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Sustainable Traditional Agriculture in the Tai Lake Region of China

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Abstract

Traditional agriculture in China's Tai Lake Region sustained high productivity for more than nine centuries. This article examines the ecological basis for this high long-term productivity in a historical context, with a focus on the role of nutrient limitation. From 1000 AD to the 1950s, agricultural technology remained basically unchanged, as did the yields of rice, wheat and other crops. Still, total grain production and net farm income increased over time, as a result of increased multiple cropping, expanded mulberry/silk production, and the intensified use of organic fertilizers. Without degrading soil resources, continuous intensive farm management supported the nutritional and other needs of the rural population, which grew to nearly ten people per hectare of cultivated land by the 1930s. Ecological limitations to human carrying capacity that seem apparent in the mid 1800s appear to have been overcome since the 1960s by chemical nitrogen subsidy of agroecosystems. Human populations are now nearly twice their traditional maximum, and the region remains one of the world's most productive agricultural regions thanks in part to heavy fertilizer applications that have changed nitrogen from a limiting nutrient to a potential source of pollution. Whether these high inputs and/or other agricultural technologies will continue to sustain food self-sufficiency for the region's farmers remains to be seen. The high long-term productivity of Tai Lake Region agroecosystems make them ideal for study of the ecological basis for sustainable agriculture.

Keywords: Sustainable agriculture; Traditional agriculture; Wetland rice; Agriculture history; Nutrient cycling; Nitrogen limitation

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1. Introduction

Traditional agroecosystems are the only time-tested examples of sustainable agriculture that exist today. This article will show that traditional agriculture in China's Tai Lake Region is a valuable model for research into the ecological basis for sustainable agriculture that can teach us much about developing a more sustainable agriculture for the future. By historical reconstruction of the factors contributing to the system's long-sustained high productivity, the importance of ecological constraints to sustainable agriculture, such as nutrient limitation, will be uncovered and discussed.

Sustainable agriculture results from the favorable interaction of social, economic and ecological factors (Cai and Smit, 1994a). This article, however, will focus on the ecological component of sustainability

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(Gliessman, 1990): the ability of agroecosystems to remain productive at a constant or increasing level, without degrading the natural resource base upon which future productivity will depend. Whenever agroecosystem productivity declines over time, or natural resources are degraded over time, an agroecosystem can be proven ecologically unsustainable. However, to prove that an agroecosystem is ecologically sustainable, it must be tested for a very long time period, because soil and other ecosystem properties can change for centuries in response to specific management interventions (Glendining and Powlson, 1995). For this reason, it is too early to prove the ecological sustainability of any modern agroecosystem, though the ecological unsustainability of many modern systems has already been demonstrated (World Commission on Environment and Development, 1987). Traditional agroecosystems with long histories of sustainable management are therefore essential for research into the ecological basis for sustainable agriculture.

1.1. Measuring sustainable productivity in traditional agroecosystems.

In studying traditional agroecosystems, it must be recognized that they differ from modern agroecosystems in both technology and ecological scale (Mitchell, 1984). Modern agroecosystems maximize the production of marketable outputs, and the link between agroecosystems and consumers is uni-directional. In traditional subsistence agroecosystems, farm families are the major consumer and the link between agroecosystems and consumers is bi-directional: agricultural and other wastes are recycled within the system. These distinctions are not absolute: traditional systems may be managed for marketable output; wastes may not be recycled; or food may be purchased. Nevertheless, to the extent that their food comes from the system and their wastes return, farmers are ecologically integrated components of traditional agroecosystems (Mitchell, 1984). Therefore, the scale of traditional agroecosystems is the farming village, and farm population a component, while the field or feedlot is the scale of modern agroecosystems.

Whole-agroecosystem productivity is the appropriate yield measure for ecological study of long-term productivity. Total annual yield per unit of land, water, or confined livestock is relevant, but the key measure for whole-system productivity in traditional subsistence agroecosystems is human carrying capacity: the human population density (population per land area) that the system can support for a given length of time (Fearnside, 1986). Though food is just part of the support traditional systems provide to farmers, the total amount of food produced per unit of village area is a reliable basis for calculating human carrying capacity in traditional systems, as long as agriculture remains the primary food and income provider (Fearnside, 1986). Given that traditional farming populations tend to expand to meet their carrying capacity, high population density is a good indicator of high agroecosystem productivity in traditional systems, as long as this high density has been sustained over several generations (Grigg, 1974). To search for examples of productive and ecologically sustainable traditional agriculture, whole-agroecosystem productivity, carrying capacity, and population density are the key indicators; by applying these tools, sustainable traditional systems can be identified.

1.2. Identifying sustainable traditional agriculture.

Meaningful examples of sustainable agriculture for future development must have relatively high levels of productivity, in the same order of magnitude as that of modern systems in the same environment: decreases in agricultural productivity cannot sustain the earth's growing human populations. In addition to this caveat, two requirements must be met before a traditional system is judged useful for the study of ecological sustainability. First, there must be evidence of continuous productivity in the agroecosystem, without decline or abandonment, for a period of many centuries. This can be shown by high and stable farm population density, human carrying capacity, and/or crop yields. The second requirement is that the system must show no signs of environmental degradation, such as loss of soil fertility, erosion, water pollution, etc.

Very few traditional agroecosystems meet the above requirements. In general, traditional systems have much lower yields than modern systems, especially when all land under fallow or pasture is considered (Grigg, 1974). Moreover, there are few traditional systems with documented histories of continuous management; land was deserted periodically in most ancient systems, often for decades or centuries, allowing the system to return to a fertile state (Howard, 1943; Dale and Carter, 1955). Though land was sometimes abandoned owing to natural disasters and warfare (Whitney, 1925), the exhaustion of soil fertility by unsustainable farm management was a factor in land abandonment and the decline of civilizations, such as those of the Romans, Mesopotamians, and others (Whitney, 1925; Dale and Carter, 1955; Olson, 1981; Sandor and Eash, 1991). In general, the history of traditional agriculture teaches us more about unsustainable management than about sustainable methods.

Fortunately, some traditional agroecosystems do meet the criteria for study of ecological sustainability. Agriculture within the Nile delta of Egypt appears to have sustained good yields of wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) for more than five millennia, but this productivity was much lower than that of modern rice (*Oryza sativa*) cropping systems in the area (Whitney, 1925; FAO, 1987). The world's most productive and ecologically sustainable traditional agricultures are the East Asian rice-based systems of the Kinki and Kanto plains of Japan, the Red River delta of Vietnam, and China's Yangtze river delta, Chengdu basin and Zhujiang (Pearl River) delta (Howard, 1943; Grigg, 1974). The highest population densities and the most long-lived civilizations are found in these regions, where populations and agriculture recover quickly from natural and other disasters (Grigg, 1974). Though all of these systems are located in fertile river valleys and deltas with stable climates favorable to agriculture, the importance of traditional farm management to ecologically sustainable agriculture should not be underestimated. In all of the systems listed above, farmers used regular, intensive applications of organic fertilizers to sustain high yields, a surprisingly rare practice in traditional agriculture (Howard, 1943; Grigg, 1974). Furthermore, the cropping systems and methods used in all of these areas originated in south China, most likely in the Yangtze delta region, more than one thousand years ago (Grigg, 1974). This may

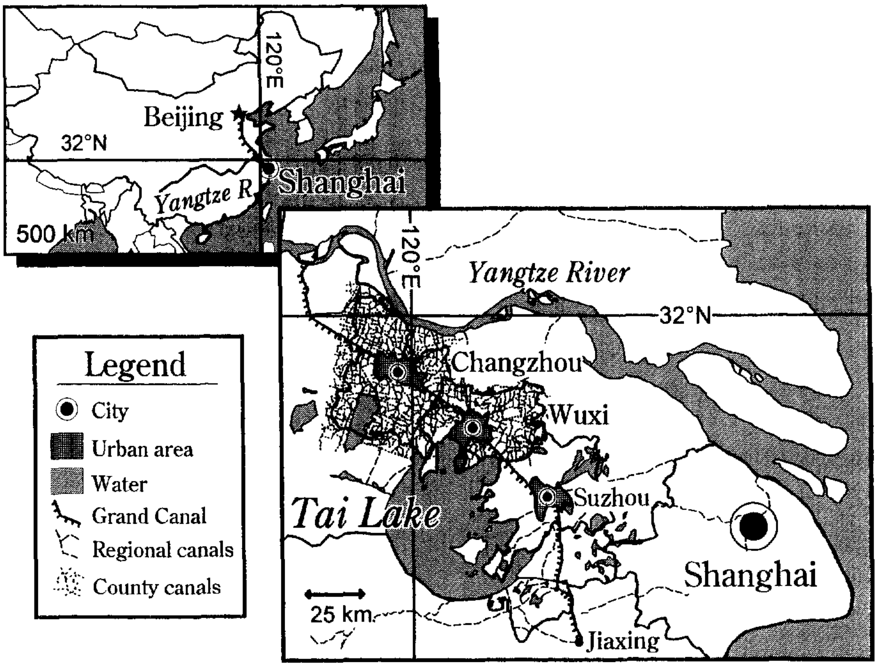

Fig. 1. Map of the Tai Lake Region, People's Republic of China, ca. 1990. The Jiangsu Province cities of Changzhou (capital of Wujin County), Wuxi and Suzhou are labelled to the right of their urban areas, as is Jiaxing city of Zhejiang Province (see legend). Heavy lines show county and city boundaries, county-level canals are shown for Wujin and Wuxi counties only.

be a coincidence, but the remarkable long-term success of this set of technologies argues for a closer look at agriculture in the Yangtze delta, also known as the Tai Lake Region (Fig. 1).

2. The Tai Lake Region as an example of sustainable agriculture.

The Tai Lake Region is an ideal place to grow rice. The region's soils are naturally fertile, ranging from permeable loess in the corridor between the Yangtze and Tai Lake from Changzhou to Suzhou, to the polder and alluvial soils south and east of Suzhou (Fig. 1; Thorp, 1936; Xu et al., 1980). The region's northern subtropical monsoon climate favors rice and other crops with 1100–1400 mm of annual precipitation, annual mean temperatures around 16°C and a growing season of 290 days, 230 of which are frost-free (Xu et al., 1980). Drought and floods, though common, are less frequent in this region than in the courses of the Yellow river (Huang, 1990). By continuous deposition of sediments and periodic flooding, the nutrient-rich waters of the Yangtze provide a long-term natural nutrient subsidy to the region (King, 1911).

The productivity of Tai Lake Region agriculture has been exceptionally high since ancient times (Elvin, 1973) and today's rice yields are still among the highest on earth (Powell, 1992). Since the Tang dynasty (ca. 800 AD), the Tai Lake Region's intensive farming practices have been promoted in agricultural treatises as the ideal model for emulation by farmers elsewhere in China (Deng, 1993). Most of China's farmers used less fertilizer, had lower yields, and endured extreme hardship using traditional methods (Buck, 1937a). The question remains: how much of the Tai Lake Region's exceptional long-term productivity is the result of a favorable environment, and how much is due to good farm management? At least part of the answer can be found in the region's long agricultural history, as documented in archaeological finds, agricultural treatises, estate records, and local gazetteers.

2.1. *Early development of the Tai Lake Region agroecosystem.*

Humans settled in the Tai Lake Region more than 15 000 years ago (Huang, 1990), and by as early as 6500 BC, sophisticated farming societies were managing livestock and growing rice and other crops in the region (Smith, 1995). Though rice is traditionally thought to have been introduced to China after domestication, current evidence suggests that rice was originally domesticated along the Yangtze river more than 8000 years ago (Smith, 1995). Domestic chickens first appeared around 5300 BC, and evidence of domestic pigs and water buffalo date to 4500 BC, just south of the Tai Lake Region (Smith, 1995). Other early domesticates were water plants such as lotus (*Nelumbo nucifera*) and water chestnut (*Eleocharis tuberosa*) (Harlan, 1995).

Though agriculture was still at an early stage of development in 9 AD, nearly all of the crops and animals now grown in the Tai Lake Region were already in use, including wheat, barley, soybeans (*Glycine max*), broadbean (*Vicia faba*), field peas (*Pisum sativum*), "a thousand varieties" of vegetables and fruits, mulberry (*Morus alba*) for silkworms (*Bombyx mori*), along with domestic water buffalo, oxen, goats, pigs, poultry, and freshwater fish (Perkins, 1969; Harlan, 1995). Tea (*Camellia sinensis*) and cotton (*Gossypium hirsutum*) were introduced between 200 and 700 AD (Perkins, 1969). With the exception of sweet potato (*Ipomoea batatus*), the New World crops introduced after 1500 have never become important in the region (Perkins, 1969).

An outline of key events in the development of Tai Lake Region agriculture is presented in Fig. 2. New technologies were often introduced at an early time and adopted more slowly. For example, rotation of cereal grains with legume green manures was first mentioned before 500 AD, but this was not common practice before 1000 AD (Chen, 1958). Animal manures, nightsoil (human manure), cooking ash, canal sludge (sediments scooped from canals), oilcakes (residues from oil pressing) and compost were all in use as fertilizer by 500 AD but their use was probably not intensive or extensive until centuries later (Elvin, 1973; Liu and Jin, 1991).

2.2. *Population and development.*

In 300 AD, when the first mass of impoverished Northerners arrived, the Tai Lake Region was still sparsely populated and economically unimportant in China (Perkins, 1969). Beginning around 400 AD,

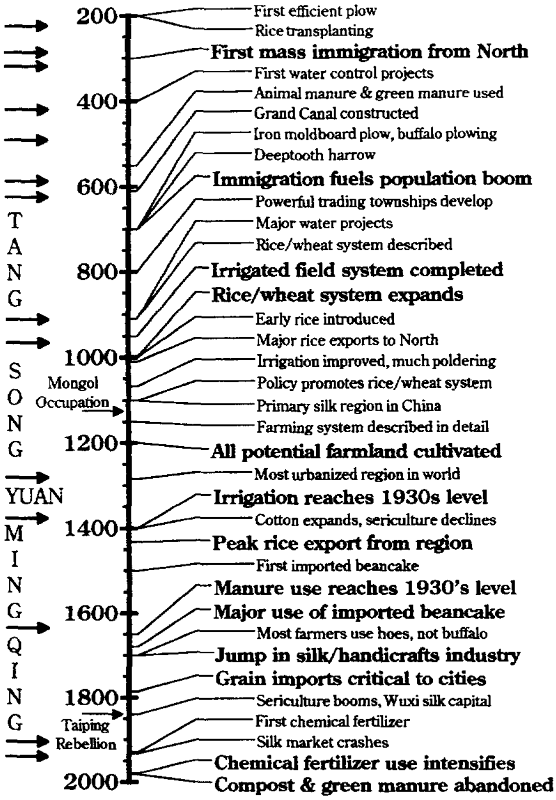

Fig. 2. Tai Lake Region agricultural development timeline, AD 200–1996. Arrows on the left mark revolutions and dynastic change; five major dynasties are labelled. On the right, turning points in agricultural intensification are marked in bold text, normal text denotes less important developments and technology introductions/descriptions (Chen, 1149; Perkins, 1969; Elvin, 1973; Stuermer, 1980; Chang, 1976; Zhu and Xu, 1988; Huang, 1990; Jiangsu Department of Agriculture, 1990; Powell, 1992; Shih, 1992; Guo, 1994; Tan, 1994).

water control projects and land reclamation began to bring more of the swampy Tai Lake plains under cultivation (Elvin, 1973). The success of this development is evident in the construction of the Grand Canal in AD 605, partly to bring rice and silk taxes to the North (Fig. 1; Elvin, 1973). The region's population swelled in the 8th century owing to the influx of famine-stricken northerners (Elvin, 1973), and by the 10th century there was enough local labor to construct the hydraulically efficient network of canals and embanked-fields that still dominate the region's landscape (Fig. 1; Huang, 1990). This development was a turning point for Tai Lake Region agriculture. Efficient irrigation and land reclamation in the 10th century facilitated the widespread adoption of paddy rice and mulberry-fed silk production that would be the basis for intensive agroecosystem management for more than one thousand years.

3. Sustainable agroecosystem management, AD 1000–1950.

The period AD 1000–1950 is an ideal timeframe for observing the impact of population growth and agricultural intensification on the ecological sustainability of Tai Lake Region agriculture. By the Song dynasty (AD 982–1279), China, and the Tai Lake region in particular, had reached a level of technological and agricultural sophistication that would not be rivalled in Europe until the 1600s (Elvin, 1973; Chao, 1986). From the 10th century to the 1950s, agricultural productivity and management intensity increased over time, in response to growing population pressure, even though agricultural systems changed little in terms of technology or ecological structure (Perkins, 1969; Elvin, 1973; Chao, 1986; Huang, 1990). To clarify the process by which Tai Lake Region agroecosystems sustained this long-term increase in productivity, their basic ecological structure and management will be described first, followed by the temporal pattern by which population increased and management was intensified.

3.1. The traditional rice / mulberry agroecosystem.

Traditional village agroecosystems of the Tai Lake Region were highly integrated: nearly all material and biota were put to use in service of the human population (King, 1911). Village agroecosystems include the human population, livestock, crops, land, water, and the myriad wild plants, animals and other biota that either competed with the domestic biota, supplemented the diet, or were simply along for the ride. The focus of this paper is the single-crop rice/mulberry-silk village agroecosystems of the Wujin and Wuxi county loessal plains (Fig. 1) and to a lesser extent those of the wetter Suzhou and Jiaxing polder areas, as distinguished from the cotton-producing systems in the region's drier north and the double-cropping rice systems in the warmer south (Huang, 1990).

3.2. The farm population.

Farmers of the Tai Lake Region lived, and to some extent still live, in familial household dwellings clustered along canal banks in small groupings called "natural" villages in Chinese (Huang, 1990). Most rural households farmed a mix of owned and rented land, though some were landless tenants (fewer than 30% of all farmers), and a few landlords did not work the fields (Shih, 1992). Land ownership varied considerably according to wealth, but the land area actually farmed per person tended to be more equal in any given year, owing to the farming system's intensive labor requirements. Most food and cooking fuel were produced and consumed on-farm, with the exception of oil, sugar, pork, and fish (Buck, 1937a; Huang, 1990). Other necessities, such as salt, tobacco, and materials to make clothing, were purchased using income generated by sale of grain, silk, cotton handicrafts and livestock (Elvin, 1973; Huang, 1990).

3.3. Land use and cropping systems.

There are two basic land-use types in Tai Lake village agroecosystems: paddy and dryland, interlaced with a network of canals and ditches for irrigation, and sometimes supplemented with fishponds (King, 1911; Wen and Pimentel, 1986a). Irrigation water was supplied to paddy fields by human- or water buffalo-driven pumps, while dryland fields were mounded above the level of rice paddies and watering was by hand, when needed (King, 1911; Cressey, 1934; Wen and Pimentel, 1986b). Though requiring much labor, paddy land was sometimes converted to dryland and vice versa in response to major changes in the relative profitability of paddy rice versus that of dryland mulberry/silk production (Huang, 1990). About 90% of cropped land was paddy, with the dryland area varying from 5–30% of total farm area (Buck, 1930, 1937a). Both paddy and dryland fields were small but numerous (less than 0.001–0.15 ha each, average ten per household), and occupied around 90% of the total farm area (Buck, 1937a). Though less than 10% of total area, "wasteland", covered with trees and/or weeds was common near buildings, along canals and on graves within the cropped areas; these areas provided fodder for goats, oxen and water buffalo (King, 1911; Buck, 1930).

By multiple cropping and intercropping, most farmland was kept covered by crops all year round. Pollarded mulberry trees were grown in most dryland fields, often intercropped with vegetables, wheat, barley, and grain legumes (broadbean, soybean, and others) in a form of agroforestry (King, 1911; Buck, 1930). In the spring, Japonica rice was planted in seed beds and then transplanted into puddled paddy fields, with soybeans often planted on the berms (Shih, 1925; Chen, 1958). After the fall rice harvest, some paddy fields were left fallow, but in most, a network of drainage trenches were dug and fields were planted to wheat, barley, Chinese milk vetch (*Astragalus sinicus*, a legume green manure), grain legumes, rapeseed (*Brassica napus*), or vegetables, usually without further tillage (Buck, 1930; Cressey, 1934; Wen and Pimentel, 1986a). Wheat and other long-season winter crops were harvested shortly before rice transplantation; by starting rice seedlings on 5–10% of the paddy area, the rice transplantation system effectively lengthened the growing season for rice and wheat by about a month (King, 1911).

3.4. Animal management.

Pig manure was once considered so essential to high yields of rice and wheat that most households raised one or two pigs per year to produce this manure, even though pig raising was not profitable in itself and farmers ate very little pork (Chen, 1958). The importance of this practice is reflected in the region's 16th century folk saying: "a farmer who doesn't raise pigs is like a scholar who doesn't read books: he will certainly be unsuccessful" (Chen, 1958). Pigs were fed purchased beancake (soybean oilcake), food and agricultural wastes, barley, rice bran, and green fodder, and lived in slate or brick-lined stalls designed for excrement collection; pig manure and urine were carefully collected and stored in the same ceramic or brick-lined tanks that also served as the household toilet (Chen, 1958). Goats were fed green fodder and straw, the uneaten portion of which accumulated in the stall, mingled with manure, and became composted before use as fertilizer; goat meat was rarely eaten and all goats were sold (Chen, 1958). Free-ranging chickens and ducks were raised, about five in total per household, for eggs and occasional meat, though most were sold out of the village (Buck, 1937a). Water buffalo and oxen were kept only for traction; there was one for every 2 ha of paddy land in the 1930s (Buck, 1937a). Aquaculture of domestic fish was concentrated near cities and towns (Bureau of Foreign Trade, 1933); outside of these areas aquaculture was uncommon.

3.5. Fertilizers and material cycling.

Tai Lake Region farmers went to great lengths to obtain and use fertilizer. Though almost all crop residues were burned for cooking, the remaining ashes were meticulously collected and stored before their return to the field, as were the excrements of all animals, including humans (King, 1911; Buck, 1937a; Chen, 1958). The most labor-intensive fertilizer of all was "oufei" compost, an anaerobically fermented mix of canal sludge, Chinese milk vetch, straw, silkworm wastes, and animal manures (King, 1911; Chen, 1958). Other common fertilizers were oilcakes, green manures, canal sludge, silkworm wastes, and any organic materials that could not be eaten, burned, or fed to animals (Chen, 1149; King, 1911; Chen, 1958). Fertilizer applications were highly crop-specific, and attention was paid to the stage of crop development and leaf color; fertilizer was added if plants became yellow (King, 1911; Shih, 1925; Chen, 1958). Some examples of this specificity are that legumes were fertilized only with ashes, oufei compost was applied only before rice transplanting, ashes were most heavily applied to rice seedling beds, and the nutrient-rich manures of pigs and humans were applied mostly to crops with the greatest nutrient needs (vegetables, cereals with yellow leaves, mulberry after leaf harvest, etc.) (King, 1911; Shih, 1925; Chen, 1958).

3.6. Population and the intensification of agriculture.

Long-term changes in human population density influenced almost every aspect of agroecosystem management in the Tai Lake Region. The pattern of the region's population growth is illustrated by the example of Wuxi County in Fig. 3; data for China and Jiangsu Province help expose trends in Wuxi where data is sparse or missing. A note on the reliability of historical data is needed here. Population statistics for traditional China are based on tax records and compulsory labor rolls; though imprecise, they illustrate general trends (Chao, 1986). Land records are also imprecise, though double accounting methods in use by the late 1300s were remarkably accurate for traditional measures (Chao, 1986). Republican and modern land data are more rigorous, but up to 1980, China's land statistics were still based on locally provided field estimates (Wu, 1984). Population density data are generally considered to be the most reliable, owing to the way that population and land data were collected (Chao, 1986). Traditional population data for China and Jiangsu Province (Fig. 3) are from Zhao (1988), who verified their plausibility using a population growth model. Population and land data for Wuxi County (Fig. 4) are raw statistics from county gazetteers (Shih, 1992;

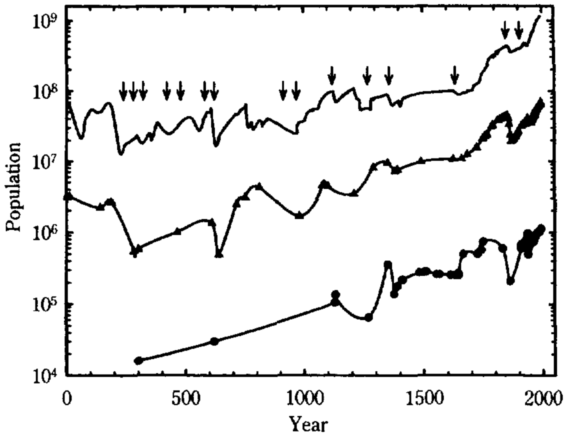

Fig. 3. Population of China, Jiangsu Province and Wuxi County, AD 0–1993. Data for pre-revolution China (line at top) and Jiangsu (▲) from Zhao (1988); post-revolution data from Editorial Board of China Agriculture Yearbook (1994). Wuxi data (●) from Tan (1994) supplemented by other sources (The Chinese Government Bureau of Economic Information, 1924; Bureau of Foreign Trade, 1933; Cressey, 1934; Du, 1987; Village Socioeconomic Survey Team of the National Statistics Bureau, 1989; Shih, 1992; Village Socioeconomic Survey Team of the National Statistics Bureau, 1993). Arrows represent the same time periods as in Fig. 2.

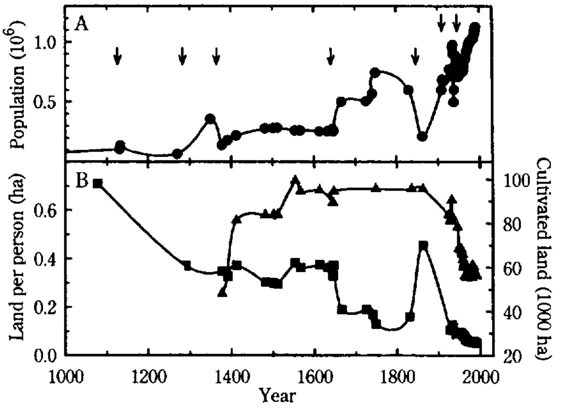

Fig. 4. Population, cultivated land, and cultivated land per person in Wuxi County, AD 1000–1993. Wuxi County population data (●) are shown in A; B shows the area of cultivated land per person (■) and the total area of cultivated land in Wuxi County (▲). Data combined from Tan (1994), Shih (1992), and other sources (The Chinese Government Bureau of Economic Information, 1924; Bureau of Foreign Trade, 1933; Stuermer, 1980; Du, 1987; Village Socioeconomic Survey Team of the National Statistics Bureau, 1989; Village Socioeconomic Survey Team of the National Statistics Bureau, 1993). Arrows represent same time periods as in Fig. 2.

Tan, 1994), and cultivated land per person was calculated directly from county records, with the exception of two pre-1300 points calculated from Changchou circuit data (an aggregate of Wujin, Wuxi and Jiangyin counties; Stuermer, 1980), and nine points which used population or land data determined by linear extrapolation from neighboring points less than 40 years distant. It should be noted that pre-1900 Wuxi County data include farmers within the administrative boundaries of Wuxi city, while later data exclude them.

Population in the Tai Lake Region increased almost 100-fold from AD 200 to the present, but this growth was far from steady (Fig. 3). Population increased by more than 300% between 700 and 1100 AD as a result of massive immigration from the north caused by famine in 700 AD and the Mongol invasion in 1100 AD (Perkins, 1969; Guo, 1994). After this, the region's population increased gradually, with periodic declines corresponding to revolutions, until the late 1600s, when the population began to boom (Fig. 3). By the late 1700s, the population of Wuxi County had risen to levels similar to those of the 1930s. This growth came to a dramatic end in the mid 1800s when populations crashed during the Taiping rebellion of 1850–1864; as many as 20 million died and emigrated during this period, as a result of war and war-induced famine (Perkins, 1969). It took nearly 100 years for the region to regain this lost population, and there is evidence that some areas had not even recovered by the 1950s (Perkins, 1969). The rapid population declines visible in the Wuxi and Jiangsu data for the late 1930s and 40s are due to deaths and chaos during the Japanese occupation.

Population growth in the Tai Lake Region reduced land availability so much that by the late 1600s, less than one fifth of a hectare of cultivated land was available per person (Fig. 4). Up to about 1100 AD, agricultural production had increased by expanding cultivated area (Chao, 1986), but after this point, nearly all readily cultivable land was in use (Stuermer, 1980) and only by reclamation of low lying land (poldering) did cultivated acreage increase until the 1400s (Huang, 1990). Land availability remained at about 0.4 ha per person in Wuxi until the late 1600s, when population growth pushed land availability down to less than 0.15 ha per person (Fig. 4B). When populations crashed in the mid 1800s, some large estates were created from abandoned land, but in general, small scale agriculture resumed as before, with a much lower population density (Chao, 1986). Population densities had returned to seventeenth century levels, and beyond, by the 1930s.

3.7. Intensification and agricultural productivity.

As populations grew, land became limiting (Fig. 4). Still, agroecosystem productivity increased over time as a result of agricultural intensification by farmers who needed more returns from the same soil and had the labor and manure needed to get them (Perkins, 1969; Huang, 1990). Increased labor availability translated into increased productivity in many ways, such as the greater attention to detail that was possible with additional labor, and the refinement and extension of the region's best methods (Deng, 1993). However, the three most important methods used to boost agroecosystem productivity over time were rice/wheat double cropping, increased fertilizer inputs, and expanded mulberry-fed silk production.

Rice/wheat double cropping was invented before 800 AD, but as late as 1000 AD, winter wheat was still rarely grown on paddy land, and tax policies were used to encourage this (there was no tax on wheat if grown after rice; Guo, 1994). Though an early-maturing Indica rice variety introduced in 1100 AD never became popular on the region's more productive soils owing to its poor quality, preference for early maturity eventually led to varieties of Japonica rice that were easier to double-crop with winter wheat (Huang, 1990). By the late 1300s, early maturing varieties and increasing demand for wheat by northern immigrants began to make rice/wheat double-cropping the most common system in the region (Guo, 1994). By the 1600s, a popular agricultural treatise described ideal winter paddy management as 2/3 wheat and 1/3 milk vetch green manure (Wen and Pimentel, 1986a). Though perhaps not universal in 1600, by the 1930s, 60% of paddy land was planted to wheat in winter (Buck, 1937b).

There is a saying that "growing wheat in winter takes away rice in autumn" (Wang and Guo, 1994), and 17th century agriculture books recommended that more fertilizer be used for both rice and wheat in the double-cropping system (Chen, 1958). There is no doubt that fertilizer use increased over time, and both wheat and rice yield may have responded to this. Growth in human population was paralleled by growth in pig population, so that pig and human manure use per hectare increased in relation to population growth (Perkins, 1969). Nightsoil was increasingly collected from cities and towns, enriching the soils within carrying distance (Thorp, 1940). In 1000 AD, the local "hu yang" goat variety was bred for use in stalls, and water buffalo and oxen were increasingly used for tillage; this increased the population of ruminants, providing even more manure for fertilizer (Liang, 1989). Increasing labor availability probably led to expanded use of canal sludge as fertilizer and increased processing of fertilizers before application; green manures were tilled directly into soil in the Song dynasty, but were later used to make "oufei" compost, at least in the most advanced areas (King, 1911; Chen, 1958). The growth in use of purchased beancake for fertilizer in the 1700s, added a net input of nitrogen to the region's agroecosystems from soybeans imported from Manchuria (Huang, 1990). By a variety of methods, fertilizer inputs increased over time.

By expanding the use of rice/wheat double cropping, productivity could rise without increasing crop yield. This begs the question: did rice yields increase over time in the Tai Lake Region? Yield increases before 1000 AD are rarely disputed, and Perkins (1969) and Chao (1986) make the case for increasing rice yield until at least 1700. The 50-year mean yields illustrated in Fig. 5A also suggest an increase, as does Chao's (Chao, 1986) comparison of rental yield records from the same land in Wujiang, in 1204–1311 and 1878–1894, which imply an increase of as much as 40%. There is also evidence that under exceptional conditions, rice yields in the 1600s could be as high as those of today (Fig. 5A and Wen and Pimentel, 1986a). Still, it must be remembered that yield data before 1920 are derived from county gazetteers, agricultural treatises and local accounts that confuse typical and exceptional yields, and use measures that vary widely over time and by locality. Though the reliability of traditional yield data is insufficient to prove that rice yield increased over time, it seems plausible that there was some increase, at least until the early 1600s, and that intensified use of fertilizers was responsible for this.

Without adding directly to food production, mulberry-fed silk production increased whole-agroecosystem productivity. Silkworm-rearing was painstaking and labor intensive, but when the market was good, it could be far more profitable than rice production (Huang, 1990). Silk production required year-round labor; mulberry leaves were harvested to feed two to three crops of cocoons from spring to fall, while silk was reeled from cocoons in winter (Huang, 1990). The markets for cotton and silk changed farming patterns radically, with rapid expansion of mulberry/silk production during boom periods in the Song dynasty, mid 1700s and mid 1800s, and with much hardship resulting when silk prices subsequently crashed and land was converted back to paddy fields (Huang, 1990). Silk reeling and cotton textile weaving during idle winter months were important ways of boosting household income, and by the early 1800s, almost every household was engaged in textile production. It is this development of supplementary income that is believed to have supported the population explosion of the 1700s (Huang, 1990; Shih, 1992). After the silk market crash of 1932, the region's silk production collapsed and did not recover (Huang, 1990).

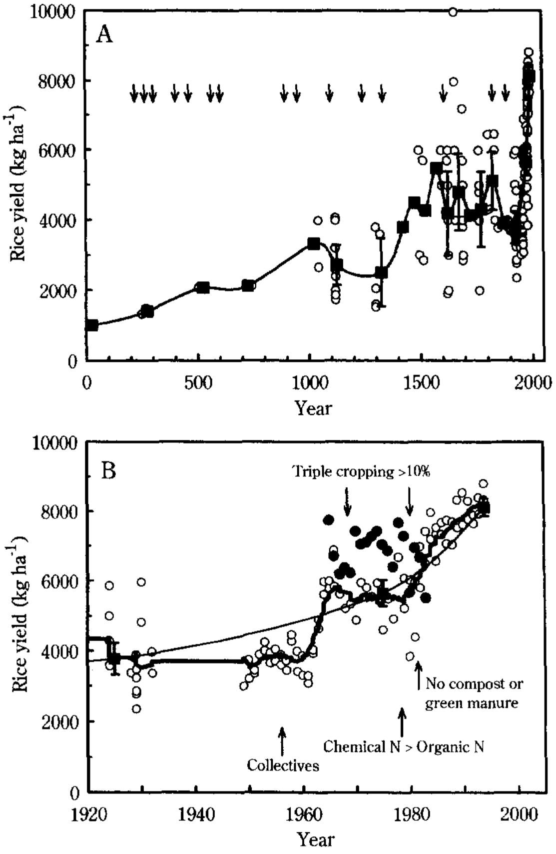

Fig. 5. Rice yield history of the Tai Lake Region, AD 0–1994. Yields of single-cropped late Japonica rice (rice + hulls) are presented at two time resolutions: (A) AD 0–2000; and (B) AD 1920–1994. Both A and B show individual yield records (○) and a curve of 50 year interval means (■) with 95% confidence error bars (the final two intervals are 1950–1994 and 1990–1994). The heavy line in part B represents an 11-point moving average of yields (5 points before and after current point). The total yield of double-cropped rice (●) is presented in part B; arrows mark key agricultural intensification events as indicated. Data before 1000 AD are for South China (Chao, 1986; Liu and Jin, 1991), data for 1000–1949 are from sites within the Tai Lake Region (The Chinese Government Bureau of Economic Information, 1924; Buck, 1930; Buck, 1937b; Perkins, 1969; Elvin, 1973; Zhu and Xu, 1988; Agriculture Heritage Institute of the Chinese Academy of Agricultural Sciences, 1990; Huang, 1990; Liu and Jin, 1991), and data after 1949 are for Wuxi and Wujin counties (Jiangsu Statistical Bureau, 1985–1995; Zhu and Xu, 1988; Tan, 1994). Arrows in part A represent same time periods as in Fig. 2.

3.8. *The standard of living over time.*

As population increased, so did production (Huang, 1990). Though this sustained increase in population and production is remarkable, it was made possible by intensifying agricultural management to the point of "involution", when additional labor and material inputs yielded rapidly diminishing returns (Huang, 1990). Labor inputs to agriculture had reached extreme levels by the 1700s (more than 3700 h ha^{-1} year^{-1}; Wen and Pimentel, 1986b), and there are many indications that this caused much hardship for farmers. Human labor replaced animal traction as populations increased, and local proverbs noted that human labor was cheaper than that of animals (Perkins, 1969). Farmers could never afford to wear the silk they produced; silk was traded for raw cotton from which they made their own garments (Huang, 1990). Poorer farmers grew Japonica rice, sold it, and purchased enough of the disliked Indica rice to survive (Bureau of Foreign Trade, 1933). By the mid 1800s, the level of subsistence was so close to production that winter clothes were pawned in summer to buy grain, to be repurchased after the fall rice harvest (Elvin, 1973).

High population density influenced both the diet of local farmers and the supply of grain to cities. By the mid 1700s, population growth had well outpaced grain production (Table 1). Farm diet was heavily dependent on grains, with rice providing 64% of all energy consumed, and protein from grains and legumes providing nearly 94% of all dietary protein (Table 1). By eating an essentially vegetarian diet, traditional Tai Lake farmers received adequate nutrition, though the lack of animal products in the diet was considered a hardship (Buck, 1937a). Increasing population and tenancy gave declining returns for grain production, as tenants generally gave half the rice crop and 40% or less of the following wheat or other crop to the landlord (Chao, 1986). The relatively slim margin between grain production and consumption in the 1750s is striking (approximately 30%; Table 1), even though this is partly explained by overestimated 1750 population density, underesti-

Table 1
Annual productivity and carrying capacity of paddy land

Productivity, demand and capacity	Chang-chou [a] ca. 1000	Jiaxing/Wuxi [b] ca. 1750	Wujin [c] ca. 1930	Wujin [d] ca. 1985	USA [e] ca. 1980
Productivity					
Multiple cropping index [f]	105%	166%	179%	190%	—
Grain yield (kg ha^{-1}) [g]	3354	4767	5116	9607	4002
Grain yield (kg refman^{-1}) [h]	1281	571	1094	708	2962
Grain energy (GJ ha^{-1}) [i]	33.7	49.2	52.2	95.7	48.4
Grain protein (kg ha^{-1}) [j]	182	288	331	750	288
Rice yield (kg ha^{-1})	3323	3900	4496	6983	5209
Rice energy (GJ ha^{-1})	33.8	39.2	45.2	70.2	na
Rice protein (kg ha^{-1})	179	210	276	518	na
Nutritional demand [k]					
Total energy (GJ refman^{-1})	*3.87*	*3.87*	3.87	3.92	3.60
Total protein (kg refman^{-1})	*25.0*	*25.0*	25.0	27.3	33.2
Rice energy (GJ refman^{-1})	*2.46*	2.45	2.46	2.95	0.304
Rice protein (kg refman^{-1})	*13.2*	13.0	13.2	14.6	1.63
Plant protein as % of intake	*94.1%*	*94.1%*	94.1%	89.5%	29.7%
Carrying capacity [l]					
Energy carrying capacity (refman ha^{-1})	8.71	12.7	13.5	24.4	na
Protein carrying capacity (refman ha^{-1})	7.28	11.5	13.3	27.5	na
Persons per hectare of paddy land (refman ha^{-1})	2.62	8.34	6.15	13.90	1.35
% Energy carrying capacity used by farm population [m]	36.0%	72.4%	46.4%	50.6%	na

Italics mark duplicated data. Food nutrients calculated from Institute of Nutrition and Hygiene (1991). [a] Chang-chou data (Wujin, Wuxi and Jiangyin counties combined) from Stuermer (1980), yields are AD 1000–1200 average (Fig. 5), assuming 5% paddy area planted to winter wheat with 70% of 1920s yields (same as rice yield difference). [b] Data from Wen and Pimentel (1986b) and Shih (1992). [c] Data from Zhu and Xu (1988) and Buck (1930, 1937b). [d] Data from Zhu and Xu (1988); nutrition data for 1982 Shanghai suburbs and Zhejiang rice area (Chen et al., 1990). [e] 1980–1982 data from World Resources Institute (1994) and FAO (1987); nutrition data from Chen et al. (1990). [f] Includes all cereal crops. [g] Total unmilled cereals. [h] "Refman" units (Chinese nutritional "reference man"; Chen et al., 1990) are used to standardize populations with different demographics: Wujin, 1930 refman units calculated from Buck (1930), Wujin 1985 from Zhu and Xu (1988), Chang-chou and Jiaxing/Wuxi calculations assume Wujin 1930s demographics, USA data is per person (not refman units). [i] Nutritional energy corrected for loss on processing. [j] Nutritional protein corrected for loss on processing. [k] Annual consumption per refman unit. [l] Carrying capacity is the number of refman units supported per ha of paddy land, assuming 100% of dietary energy or protein comes from cereals; actual cereal energy and protein consumption is closer to 80% of diet, except for USA (less than 25%). [m] Portion of cereal energy production needed to support the farm population (persons per ha/energy carrying capacity).

mated 1930 population density, and the generally higher population density of Jiaxing and Wuxi relative to Wujin. In the 1930s, most rice and wheat grown in Wuxi and Wujin counties was consumed by the farmers themselves (Bureau of Foreign Trade, 1933).

As populations increased and cities grew, the Tai Lake Region shifted from being a net rice exporter to being a textile-based economy that required net rice imports (Perkins, 1969). In 1285, the region had already developed to the extent that Marco Polo called it the most urbanized region in the world (Elvin, 1973). Still, the Tai Lake region was known as the "granary of the empire" well into the 1400s, exporting up to 300000 t of rice North on the grand canal in 1432, the peak year of grain export from the region (Elvin, 1973). Growth in silk and cotton textile industries continued to fuel development of trading townships and cities such as Shanghai, until the region could no longer feed itself (Perkins, 1969; Elvin, 1973). Although farmers remained self-sufficient for food and sold 20–40% of grain production to market towns (Perkins, 1969), they were unable to meet the needs of the cities, which began importing significant quantities of rice from Sichuan, Hunan, and other regions in the late 1700s (Elvin, 1973; Huang, 1990).

Though farm families met most of their nutritional needs by household-level agriculture, their other needs required silk and cotton handicraft income, which became critical to survival by the 1800s (Huang, 1990). While silk production did make it possible to increase farm profits on a limited land base, it was a far less reliable source of support than grain production (Huang, 1990). When the markets for silk and cotton had problems, which was frequent, so did the people (Huang, 1990). The conversion of land from rice to mulberry in the mid 1800s may have decreased the region's already limited carrying capacity to the point where an externally generated pressure, the Taiping rebellion, was able to cause a disastrous drop in population. Even though their agroecosystems were highly productive, the dense population of Tai Lake Region farmers left no margin for error in the intensively farmed traditional system.

4. The modern Tai Lake system.

4.1. Technology and productivity.

With the founding of the People's Republic in 1949, agricultural development by modern methods became a government priority (Huang, 1990). Though chemical fertilizer and pest control were first introduced to the region in the 1920s, their use was insignificant (Zhu and Xu, 1988; Tan, 1994). Agricultural modernization began in earnest in the late 1950s, when peasants, organized into collectives, were extended new technologies (Huang, 1990). New varieties and pesticides were introduced, but the primary approach to improving yields was by increased efficiency of irrigation, denser plantings and more intensive use of traditional fertilizers (Zhu and Xu, 1988; Tan, 1994).

Before 1949, traditional fertilizers typically supplied about 70–100 kg of N ha^{-1} $year^{-1}$ to rice/wheat systems, but by the late 1950s, these fertilizer applications had doubled, mostly owing to increased pig production (Wen and Pimentel, 1986a; Tan, 1994). At the same time, rice yields began to increase (Fig. 5B). In the early 1970s, hybrid rice and especially rice triple cropping (rice/rice/barley) became increasingly common (Fig. 5B), rising from 10% of paddy area to more than 65% by the late 1970s (Tan, 1994). In parallel with the increase in rice triple cropping, total N inputs surged to nearly 800 kg ha^{-1} $year^{-1}$ by 1979, their highest level in history, with ammonium sulfate and bicarbonate prevailing over organic fertilizers as the main source of N for the first time, accounting for almost 70% of total N inputs (Zhu and Xu, 1988; Tan, 1994). Use of P and K fertilizer also peaked in 1979, at 30 kg of P ha^{-1} $year^{-1}$ and 20 kg of K ha^{-1} $year^{-1}$ (Tan, 1994). By 1982, when introduction of the household responsibility system ended direct state control of agricultural production, triple cropping had already ceased and fertilizer inputs had also lightened (Zhu and Xu, 1988; Huang, 1990; Tan, 1994). At the same time, the growing of green manures, use of canal sludge fertilizer, and preparation of oufei compost ceased almost entirely and household animal raising also began to decline (Zhu and Xu, 1988; Tan, 1994). In the current rice/wheat system, annual fertilizer applications have stabilized at about 500 kg of N ha^{-1} $year^{-1}$, with more than 80% of this N from chemical fertilizers (Fu and Meng, 1994; Tan, 1994).

4.2. Population, land and grain.

Populations exploded after 1949 and total cultivated area declined, pushing rural population densities to twice their traditional maximum (Figs. 3 and 4). The productivity of the rice/wheat system expanded as well (Fig. 5B), but not as fast as population; Table 1 illustrates that there was less grain available per person in 1985 than in 1930. This would seem to present a major problem, but the development of village and township enterprise in the 1980s has increased local incomes far beyond anything that agriculture could produce on less than 0.1 ha of land per person (Powell, 1992). Labor requirements per ha and per kg of output have dropped considerably owing to modern irrigation, tillage, and chemical fertilizers (Huang, 1990). By the adoption of high-yielding technologies and the development of local industry, living standards have soared, and agriculture no longer limits the opportunities of rural households (Huang, 1990; Powell, 1992). Attention to agriculture has waned, and despite a net decrease in per capita grain production in the 1980s, two key methods for raising productivity were abandoned: hybrid rice, because of its lower quality, and triple cropping, because of poor return on labor (Powell, 1992). Nevertheless, most rural households continue to produce their own grain, even selling a small surplus (Huang, 1990; Powell, 1992). The Tai Lake Region remains one of China's most prosperous areas, by both agricultural and industrial standards (Powell, 1992).

China's policy of local self-sufficiency for grain requires the region's farmers to produce it, even though this production is not profitable (Cai and Smit, 1994b). Whether this policy will continue is a matter of debate. Whether the region is ecologically capable of supplying enough grain to rural households hinges on the question of whether yields will continue to increase. This question can only be answered by time, but if the experience of IRRI in the Philippines is relevant (Cassman et al., 1995), a future stagnation of yields is not unlikely. To avert this, an understanding of the ecological basis for sustained productivity in traditional agroecosystems is paramount.

5. Learning by comparing: traditional versus modern

Two things are certain about the traditional rice/wheat system of the Tai Lake Region: yields did not decline and soil quality was not degraded over time. Rather, there is evidence that long-term rice production actually increased soil organic matter and that the height of fields increased over time in a form of negative erosion caused by regular applications of canal sludge and oufei compost (Thorp, 1940). Long-term cultivation of paddy soils increased their fertility and changed their structure to the point that they are best classified as anthropogenic soils (Thorp, 1940; Xu et al., 1980). There can be little doubt that the traditional farm management that sustained soil fertility and high crop yields for centuries could have continued to do so indefinitely, using the same methods.

Though traditional yields were often quite high and may have increased somewhat over time (Fig. 5), the dramatic productivity increase caused by the introduction of modern technologies was much greater than anything seen before (Fig. 5; Table 1). The factors responsible for this increase and their implications for sustainable agriculture are significant. Modern pest control and improved irrigation have helped to increase harvests, but the most likely explanation for the region's large increase in agroecosystem productivity is the heavy use of chemical nitrogen fertilizer and the introduction of rice and wheat varieties that can make use of these increased inputs (David and Barker, 1978).

5.1. Nitrogen limitation in traditional agroecosystems.

Crop yields were limited by nitrogen in the traditional farming systems of China (Thorp, 1936; Richardson, 1952). A series of N P K factorial experiments conducted in more than 300 locations in China by Imperial Chemical Industries (ICI) during the 1930s showed high response to nitrogen in every cropping system studied; responses to P and K were always smaller, and more localized (Richardson, 1952). Yields of paddy rice in the Tai Lake Region were increased 18% on average by 60 kg of chemical nitrogen per hectare applied in the 1930s (Richardson, 1952). Response to P was 11%, and there was no response to K. Longer-term experiments confirmed these results, demonstrating that only nitrogen produced significant increases in rice yield (Chang and Chu, 1948; Hwang et al., 1948). The development of N limitation in traditional systems has been explained by the efficiency with which traditional farm management conserved P and K, while N was lost by leaching, gaseous loss from soils and manures, and by the burning of crop residues for cooking fuel (the P-and K-rich ashes served as fertilizer) (Richardson, 1952). The use of purchased N-rich beancake for fertilizer was an early attempt by farmers to overcome N limitation of productivity and it is significant that beancake merchants were also the first to sell chemical N fertilizers in China (Brodie, 1990).

5.2. Nitrogen overapplication in modern systems.

Though nitrogen was a limiting factor in traditional systems, the current high N inputs used in rice/wheat systems appear much greater than needed to support high yields: added N is about twice the amount removed in crops and residues (Fu and Meng, 1994). N input and output were about equal in the traditional rice/wheat system (Wen and Pimentel, 1986a). Up to the early 1970s, the nitrate content of ground and surface water was not significantly influenced by agriculture, traditional or modern, but in the past decade, nitrate levels in surface water have increased by a factor of seven (G.X. Cai, personal communication, 1994), and may soon pose a health hazard. Tai Lake eutrophication has also become serious (Chang, 1987), and there is evidence that modern methods are causing a decline in soil organic matter and tilth (Han, 1989). The growing pollution problem and potential for long-term yield decline (Cassman et al., 1995) indicate that the region's modern farming systems may not be ecologically sustainable.

5.3. Ecological limits to population growth.

Though massive nutrient subsidies have overcome the nitrogen limitation of traditional agriculture, this does not mean that other limits do not apply. The catastrophic population decline of the 1850s may have been expedited by high rural population densities that required more than two thirds of agroecosystem carrying capacity (Fig. 4; Table 1). The current farm population is now nearly twice 1700s levels, and by 1985, farmers were consuming 50% of the grain calories that they produced (Table 1). Still, the wealth of rural households has increased greatly since 1985, facilitating greater purchase of animal products and other foods that have changed the diet to a large extent (Wang et al., 1993). Local animal production is still nearly enough to meet farmer needs (Village Socioeconomic Survey Team of the National Statistics Bureau, 1993), while the purchased feeds needed to support this production have increased net nutrient input to the region. Continued use of nightsoil for fertilizer and dependence on household grain production mean that Tai Lake farmers are still integrated into village agroecosystems (Tan, 1994). Therefore, a detailed analysis of how whole village agroecosystems have changed is essential to understanding the impacts of increasing population and demand for animal products on the future of food self-sufficiency in the region.

5.4. The importance of nitrogen in agroecosystems.

N limitation of crop yields may have been a factor restraining human carrying capacity in traditional subsistence systems: food production was limited by N; and food supply limited population. Is N supply a potential measure of agroecosystem carrying capacity? The N limitation in traditional systems also suggests further questions. What was the relative importance of N conservation, recycling, and/or fixation to sustained agroecosystem productivity? Could traditional system productivity be increased to modern levels without importing N from outside the system? Will dependence on chemical inputs continue to sustain food self-sufficiency for Tai Lake Region farmers?

To answer these questions, we need to learn more about the relationship between nutrient management and long-term sustainability in whole agroecosystems. Large-scale studies of ecosystems, at the national and regional level, lump many different environments together, which obscures the relative importance of management and environment in supporting sustainable productivity. Given their small scale and relative self-sufficiency, Tai Lake Region farming villages are ideal units for the ecological study of sustainable agroecosystem management. By comparing the effects of traditional and modern management on the efficiency of nutrient cycling and retention within village agroecosystems, the importance of specific management factors to long-term sustainable agriculture may be determined.

6. Conclusions

It is disquieting that so few traditional agricultures meet the criteria for ecologically sustainable agriculture. Clearly, there is little historical precedent for long-term sustainable agriculture. High population densities combined with the need for local subsistence seem a recipe for disaster in traditional agriculture: Malthus' paradigm of population limitation by agriculture seems well proven by the history of catastrophic population declines in most civilizations. However, the Tai Lake Region's high population densities induced the agricultural intensification that led to high productivity (Boserup, 1965). Unfortunately, this was at the cost of labor efficiency, which is socially unsustainable in a modern world where there are other options for one's labor. Furthermore, rapid population growth in the Tai Lake Region meant that agriculture could only support the farmer, and not the city. Though modern technologies have dramatically increased agricultural productivity, this will not avert nutritional limitations when populations increase faster than productivity.

The best-documented examples of ecologically sustainable agriculture are based on the intensive production of wetland rice on river floodplains in monsoon regions of East Asia (Howard, 1943; Grigg, 1974). A combination of factors may be responsible for this: wetlands are the most productive natural ecosystems (Mitchell, 1984); paddy rice is generally more productive than other grain crops; nitrogen-fixing blue-green algae maintain soil fertility in rice paddies; the East Asian climate is well suited to rice; river flood plains are dependable sources of nutrient-rich sediments and water for irrigation; and organic fertilizers have been used in these systems for centuries (Howard, 1943; Dale and Carter, 1955; Grigg, 1974; Watanabe et al., 1981). The use of fertilizers is certainly an important factor, as unfertilized rice generally yields less than 2500 kg ha^{-1} on average over the long term (Watanabe et al., 1981), while yields of rice in the Tai Lake Region were sustained for centuries at more than 4000 kg ha^{-1} (Fig. 5).

Comparison of traditional and modern Tai Lake Region agriculture raises many questions about the relationship between population, technology and sustainability. From an ecological point of view, traditional Tai Lake Region agroecosystems were maintained at a high efficiency: every scrap of material was put to use in support of high productivity to feed a large population on a little land (King, 1911). Nevertheless, what was efficient ecologically was hardship for the people; farmers worked to the limits of endurance and saw no opportunity for improving their situation (Bailey, 1917). That the system was near its ecological limits in the late 1700s is a theory supported by the catastrophic drop in population during the Taiping rebellion of the mid-1800s (Perkins, 1969). Despite these shortcomings, it must be remembered that the Tai Lake Region was one of the world's most productive and stable agricultural regions for most of history (Shih, 1992). By studying the role of nitrogen cycling and other ecological factors in sustaining the region's exceptional long-term agricultural productivity, methods for increasing the sustainability of modern agriculture may be developed.

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