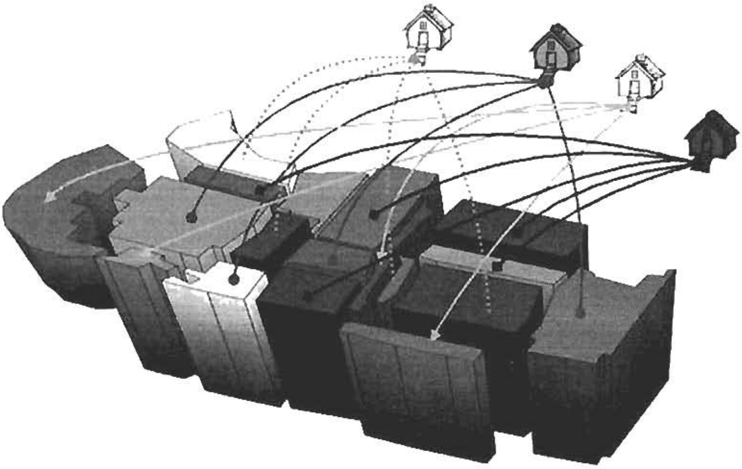

Figure 6.1 Concept diagram illustrating the interaction of management diversity and landscape heterogeneity in anthropogenic landscapes.

We will use two examples to demonstrate our village scale approach to assessing and remedying the negative impacts of synthetic N fertilizers in subsistence village ecosystems. We will show that N loading and losses from paddy fields vary greatly between land managers, and that solutions to N overapplication require a full understanding of the basis for this management variability. We will demonstrate that adoption of synthetic N fertilizers has changed soil N sequestration, a key biogeochemical process, across entire village landscapes, even in many areas where fertilizers are not applied.

6.3 NITROGEN IN PADDY AGROECOSYSTEMS

Traditional rice/wheat paddy double cropping systems sustained 4 Mg/ha rice yields for centuries in the Tai Lake region, earning the area the title "land of fish and rice" (Ellis and Wang, 1997). In the 1930s, N inputs to these systems in the form of traditional organic amendments were less than 100 kg N/ha/yr, about the same as N removal in grain and straw; there was no significant N runoff or leaching. Synthetic N applications began increasing rapidly in the 1960s, reaching 500 kg N/ha/yr in the late 1980s. By 1994, synthetic N had increased from 0% of paddy fertilizer N to more than 80%, displacing traditional organic inputs (Ellis and Wang, 1997). Over the same period, nitrate pollution and eutrophication became serious regional problems (Ma, 1997).

Relationships between N fertilizer loading, yield, and N losses in rice/wheat paddy fields are illustrated in Figure 6.2, along with 1994 N fertilizer inputs (chemical plus organic) by surveyed farmer households in Xiejia village. If relationships between N loading, loss, and yield were linear, every increment in N loading would boost both yields and losses. However, as Figure 6.2 illustrates, these relationships are nonlinear, and are best described by three phases: a limiting phase, in which yields can be increased without major N losses, an optimal phase, in which yields are maximized, and a saturating phase, in which every increment in N loading intensifies N losses while diminishing yields.

N applications by a surprising number of farmers, about 20%, are in the saturating phase, with yields reduced significantly by N overapplication (Figure 6.2). Although the average N loading for village farmers is within the optimal phase (~480 kg N/ha/yr), about half of village farmers apply more than the average and are contributing to N losses without any possible yield benefit. As a result of the nonlinear relationship between N loading and loss, using the average farmer N loading to estimate village paddy N losses underestimates the true value of such losses by ~5% compared with the average across each farmer's paddy land ~184 vs. 194 kg N/ha/yr; Village households have about the same amount of grain land in China.

To reduce N losses without reducing yields, an extension program might encourage all farmers to limit their N inputs to the current annual average (~480 kg N/ha/yr). According to the simple N loading/loss model of Figure 6.2, this strategy could reduce village paddy N losses by ~19% of their current total without reducing yields. However, the wide variability of household N inputs suggests a solution that might require less effort.

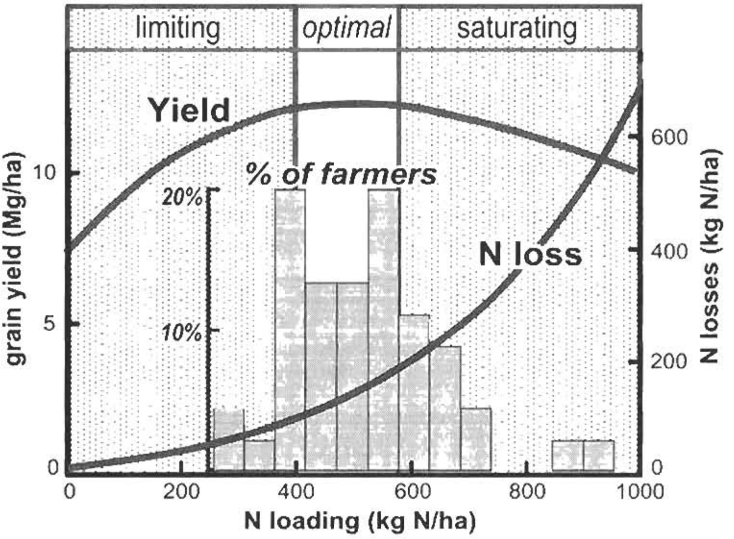

Figure 6.2 Annual N loading to paddy fields, yields of rice and wheat (unprocessed), and N loss (including denitrification, leaching, and runoff), superimposed on a histogram of N loading by a sample of 50 farmer households surveyed in Xiejia Village, 1994 (Ellis et al., 2000b).

When household N inputs are divided into four groups based upon input levels, as shown in Figure 6.3, it is evident that the group applying the most N uses much greater amounts than the others. By reducing the inputs of this highest group, comprising only 25% of village farmers, N losses would be reduced by ~16%, nearly the same as if all farmers reduced their inputs to the average.

Farmers in the highest input group also have proportionately higher organic N inputs than other farmers (Figure 6.3; R2 = 0.46). Village animal managers tend to overapply both organic and chemical nutrients as "insurance" because it is difficult to estimate manure nutrient content and because manure storage is limited. This same effect has been observed in North America (Nowak et al., 1998).

To generalize, whenever *farmer types* with consistently higher nutrient inputs (such as *animal managers*) can be identified, programs to lower nutrient losses can maximize their success by targeting these farmers over the bulk farmer population. This strategy, however, depends on understanding the full range of fertilizer management by farmers; using averaged data both obscures the biogeochemistry of N losses and eliminates the management information needed to eliminate these losses.

6.4 NITROGEN SEQUESTRATION IN VILLAGE SOILS

The majority of N in most ecosystems is stored in soil organic compounds (Stevenson, 1986). As a result, relatively small changes in soil N storage can transform landscapes from sources to sinks of N, with potentially global implications (Simpson et al., 1977). Soil N storage varies considerably across landscapes, influenced by

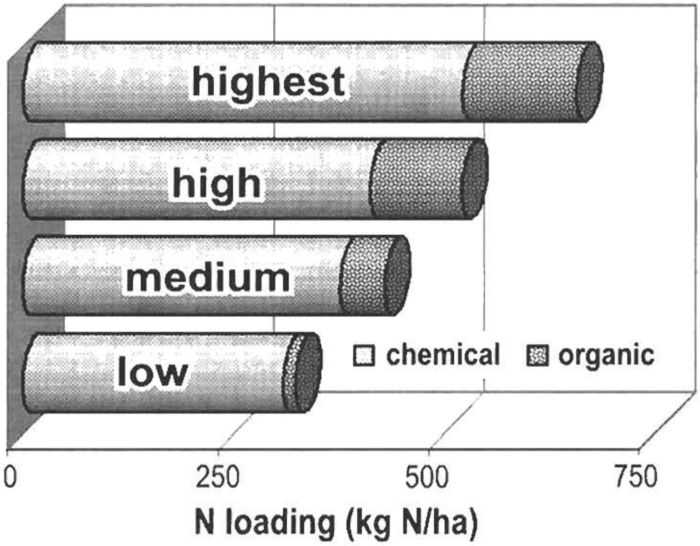

Figure 6.3 Annual N loading to paddy fields by 50 households in Xiejia village, 1994, separated into quartiles based on their amount of N loading and averaged within quartiles. Chemical inputs are urea, ammonium bicarbonate, and compound fertilizers; organic inputs are human and animal manures.

such factors as terrain (erosion and runoff), management (fertilizer, harvest, burning), and hydrology (dry areas leach more nitrate, moist areas have greater ammonia volatilization and denitrification) (Stevenson, 1982). See Figure 6.4.

To measure long-term changes in soil N storage, subsistence village landscapes must first be stratified into relatively homogeneous landscape components for

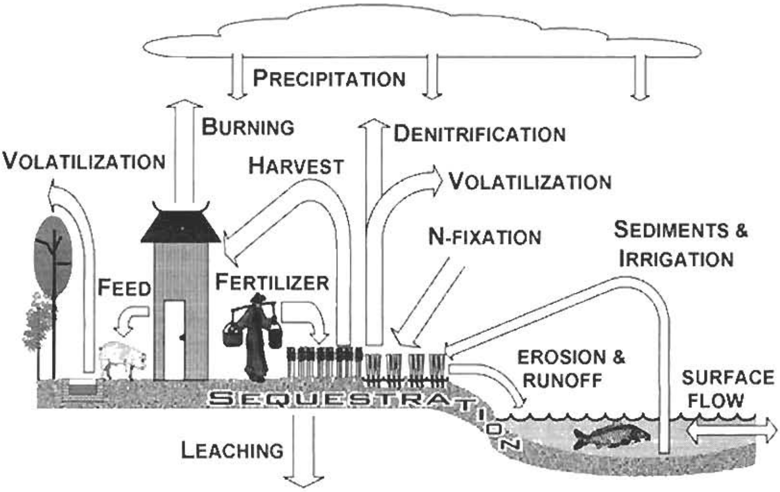

Figure 6.4 Biogeochemistry of nitrogen across village landscapes.

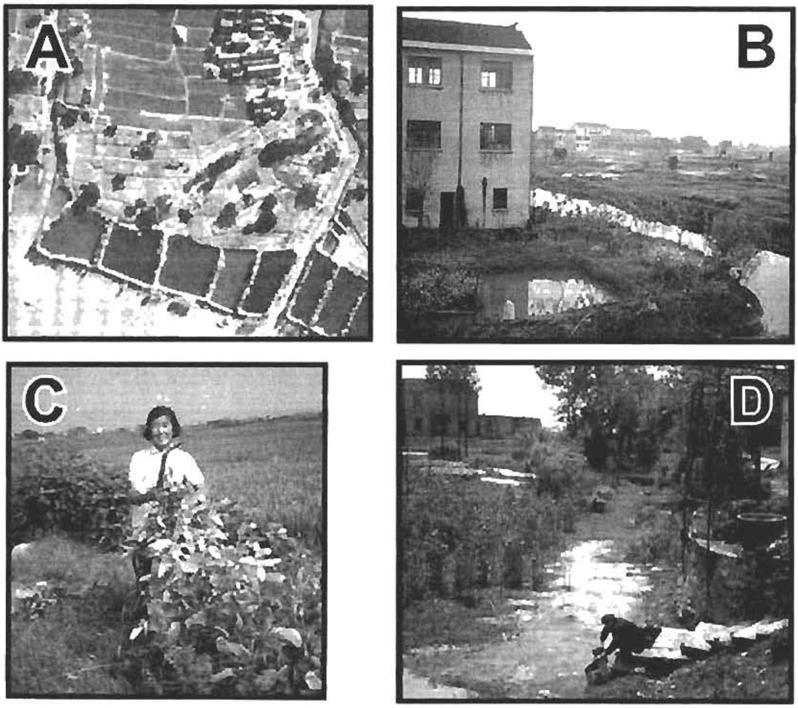

Figure 6.5 Fine scale heterogeneity in village landscapes. (A) Village landscapes near Tai Lake, Wuxi, China 1924, illustrating rice paddy fields, paddy bunds, paths, houses, upland plots, fish ponds, village canals and individual mature trees; pond edges are lined with mulberry trees (Buck, 1937). (B) Canals, houses and upland plots in Xiejia village, 1994; note fine scale landscape management, including individual evergreen trees. (C) Harvesting soybeans from field borders; soybeans and broadbeans are grown only in field borders. (D) Canal nearly filled with sediment in Xiejia village, 1995.

sampling and analysis. Figure 6.5 illustrates the fine scale heterogeneity of village landscapes. Figure 6.6 presents the anthropogenic landscape classification system used to stratify heterogeneity into ecologically homogenous "ecotope" landscape components in Xiejia village (Ellis et al., 2000b). By measuring soil and sediment N storage in the top 40 cm of soil and in the low density sediments (<1.3 g/cm^3) of each village ecotope in 1930 and 1994, long-term changes in N sequestration were calculated by subtracting the ecotope N storage estimates for 1994 from the estimates for 1930 (Ellis et al., 2000a).

N storage in Xiejia village soil and sediment increased by ~25% overall from 1930 to 1994 because N concentrations in agricultural soils increased by ~20% and N-rich sediments have filled village canals (Ellis et al., 2000a) Figure 6.5D shows such a canal. Increased N concentrations in paddy and other agricultural soils account for about half of the total village soil N storage increase; they are best explained by the stimulation of plant and soil biomass production by synthetic N subsidy of agroecosystems. The remaining half of the N buildup was caused by sediment accumulation since the end of communal agriculture in 1982, when inexpensive

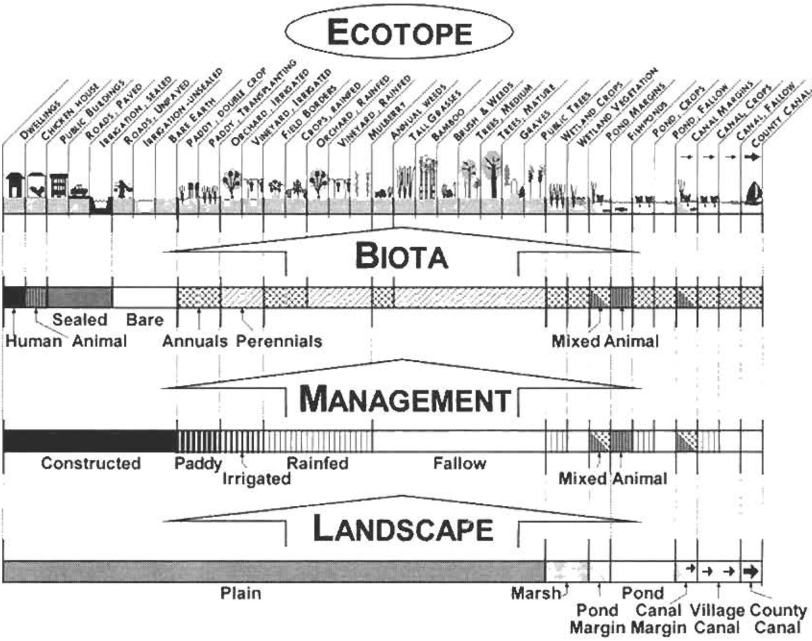

Figure 6.6 Anthropogenic landscape classification hierarchy for all ecotopes in Xiejia village (Ellis et al., 2000b).

synthetic N replaced the traditional labor intensive practice of harvesting canal sediments for fertilizer. At current rates, sediments will completely fill most village canals within 25 years, increasing flood risk and impeding irrigation and transport. This unanticipated environmental impact is an indirect result of the transition from traditional organic fertilizers to synthetic N.

In the traditional system, conflicts arose over rights to use nutrient rich sediments for fertilizer. Now, there are clashes over who is responsible for clearing irrigation canals when water fails to reach irrigation pumps as it did in the regional drought of 1994. What can be done with nearly 30 tons of sediment entering canals, marshes, and ponds every year for every hectare of village land? Some efforts have been made to mechanize the use of sediments for fertilizer, but farmers have little incentive to use these methods when inexpensive fertilizers are such convenient, labor saving substitutes. It is likely that money will have to be spent to clear sediments in village irrigation canals — an unforeseen cost of synthetic N that will have to be accounted for eventually.

Synthetic N has also displaced another traditional fertilizer — nightsoil (human manure). In the past, most nightsoil was applied primarily to paddy land, at rates rarely exceeding 40 kg N/ha/yr. Now, to save labor, most nightsoil is applied to small upland plots near houses at rates often exceeding 200 kg N/ha/yr, transforming nightsoil from a valued fertilizer into an excess nutrient input in the drier areas of the village most susceptible to nitrate leaching. It is likely that manure management systems will need to be developed to reduce the labor requirements of composting and spreading these manures over larger areas, most likely at some cost to farmers or the state.

Inexpensive synthetic N, combined with the high demand for rural labor in the Tai Lake region, is driving major changes in N biogeochemistry across subsistence village landscapes. These changes are evident in village canals and wetlands, and in the upland plots that are still fertilized using only manures. To assess the long-term ecological impacts of synthetic N in subsistence agriculture regions, biogeochemical changes must be monitored across the highly heterogeneous anthropogenic landscapes of rural village ecosystems. The economic impact of the displacement of traditional fertilizer management by synthetic N must be considered in assessing the agroecological impact of this input. Considering the cost of sediment and waste management reveals that traditional fertilizer systems provided "agroecosystem services" that must now be replaced, most likely at considerable cost to the state.

6.5 NITROGEN AND SUBSISTENCE

Though traditional grain yields were ecologically sustainable in the Tai Lake region, they are insufficient to feed today's doubled village populations. This predicament is illustrated by the question mark and arrow in Figure 6.7, which points from the 1985 population per hectare of paddy land in Wujin county to the number of people who could be fed by grain protein produced by paddy land under the traditional management conditions of 1930 since subsistence populations must generally produce at least twice their minimum food requirements to attain food security (Luyten

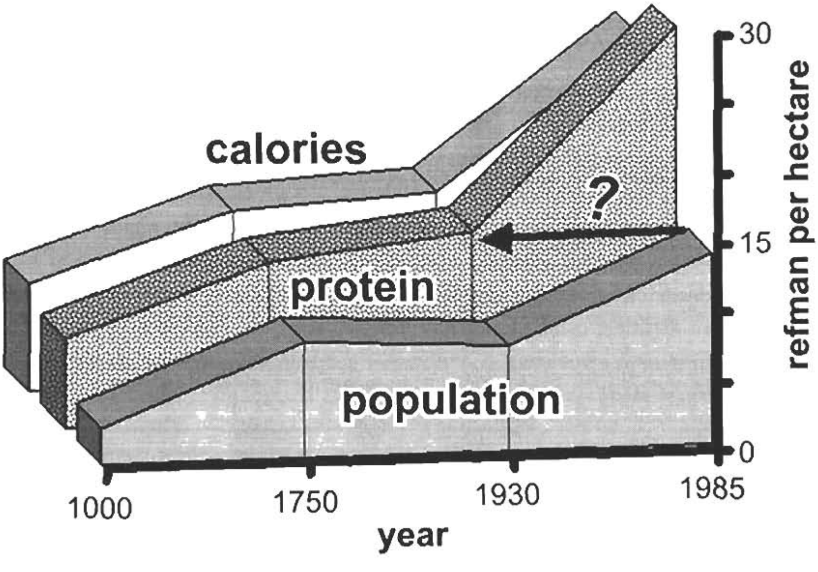

Figure 6.7 Human nutritional carrying capacity of rice/wheat systems, 1000 A.D. to 1985. Chinese standard "reference man" (refman) units are used to express population per hectare of paddy land (refman per hectare); these units standardize populations by the size of their nutritional requirements. "Protein" and "calories" describe the number of people who could be fed by the grain protein or calories produced per hectare of paddy land at the times indicated (Ellis and Wang, 1997).

et al., 1997), it is clear from Figure 6.7 that current populations would have inadequate food under traditional production conditions.

Paddy land per capita dropped from 0.11 ha in 1930 to 0.05 ha in 1994 and is still declining. Although they require more than 5 times as much N overall, modern varieties and synthetic N now appear essential in producing the ~12 Mg/ha of rice and wheat that feeds current village populations. The availability of nitrogen limited traditional rice yields, even with the best traditional management using legume green manures, sediment composts, and careful husbanding of animal and human manures. Nitrogen removal in current grain and straw production is about 230 kg N/ha, more than twice the total N loading from traditional fertilizer inputs to paddy land.

These data confirm the basic facts: N is most often the limiting nutrient in ecosystems. Sustaining high grain yields is critical for village food security. To maintain food security in subsistence agricultural regions, N management must sustain high yields without causing excessive environmental damage. Evidence from China's Tai Lake region reveals that synthetic N management can be improved to lessen its negative impacts. There is potential for revitalizing the use of traditional N inputs, such as sediments and nightsoil in order to substitute for much of the N now supplied by synthetic fertilizers; this will require both labor saving technology and political intervention.

6.6 CONCLUSIONS

A village scale approach to measuring and mediating the impacts of synthetic N is essential in securing the long-term sustainability of subsistence agriculture. In contrast with regional analyses based on data from the county level and above, village scale analysis can identify both the sources of environmental problems and the pathways toward solving these problems. In the densely populated agricultural landscapes that cover as much as 8×10^6 km^2 of the earth's surface, these methods are necessary both for assessing long-term biogeochemical change and in forming policies that can remedy the negative impacts of these changes. Similar methods for anthropogenic landscape classification and manager level analysis should prove useful in other densely populated anthropogenic landscapes as well, such as those of urban and periurban areas. By monitoring the long-term impacts of synthetic N and other industrial inputs across entire village ecosystems, solutions can be developed that sustain both agricultural productivity and environmental quality for the populations of subsistence agricultural regions.

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