Chapter 6
An Integrative Approach to Modeling Land Use Changes: The Multiple Facets of Agriculture in the Upper Yangtze Basin

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Abstract Land change science has emerged as a fundamental component of global environmental change and sustainability research. Still, much remains to be learned before scientists can fully assess future roles of land use/cover changes (LUCC) in the functioning of the earth system and identifying conditions for sustainable land use. The objective of this chapter is to gain a better understanding of the complex interactions of human and natural drivers underlying LUCC. We do so by developing and estimating a novel structural model of land use and by using spatially explicit longitudinal observations from the upper Yangtze basin of China. Our analysis focuses on the multiple dimensions of agriculture—not only cropland use itself, but also grain production, soil erosion, and related technical change; and our data cover 31 counties over four time periods from 1975 to 2000. Our results show that technical change plays an important role in supplying food on a limited cropland; limiting cropland expansion in turn reduces soil erosion, which then benefits grain production in the longer term. It is also found that policies and institutions have significant impacts on land use and the status of soil erosion. Together, these results carry some great implications to sustainable land use and ecosystem management.

Keywords Land use and land cover change · Coupled human and natural processes · Driving forces · Structural model of multiple equations · Upper Yangtze basin

6.1 Introduction

Human-driven changes in the terrestrial surface of the planet hold broad significance for the structure and functions of ecosystems, with equally far-reaching consequences for human well-being (Turner et al., 2007). Past land-use and

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land-cover changes (LUCC), while enabling humans to appropriate an increasing share of the earth's resources, have profoundly altered its conditions and adversely affected carbon and water cycles and ecosystem functions (Foley et al., 2005; Geoghegan et al., 2001); and LUCC in the future will further intensify the trends of climate change, groundwater depletion, species extinction, and soil nutrient losses (Millennium Ecosystem Assessment, 2005). Hence, LUCC have been widely recognized as an important field of scientific research. The US Global Change Research Program stated that: "A better understanding of the processes, rates, causes, and consequences of land use change and land management practices is essential for many areas of global change research" (USGCRP, 2004). More recently, "land change science has emerged as a fundamental component of global environmental change and sustainability research" (Turner et al., 2007).

Significant progress in quantifying LUCC in the past decade notwithstanding, a lot remains to be learned before scientists can fully assess the future roles of LUCC in the functioning of the earth system and identifying conditions for sustainable land use (USGCRP, 2004, Lambin, Geist, & Lepers, 2003). Early studies of the LUCC causes tend to feature some sort of discrete choice or reduced-form model, which prescribes that the share or quantity of LUCC is determined by land rent, land and/or landowner characteristics, and other external factors (Walker & Moran, 2000; Kaimowitz & Angelsen, 1998; Chomitz & Gray, 1996). Among other things, these studies identify economic return, market access, industrial development, demographic change, and macro policy as major drivers of land use decisions. However, they have given little attention to the interactions of biophysical factors, such as soil and water conditions, and socioeconomic factors, such as technical change in the LUCC process (Veldkamp & Fresco, 1996; Lambin, Rounsevell, & Geist, 2000).

The study by Xiang et al. (Chapter 5) was conducted to illustrate the strengths and weaknesses of the current analytic approach. Using a fractional logit model, they examined the LUCC driving forces in China's Upper Yangtze basin. Their results show that industrial development had a significant effect on reducing cropland expansion and conserving forests, whereas population pressures contributed to deforestation and grassland degradation. Further, land use decisions were not significantly influenced by the distorted, and often depressed, price signals. In addition, institutional and policy factors played critical roles in shaping the land use patterns. Nonetheless, that type of model failed to capture the connectivity of various factors in influencing LUCC. Also, technical change was not incorporated. So, they came to the conclusion that more sophisticated modeling strategy is called for to reflect the dynamic LUCC linkages.

In fact, as a coupled natural-human process, not only are LUCC affected by the interactions of biophysical and socioeconomic factors, these factors also can in turn be affected by LUCC and their induced feedbacks. So far, few efforts have been made to investigate these complex relationships. Also, empirical linkages between proposed causal variables and LUCC commonly involve the more proximate factors to the land-use end of explanatory connections, such as subsistence farmers and deforestation; the root causes that shape the proximate ones, such as poverty or policy, tend to be difficult to connect to land outcomes, due to the number and complexity of the linkages involved (Turner et al., 2007). For instance, it is poorly understood how technical change can mitigate the pressures of population growth and ecological degradation (Müller & Zeller, 2002). To overcome these difficulties, it is essential that LUCC studies incorporate the relevant variables and account for their endogenous effects (Irwin & Geoghegan, 2001). To that end, however, continuous and long data series are needed.

The objective of this chapter is to address the above challenges in LUCC research. We will do so by developing and estimating a novel structural model of land use and by using spatially explicit longitudinal observations from the upper Yangtze basin of China. Our model will focus on the multiple dimensions of agriculture—not only cropland use itself, but also grain production, soil erosion, and related technical changes. That is, we will develop a system of four equations to characterize the various facets of agriculture and their interactions in elucidating the LUCC driving forces. Notably, cropland is a main category of land use in the study region, and data for an integrative study of the agricultural sector are more likely available.

It is expected that this effort will contribute to a better understanding of the complex human and nature processes underlying the LUCC. In particular, our results show that technical change plays an important role in producing food on a limited land base; limiting cropland expansion in turn reduces soil erosion, which then benefits grain production in the longer term. Our results also highlight that policies and institutions have significant impacts on land use and the status of soil erosion. Together, these results carry some important implications to sustainable land use and ecosystem management. The chapter is organized as follows. We present our methods and data in the next section, followed by estimated results. The final section contains the conclusions and discussion.

6.2 Methods and Data

6.2.1 Conceptual Framework

To disentangle the complex interactions of LUCC drivers, we will concentrate on the multiple facets of cropland use. Our model of the causal relationships for cropland use is composed of four interactive components: grain production, farming technical change, and soil erosion, in addition to cropland itself. Grain production is determined by labor, land, capital, and other inputs with embedded technical changes, such as irrigation and fertilization. Technical changes are induced by the relative prices or opportunity costs of production factors (Ruttan, 2001). That is, farmers make their decisions of land use and technical adoption in response to the external economic conditions. When land rent becomes lower compared to capital or labor costs, land-extensive technology as well as production mode will be employed. When land becomes scarcer and thus rent increases, substitution of land with labor or capital will occur, and corresponding farming technology will be adopted (Müller & Zeller, 2002).

Technical adoption enhances grain productivity, which will in turn affect land use decisions. Changes in land use patterns can then alter the status of resource scarcity, which has implications to resource rent (price) and technology adoption. Of course, technical change must be brought to bear by institutional changes, such as improved land tenure and price liberalization (Lin, 1992; Yin & Hyde, 2000). Furthermore, not only does land use change interact with technical change, but its environmental consequence also generates feedback. Extensive farming on sloping land can lead to increased soil erosion, which adversely affect land productivity, forcing farmers to reclaim more cropland on even steeper slopes to meet their food needs (Xu et al., 2006). Of course, this will result in even more severe soil erosion.

In contrast, intensive farming can reduce disturbances to sensitive ecosystems. For example, if farming technology improves grain production to an extent such that the existing cropland meets farmers' food needs, cropland expansion will thus be halted; in certain cases, some sloping or inferior cropland may even be converted to forest or grass coverage. Consequently, soil erosion can be mitigated. In this sense, technical change also contributes to environmental improvement, which will benefit grain production in the longer term. Increased grain productivity can further relieve human pressures on cropland expansion, encourage environmental conservation, and finally drive land use onto a sustainable path.[1] That is why it is so crucial to incorporate technical change and environmental consequences into LUCC research.

6.2.2 Empirical Approach

Given that in agriculture, cropland change interacts with farming technology, grain production, and their environmental feedbacks in a complex manner, it becomes plausible and beneficial to represent these interactions and feedbacks with a system of equations. Here we specify four equations for our empirical analysis, with the four dependent variables being cropland use (C) grain production (P), farming technology (T), and soil erosion (S). The interactions of these variables mean that they are endogenous and thus each shows up as explanatory variables in other equations.

The empirical model can be written as:

$$\begin{aligned} P_{it} &= f_1(X_{it}, T_{it}, S_{it}) + \varepsilon_{it} \\ T_{it} &= f_2(C_{it}, Y_{it}) + \delta_{it} \\ C_{it} &= f_3(T_{it}, P_{it-1}, Y_{it}, Z_{it}) + \upsilon_{it} \\ S_{it} &= f_4(C_{it}, X_{it}, Y_{it}) + \tau_{it} \end{aligned} \tag{6.1}$$

where f_1–f_4 are functional forms of the four equations, X, Y, and Z are conventional input variables and other socioeconomic and biophysical variables (see detail below), i and t denote the spatial and temporal units of observations, and ε, δ, ν and

[1] To be sure, intensive farming has its own environmental problems as well, such as soil salinity and toxicity due to improper chemical applications (Ruttan, 2001).

τ are error terms. Note that cropland area at each time point, instead of cropland change between two points, is used to ensure that the time-series data are consistent for each equation.

Specifically, grain production is defined as a function of farming labor, cropland, other inputs with embedded technical change,[2] and the environmental condition represented by the status of soil erosion and elevation. In our analysis, technical change encompasses three components—fertilizer use, irrigation infrastructure, and multiple cropping. As noted, technical change is affected by resource endowment, changes in relative prices (such as input costs and output prices), and other external socioeconomic and biophysical factors. Therefore, technical change is defined as a function of cropland area, grain price, input cost, farmer net income, market access, and elevation. While cropland area represents resource endowment, elevation denotes the biophysical environment of the observation unit. Farmers' net income affects their abilities to apply technology—a farmer with a higher income has the ability to afford more technical inputs and is more willing to try new farming technologies (Ruttan, 2001). On the other hand, escalating input costs may reduce farmers' incentive for technological adoption because of the application of more technology-embodied inputs (Ruttan, 2001).

Cropland use is determined by grain production, technical change, returns from each land uses, population pressure, and other variables. We use the procurement prices for grain, logs, and livestock to represent the comparative economic returns from cropland, forestland, and grassland. Relative to these market signals, however, decisions on land use in China were and still are influenced by government regulations, such as the food self-sufficiency policy and forest tenure arrangement. The former, reflected in the grain procurement quota, encouraged cropland expansion on slopes previously covered by forest or grassland (Xu et al., 2006). It is hypothesized that a decreasing quota, as a sign of relaxing the policy, should relieve the pressure on cropland expansion. The latter, if clearly defined and enforced, forms the basis for at least stable forest management. In the study area, sloping lands that belonged to the collectives or those without clear ownership, forestland or grassland loss to cropland often occurred (Xu et al., 2006). Soil characteristics affect land suitability for different uses. But measuring soil characteristics for a county is hard because of their variations and data unavailability. So, the average elevation of a county is used as a proxy of soil features as well as other biophysical conditions that affect land use.[3]

Cropland expansion on slopes was deemed as one of the major causes of soil erosion in the Upper Yangtze basin (Xu et al., 2006). Deforestation and forest degradation also damage on ecosystem's abilities to regulate water and soil. On the other

[2] Note that technical change and technical adoption are conceptually the same, but they are used interchangeably in this chapter.

[3] Our prior knowledge indicated that elevation, varying from 295 meters (m) to 6109 m for the study region with a mean of 3070 m, is a more meaningful variable, compared to, for instance, slope or range. Because elevation does not change over time, through, it will not be listed in the table of summary statistics of variables below.

hand, the government has been implementing a series of projects to contain soil erosion in the study region. The status of soil erosion is represented by the actual eroded area, which is defined as the function of cropland area, timber harvest, industrial development, implementation of restoration projects, and other biophysical features.

Appropriate estimation method and identification are two critical issues in the following empirical estimation. Since at least one of the explanatory variables in each equation is endogenous and thus correlated with the error term, *OLS* is no longer a valid method to provide unbiased and consistent coefficient estimates. Thus, the 3-stage least squares (*3SLS*) technique is applied in estimating the four-equation system in (6.1). To apply that technique, it is commonly assumed that: (1) all exogenous variables are uncorrelated with any error term at each time point; (2) the covariance matrix of the error terms has a kind of system homoskedasticity; and (3) the rank order condition is satisfied. An equation satisfies the rank order condition if the number of excluded exogenous variables from it is at least as many as the number of the endogenous variables included in it (Wooldridge, 2002). Thus, variables are chosen so as to ensure the identification requirement.

6.2.3 Study Site and Data

The study site was selected along the Jinsha River, part of the upper Yangtze basin with a length of 2,290 km. Included for this study are 31 counties fully located inside the Jinsha River catchment (97.7°–104.8°E, 25.4°–32.7°N), with a total area of 14 million ha. Nineteen counties are in Yunnan province, with an area of 7.2 million ha; and the other 12 in Sichuan, with an area of 6.8 million ha (see Fig. 5.1 of last chapter). The Jinsha River is known for its sharp descent, fragile geological structure, and severe soil erosion. Also, the unfavorable farming condition and poor transportation infrastructure causes the inhabitants of the region to suffer from a high incidence of poverty. Nonetheless, farming has long been the major income source. From 1975 to 2000, the average annual value of farming output accounted for at least 55% of the total agricultural output.[4] Meanwhile, this region plays a critical ecological role in the Yangtze basin because its head waters and primary forests serve important ecosystem functions (Wang & Deng, 2007).

The dataset covers five time points from 1975 to 2000: mid-1970s, mid-1980s, late 1980s, mid-1990s, and late 1990s (hereafter, 1975, 1985, 1990, 1995, and 2000). The land-use data were derived from remote sensing images processed by the Chinese Academy of Sciences (CAS) Liu et al., 2003. The topographic information, such as elevation, also was provided by CAS. The socioeconomic data were from local statistics bureaus or surveys conducted by the authors. Chapter 5 has documented the data details.

In general, cropland is mostly located in the valleys and it has been fairly stable throughout the whole period. However, this aggregation may obscure cropland

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[4] According to the government statistics, included in agriculture production value are the values of animal husbandry and forestry as well as that of farming.

changes at the county level. Further, opposite land conversions (e.g., from cropland to forest and vice versa) take place simultaneously (see Chapter 5). For example, about 136,000 ha of cropland were converted to grassland, forestland, or other lands from 1975 to 1985; meanwhile, around 147,000 ha of land were converted to cropland from grassland, forestland, and other lands. Notably, the extent of cropland converted to forestland, grassland, and other lands was larger during 1975–1990 than that during 1990–2000. On the other hand, forestland was the largest source of converted cropland, except for the period of 1975–1985 when more grassland became cropland. This situation makes it preferable to identify the LUCC spatial and temporal variations and model their drivers based on county-level data.

Here, grain consists of cereals, beans, and tubers in Chinese statistics. The sown area for grain production accounted for 90% of total sown area of all crops in 1975, and its share was still as high as 77% in 2000. Other inputs include fertilizers, irrigation, and multiple cropping that embody modern farming technologies.[5] In the study region, grain production rose by 70% from 1975 to 2000, with the largest increase taking place between 1990 and 1995 when applications of technical inputs were substantially expanded. In comparison, cropland decreased by 41,000 ha from 1975 to 2000, while farming labor increased by 66%. Yield per farming worker increased by only three percent during that period, leading to a productivity increase of 76% per unit of land. Clearly, production growth cannot be fully explained by land and labor increase; and technology-embodied inputs have made a major difference.

We represent technical change with an index that is a weighted average of the growth rates of the three elements at a given point of time. For instance, the technical change index in 1975 was obtained by multiplying the growth rates of fertilization application, irrigated area, and multiple cropping index in that year. Thus, the larger the derived figure, the greater the technical change rate is. Fertilization application in a county is the amount of fertilizer applied, while the scale of irrigation infrastructure is represented by the irrigation area.[6]

Both grain price and input cost are provincial-level indices. Grain price is the government procurement price index (Chapter 5), while input cost index is an indicator for agricultural input costs given that its calculation takes into account various inputs including fertilizer, machineries, feeds, pesticide, etc. Chomitz and Gray (1996) pointed out that the distance of a parcel of land to roads, representing market access, affects both output and input costs and thus land use patterns. For this study, the total road length in a county is used to reflect transportation cost and market access for the county. The longer the road in a county, the lower transportation costs and the better market access are. As such, the county has more lands allocated to farming. The highway mileage in a county is used to represent road length. Highway rate, the ratio of highway length to county area, is the variable used in the model to remove the effect of county size.

[5] Multiple cropping refers to the situation where the cultivated land is used more than once a year. It is thus measured with the ratio of the total sown area divided by the total cultivated area. As such, it enhances the land-use intensity.

[6] Field visits indicate that plastic sheeting in high elevations can effectively raise soil temperature and maintain moisture, resulting in greater probability of crop success and higher grain yield.

The eroded area in a county was estimated by local water resource bureaus based on their field surveys. The Erosion Control Project along the Upper Yangtze, carried out since the late 1980s, is the largest of such projects along the Jinsha River (Wang, 2003), and it combines biological, engineering, and tilling measures. Also, the Upper Yangtze forestation project launched in 1989 listed erosion control as one of its objectives. Table 6.1 summarizes all the variables.

Table 6.1 Summary Statistics of Variables Used in the Structural Model

	Measurement	1975	1985	1990	1995	2000
Endogenous						
Cropland area	Ha	1,603,687	1,614,621	1,561,700	1,563,426	1,560,719
Grain production	Ton	1,623,484	1,953,656	1,941,526	2,632,755	2,786,049
Technology index		0.073	0.044	0.054	0.065	0.035
Soil erosion area	1,000 ha	2,033	2,385	2,894	3,011	2,743
Exogenous						
Population density	Person/km^2	0.66	0.73	0.78	0.82	0.86
Agricultural labor	1,000 Person	2,178	2,798	3,047	3,509	3,623
Irrigation area	Ha	189,588	192,676	194,511	212,489	269,180
Fertilizer	Ton	35,984	62,444	72,991	140,065	215,603
Multiple cropping index		1.397	1.390	1.448	1.623	1.707
Grain price[1]	Index (1990 = 1)	0.587	0.669	0.972	1.619	2.035
Log price[1]	Index (1990 = 1)	0.589	0.531	0.927	1.046	1.294
Livestock price[1]	Index (1990 = 1)	0.860	0.863	1.085	1.873	2.218
Industrial output (IO)[2]	1,000 RMB	69,534	141,243	169,494	516,442	698,396
Agricultural output (AO)[2]	1,000 RMB	189,063	329,188	351,141	533,255	729,546
IO/AO		0.320	0.403	0.443	0.768	0.762
Grain procurement quota[3]	Ton	170,423	141,292	111,231	115,691	107,481
Highway rate	km/ha	0.0009	0.0014	0.0016	0.0021	0.0031
Farmers' income	RMB	81	278	344	565	1,132
Cost index[1]	Index (1975 = 100)	100.100	107.127	136.255	238.744	361.973
Timber harvests	m^3	259,925	833,007	850,862	854,845	380,868
Erosion control project	Dummy	=1, if project implemented; = 0, otherwise				
Forestation project	Dummy	=1, if project implemented; = 0, otherwise				
NFPP project	Dummy	=1, for the year of 2000; = 0 for other years				

[1] Grain, log, and livestock price indices are provincial aggregates.
[2] Agricultural and industry outputs are output values at 1990 constant price.
[3] Grain quota is from the local grain bureau, and soil erosion area is from the local Water Resources Bureau. All other data come from local statistics bureaus and government documents.

6.3 Estimated Results

Table 6.2 lists the estimated results. Yearly and provincial dummy variables are included in each equation to control the temporal trend and regional heterogeneity, but results are omitted to save space. The coefficient for each variable in the grain production, cropland, and soil erosion equations is the corresponding elasticity, not the partial effect. This presentation can indicate the extent of driving forces' effects on each of the dependent variables. For the farming technology equation, a coefficient value is the estimated partial effect because the technical change itself is a variable of percentage. In general, the Chi-square test shows that every equation is significant, meaning that there is a significant relationship between all independent variables with dependent variable. R^2 values further indicate that the independent variables in grain production and cropland equations fit very well. Many variables are statistically significant with expected signs. When those four dependent variables are used as independent variables in other functions, they are all statistically significant. This proves our claim that interactions and feedbacks exist among cropland use, grain production, farming technology, and environmental consequence.

Results for grain production are mostly as expected. Land, labor, and technical input all have significant positive effects, while deteriorated soil condition has a significant negative effect on production. Grain production increases by 0.6% and 0.27% with one percent increase of cropland area and labor, respectively, holding other variables constant. One percent increase of fertilizer application leads to 0.16% increase of grain production, and one percent increase of the multiple cropping index results in a 0.26% increase in grain production. The effect of irrigation is not significant, probably because its effect is partially captured by the fertilizer variable. Irrigation promotes the application of fertilizer because they work more effectively with adequate moisture (Wang & Deng, 2007). Soil erosion negatively affects production. Holding other variables constant, if a county has 1,000 more ha of eroded land, grain production is reduced by 0.1%. The effect of elevation is positive on grain production. Although different from our expectation, its magnitude is small.

Most variables in cropland equation also have the expected effects. Livestock price, highway density, and grain procurement quota have significant positive effects on cropland expansion, whereas cropland area decreases significantly with altitude and technical change. That is, cropland area increases by 0.55% when the highway in a county increases by one percent, indicating that better road access leads to more crop production and thus more demand for cropland. One percent increase of per capita grain procurement quota leads to 0.06% increase in cropland, and cropland area in a county decreases with rising elevation. The effect of livestock price increase on cropland expansion is relatively large: one percent of livestock price increase causes cropland to expand by 2.6%. This suggests that some crops are planted for animal feeding stocks, such that a higher livestock price drives more cropland use to expand livestock production. Animal husbandry is indeed regarded as a major means of improving income and alleviating poverty in many mountainous regions (Wang & Deng, 2007). One of the most interesting results for the cropland

Table 6.2 Estimated Results of the Structural Model for Cropland Use

	Grain production	Cropland use	Farming technology	Eroded area
Grain production		0.392 (0.002)***		
Cropland use	0.604 (0.062)***		–0.198 (0.064)***	0.380 (135.085)***
Farming technology		–0.035 (0.353)**		
Eroded area	–0.099 (0.041)**			
Agri. labor	0.267 (0.052)***			
Fertilizer	0.158 (0.027)***			
Irrigation	0.039 (0.034)			
Multiple cropping	0.255 (0.070)***			
Log price		–0.073 (0.998)		
Livestock price		2.588 (1.067)*		
Grain price		–1.322 (0.605)	0.138 (0.078)*	
Population density		0.076 (0.699)		
Grain procurement quota		0.058 (1.847)*		
Highway rate		0.547 (0.156)***	0.095 (0.047)**	
Farmers' income			0.008 (0.004)*	
Cost index			–0.119 (0.049)**	
Forest ownership		0.223 (0.196)***		
Industrial development		0.013 (0.063)		0.049 (133.162)
Erosion control project				–0.165 (228.745)**
Forestation project				–0.114 (230.160)
Timber harvests				0.156 (0.003)***
Elevation	0.101 (0.028)***	–1.000 (0.055)***	0.002 (0.003)	–0.114 (0.097)
R^2	0.98	0.80	0.17	0.49

Note:
1. Numbers in parentheses are standard error of the coefficient.
2. There were 98 observations used, because of some missing values for variables.
3. The level variables were log transformed before estimation.
"*", "**" and "***" represent 10, 5 and 1% significance level, respectively.

equation is that technical change has a significant effect on reducing cropland expansion. Controlling other factors, cropland area decreases by 0.04% with one percent increase in the technical change index.

The effects of the explanatory variables on technical change conform to our expectations to a large extent as well. Farmers' income, grain price, and road length all have significant positive effects on technical change, while higher input costs and abundant cropland resource reduce their incentives to apply technologies intensively. Despite its significance, the magnitude of the income coefficient is small. Holding other factors constant, the rate of technical change is expected to increase by 0.007 if farmers' income increases by 100 yuan. One unit increase of grain price induces a 0.14% increase of technical change, and one thousand kilometers of newly constructed highway in a county result in a 0.09% increase in technical change. On the other hand, one unit increase in agricultural input cost causes the rate of technical change to drop by 0.12%. The adoption rate of land-intensive or land-saving technology is 0.198% lower if the cropland area in a county increases by 10,000 ha. This result further validates our hypothesized interaction between technical change and cropland use. Although most variables have significant effects on technical change, the overall explanatory power of this equation is poor—only 17% of the variation of technical change.

Eroded area is significantly related to human activities, and the implementation of conservation projects effectively reduces it (Yin et al., 2005). On average, erosion control projects reduce around 470 ha of eroded area in a county, controlling the effects of other variables. Afforestation and reforestation also have the same effect on erosion control, but it is insignificant, probably in part because forestation projects were introduced much later than the engineering ones (Yin et al., 2005). In addition, cropland expansion has significant effect on erosion deterioration. One percent of cropland increase induces 386 more ha of eroded land. Meanwhile, timber harvests also intensify soil erosion. One percent increase in timber harvest causes eroded areas to increase by 0.16%, holding other variables constant.

6.4 Conclusions and Implications

This chapter has developed a structural model to capture the interactions and feedbacks in the dynamic process of cropland change, based on the experience in the upper Yangtze basin of China. We proposed and proved that cropland use interacts with grain production and agricultural technology and that the environmental consequence of the land use also imposes significant feedbacks. Our results demonstrate the critical role of technical change in providing food on limited cropland. Counties with greater technical change have less land allocated to grain production, leading to more intensified use of existing cropland and the conversion of marginal cropland to other uses. Thus, it can be inferred that when the increased productivity resulting from technical change can satisfy the food supply from a limited land base, farmers will transfer labor and land resources to other activities to earn more income. Controlling cropland expansion reduces the extent of soil erosion, which then benefits grain production. The study also highlights the importance of institutions and policies in environmental protection and sustainable land use. For instance, the food self-sufficiency policy causes cropland expansion, especially in counties where cropland resources are very scarce. While timber harvests induce more soil erosion, erosion control projects can effectively reduce the eroded area.

These and other results not only improve our understanding of the complex human and natural connections in LUCC, but also carry significant policy implications for sustainable land use. First, technical change and technology innovation should be encouraged and supported by governments at the national and local levels. Higher input costs and lower crop prices compared to off-farm wages discourage the adoption of technology by individual farmers. And our data show that the rate of technical change was slowing down from 1975 to 2000—the conventional technology is reaching its maximum potential, and the amount of fertilizers or irrigation cannot be applied limitlessly. Technical innovation and adoption have thus become even more important to continued grain production. The policy environment should be improved to promote extension services, enhance the distribution network of inputs, and strengthen investment in agricultural research and development.

Further, as more and more efforts are devoted to increasing farmers' income from livestock-based activities, the challenge to balance cropland expansion for feed stock production and natural resource protection becomes more acute. This is because a higher livestock price induces more animal production, which leads to greater demand for cropland to provide more feed stock (e.g., corn and beans). Expanded cropland will cause more soil erosion and other environmental problems. Our work also justifies the environmental protection and ecological restoration projects undertaken by the Chinese government. Meanwhile, the role of the market should be respected when it can exert its function in efficient resource allocation. For example, when farmers are subsidized to plant trees, it is not necessarily the right move for the government to dictate the decisions of tree planting and harvesting (Yin et al., 2005). Even if certain species and management practices may not be the best from the perspective of environmental protection, government dictation can lead to worse outcomes. Rather, the government ought to provide farmers with the needed market information and technical know-how. Also, the government should let farmers face the market prices and possess secure use and disposal rights for their trees. Farmers can make rational long-run decisions about land use based on the market signals and thus achieve more sustainable land use.

Timber harvest has a significant negative effect on soil erosion. The "logging bans" policy effectively reduced the commercial timber production in the late 1990s. However, timber production amounts to only a small percentage of the total forest removals. Fuelwood consumed by rural households and logs used for local construction take up a large share of the annual resource consumption (Xu et al., 2006). Therefore, in addition to reducing commercial timber production, the use of electricity, biogas, and fuel-efficient stoves in the rural area can reduce the demand for fuel wood. The government should invest more in such technologies and encourage their adoption.

It should be noted that while this study has generated some important results, more needs to be done in future research. First, LUCC are regarded not only as a driver of climate change, climate change can in turn impact LUCC (USGCRP, 2003) through hydrological and terrestrial biological systems. Thus, incorporating the effects of climate change and other biophysical factors into the land-use change model will allow us to reflect natural and human interactions more comprehensively. Second, in view of real-world complications, this study has focused only on the multiple facets of agriculture and cropland use in the structural model. Such a systematic method can be applied to other land uses. Moreover, the connections among these models should be established. In doing so, we will gain a more complete picture of the dynamics of all major land categories. Finally, the characteristics of LUCC may be different at different scales (e.g., county vs. household scale). The broad scale LUCC analysis will obscure the variation at the finer scale; on the other hand, the land use changes at the fine scale will result in environmental and economic changes that can only be fully appreciated at the broad scale. Also, the effects of policy or institutional factors may vary at the different scales. Thus, it is worthwhile to conduct LUCC research at multiple scales and to examine the LUCC driving forces in a spatially explicit way.

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