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A scenario exploration of strategic land use options for the Loess Plateau in northern China

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Abstract

Soil loss, food insecurity, population pressure and low income of the rural population are interrelated problems in the Loess Plateau of northern China, and result in a spiral of unsustainability. This paper examines Ansai County as a case study to explore strategic land use options that may meet well-defined goals of regional development, using a systems approach that integrated the fragmented and empirical information on the biophysical, agronomic and socio-economic conditions. We used production ecological principles, simulation modeling and multiple goal linear programming as integrative tools. Four scenarios were explored, representing major directions of agricultural development in the region and views of national and local stakeholders, farmers and environmentalists. The results indicate that soil conservation, food self-sufficiency and income for the rural population can be substantially improved by efficient resource use and appropriate inputs. In the long-term, terracing and use of crop rotations with alfalfa may be the best options for soil conservation. The large rural population and the lack of off-farm employment opportunities could be the most important factors affecting rural development in Ansai. This study contributes to the understanding of regional problems and agricultural development potentials, and shows agro-technical possibilities for alleviating the unsustainability problems in this fragile and poorly endowed region. To promote actual development towards the identified options, on-farm innovation and appropriate policy measures are needed. The explored land use options enable a much more targeted innovation and development of policies.

Keywords: Land use; Sustainability; Soil conservation; Food security; Linear programming; Policy scenarios

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1. Introduction

Food security and sustainable development are two fundamental and strategic goals in China. Several studies indicate opportunities for China to realize these goals (Cao et al., 1995; Luyten et al., 1997; Heilig, 1999), however, great challenges exist (Brown, 1995). Among the factors that may heavily affect a food secure and sustainable development (Brown, 1995; Heilig, 1999; Hubacek and Sun, 2001), land degradation is a crucial one, particularly in the western areas of China, including the Loess Plateau.

The Loess Plateau is located in the mid-upper reaches of the Yellow River and extends between a latitude of 35–41 °N and a longitude of 102–114 °E, with an area of 0.63 million km^2 and a population of 82 million (Du and Gao, 1992; He et al., 2003). The plateau is covered by deep loess deposits (over 100 m), and characterized by hilly terrains with an elevation between 1000 and 1600 m a.s.l., and a semi-arid climate with an annual precipitation between 400 and 600 mm in most parts. Problems with soil erosion, food insecurity, population pressure and low income/poverty of the rural population are major obstacles for sustainable land use in the region (e.g. Tang and Chen, 1991; Du and Gao, 1992; Zhang et al., 2002). These problems are interrelated and each problem is often enhanced by others. This can be illustrated by familiar sayings in China, such as ‘the poorer the population is—the more (marginal) land will be reclaimed, and the more land that is reclaimed—the poorer the population will be’, and ‘the poorer the population is—the higher the birth rate will be and the higher the birth rate is, the poorer the population will become’. The consequences of the adverse factors can be presented as a spiral of unsustainability (Rhoades and Harwood, 1992; Rabbinge, 1997), in which each factor is not only the result, but also often the cause of other problems. Breaking of this unsustainability spiral requires strategic options for more efficient and sustainable use of land resources and appropriate policy measures.

As a first step towards strategic innovations in agriculture and formulation of specific policies, it is essential to explore bio-physical and technical opportunities under different priorities of societal, economic and environmental objectives using a systems analysis method capable of integrating biophysical and socio-economic information (Van Ittersum et al., 1998). Such an exploration can reveal possibilities of agricultural development and help policymakers and stakeholders making choices by showing the consequences of different policy directions.

This paper presents a systems analysis of future land use for the case of Ansai County in the Loess Plateau. Ansai faces land use and development problems that are typical for the hilly Loess Plateau and is relatively data-rich. Much empirical and experimental research has been carried out in Ansai on land resources, soil erosion and agricultural production, but it is often of a fragmented nature. Ansai was therefore a suitable case region to operationalize a method for exploring land use options for poorly endowed and fragile areas with soil erosion, lack of opportunities for off-farm employment and food insecurity as major environmental and societal issues.

Section 2 of this paper describes general conditions in the case area, its problems and possible policy scenarios, followed by a description of the research methodology concerning identification and quantification of production activities, objective variables and basic constraints integrated in a multiple goal linear programming (MGLP) model in Section 3. Next, model results are presented in Section 4. Finally, highlights of the scenario results and policy implications are discussed in Section 5.

2. Problems and policy scenarios

2.1. Site description

Located between 36°31′–37°20′ N and 108°52′–109°26′ E and covering an area of 2951 km^2, Ansai is a typical county characterized by semi-arid climate and hilly loess landscape in the Loess Plateau. The county has a mean annual precipitation of 520 mm and mean annual temperature of 8.6 °C, with apparent seasonal variation (Fig. 1). Of the total rainfall, 74% falls in the rainy season from June to September. The land surface, mostly at an elevation between 1200 and 1500 m a.s.l., is highly dissected by deeply incised gullies with about 95% of the area being hilly land, and ca. 5% floodplains. Soils in Ansai, formed on deep and loose loess sediments, have a rather homogenous silty loamy texture. The agriculture comprises crop, livestock and orchard production systems. Arable farming includes the growth of millet, winter wheat, potatoes, corn and soybean, mostly on sloping lands without irrigation. Animal husbandry mainly comprises pigs, sheep and goats, and draught animals of cattle and donkeys. Sheep and goats graze on grasslands in summer and are fed indoor in winter, and other animals are mainly raised in stables. Milk and beef production is not practiced in the region. Orchard systems comprise mainly

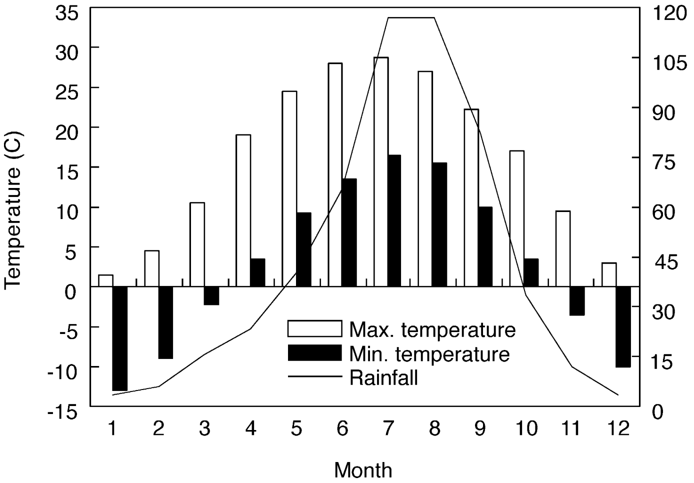

Fig. 1. Monthly average of minimum and maximum daily temperature and rainfall at the Ansai Meteorological Station.

apple and some pear production, practised on floodplains and on hilly slopes near the main roads.

2.2. Land use problems and policy views

Rural development in Ansai involves interrelated issues typical for the Loess Plateau region, such as indicated in the introduction section. The problems are largely caused by the rapid population growth. In the third census, held in 1990, total population in Ansai was 14.7 10^4 persons or 50 habitants per km^2, more than twice the 6.0 10^4 persons in the first census of 1953. This high population growth greatly increased food requirements and employment pressure, resulting in extensive cultivation of marginal lands. According to Tang and Chen (1991), slope cropland area in Ansai was increased by 2.8 times in 1985 compared with that in 1964. In the late 1980s, a total of 0.12 million ha accounting for 41% of the county area (Chen, 1988) was cultivated with crops, 89% of which had a slope gradient from 19 to 70%. Although croplands have been partly converted to apples and forest/grasslands in the past decade (as a result of government programs), the cropland area in 2000 was still 0.10 million ha (land monitoring data of the Ministry of Land and Resources of China). As non-agricultural production sectors such as rural enterprises are hardly developed, most labor in Ansai (86% of the total labor in 1998) is involved in the cropping-dominated agriculture. A lack of opportunities for off-farm employment and income-generation has caused problems such as rural unemployment, poverty and shortage of capital for agricultural inputs. Insufficient inputs reduce agricultural productivity, and thus are associated with low income and food insecurity, and quite often with an expansion of croplands to ensure self-sufficiency, which is deemed crucial for the rural population due to the relatively isolated conditions (steep terrains and poor infrastructure) and traditional ideology.

To alleviate these problems and to reverse the unsustainability spiral, changes in the current land use are required. The required and feasible changes depend on policies and preferences of different stakeholders, such as decision-makers and farmers. By reviews of literature and planning reports (e.g. Peng et al., 1991; Tang and Jing, 1992; CAAC, 1993; OPGS, 2001) and interviews with local officers and farmers in the late 1990s, we formulated four scenarios abbreviated as *Nat*, *Loc*, *Farm* and *Envir*, representing major potential directions of agricultural development in the region.

- *Nat*: This scenario concentrates on soil conservation by promoting restoration of the destroyed natural vegetation. For this aim, arable farming should be practiced with the most efficient techniques regarding soil loss control and crop productivity, and be restricted to the most productive land units, to increase the area available for nature conservation. This scenario is in line with the *national* goals of the so-called 'ecological construction/restoration', by converting marginal farmlands to their original forms of land use (forests, shrubs or grass).
- *Loc*: This scenario accords priority to employment in agriculture and crop production. Traditionally in Ansai, both farmers and the government always

address crop production due to food insecurity problems. This scenario favors continuation of current labor-intensive and cropping-based agriculture and seeks food security, as traditionally prioritized by *local communities and farmers*.

- *Farm*: This scenario aims at increasing profits of agricultural production, i.e., the ratio of total net return to total inputs in monetary terms should be as high as possible. This scenario may represent a general goal for agricultural production from a *farmers*' point of view.
- *Envir*: Under this scenario, use of biocides, fertilizer N and machinery is kept as low as possible to serve environmental aims, through an integrated use of the land resources. This scenario uses concepts of organic or ecological agriculture that emphasize low use of agro-chemicals (fertilizer N and biocides). This scenario may seem most appealing to *environmentalists*.

3. Methodology

The methodology was based on concepts in production ecology (Rabbinge, 1993; Van Ittersum and Rabbinge, 1997), a target-oriented approach for quantification of alternative land use systems (production activities) and an MGLP model for an integration of all information (De Wit et al., 1988; Rabbinge et al., 1994; Bouman et al., 1998). The core of the methodology is to confront biophysical possibilities for land use with societal objectives and constraints, using an MGLP model that generates strategic land use options for different priorities with respect to the societal objectives and constraints. The methodology (Fig. 2) included the following major components/steps. The first one was identification of land use problems and policy issues by literature study, stakeholder interviews and field surveys, from which regional land use scenarios and objectives (Section 3.1) were formulated concerning future regional development. Next, future-oriented production activities were defined that meet different objectives related to environmental protection, productivity, employment and income, taking into account land suitability and feasibility of agro-technologies and socio-economic conditions (Section 3.2). In the quantitative land evaluation, suitability of different physical environments (land units) was quantified for various land use systems under potential, water-limited and N-limited production situations (Lu et al., 2003). The quantitative information in combination with literature data and expert knowledge was then used for determination of the input–output coefficients of production activities (Section 3.3). The next step was the development of an MGLP model with all the production activities, objective variables, and resource (land and labor) and demand (for food and firewood) constraints (Section 3.4). After model testing, iterative analyses were conducted to determine the solution space and trade-offs among the objective variables under various basic constraints, to serve the definition of scenarios/policy views. The final step was the implementation and evaluation of land use scenarios (Section 3.5).

In this study, we assumed a time horizon of 2020, meaning that production activities considered (Sections 3.2 and 3.3) may not all be feasible in the very near

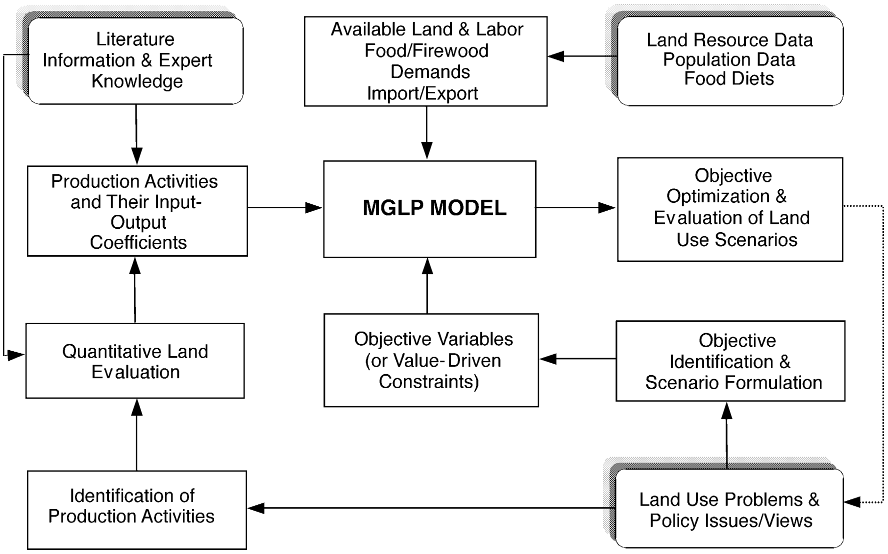

Fig. 2. A schematic presentation of the methodology/procedure used in this study. Ellipses indicate information sources.

future due to a variety of reasons, such as educational, economic (access to capital and markets) and land tenure constraints. We considered a period of ca. 20 years as potentially sufficient to overcome such factors, if appropriate policy measures are adopted (Section 5.2). The study further made a number of assumptions regarding, for example, labor forces, food diets, markets for products and prices (Section 3.4). Although these assumptions were well considered, they are still debatable. The methodology, however, allows investigation of assumptions by simply changing constraints or parameters of the MGLP model. Another important assumption was that inputs and outputs of all production activities were identical each year. Temporal variation was not considered in the production activities but was considered in food self-sufficiency constraints (Section 3.4.2).

3.1. Objective variables

Based on the land use issues (Section 2), 10 objective variables were identified that were related to environmental, social and economic aspects of sustainable land use and regional development in Ansai. Soil conservation was indicated by two objective variables: *minimization of total soil loss* and *minimization of total land area under crops* while satisfying food self-sufficiency (the latter aim is equivalent to maximization of land productivity to promote conversion of farmland for the aim of ecological restoration). The policy goals of food security and employment were explored by *maximizing total crop production* and by *maximizing total employment in agriculture*, respectively. Three objective variables were considered for economic/income goals: *minimization of total costs for agricultural production, maximization of total net* *agricultural return* and *maximization of net return per agricultural laborer*. In addition, possible environmental issues related to use of agro-chemicals were considered and interpreted as three policy objectives: *minimization of total fertilizer N use*, *minimization of total biocide use*, and *minimization of total N loss*.

3.2. Identification of alternative production activities

Identification of production activities was problem-based and future-oriented. Considering the land use problems and regional development objectives, five types of production activities were distinguished: (1) cropping activities for producing food grains and forage; (2) fruit production activities for income generation; (3) natural and sown grasslands for animal grazing; (4) natural and planted shrubs for producing firewood to meet energy requirement of the rural population; and (5) livestock activities for income generation and for supplying animal traction and manure. This subsection gives a brief description of the identification of production activities. Further details were given in Lu (2000) and Lu et al. (2003).

3.2.1. Identification of cropping activities

Since this explorative land use study focused on food security and soil conservation, cropping activities were defined in detail, using a similar procedure as described by Hengsdijk and Van Ittersum (2002). Six design criteria were selected for the identification of cropping activities (Table 1), and four of the criteria were described by Lu et al. (2003), including the suitable land units, crop rotations, yield levels

Table 1
Design criteria and their variants for identification of cropping activities

Design criteria	No. of variants	Variants
Suitable land units	6	Six units: floodplains; existing terraces; gently sloping; moderately sloping; steeply sloping; very steeply sloping
Crop rotations[a]	17	Two monocultures: corn, winter wheat Eight rotations without alfalfa: corn/soy/corn, mlt/soy/corn, corn/mlt/pota, pots/wht/corn, mlt/soy/mlt/pota, flax/wht/pota/mlt, pots/wht/corn/mlt, wht/pota/mlt/corn/flax Seven rotations with alfalfa: A3/corn/mlt, A3/corn/pota/mlt, A3/mlt/pota/mlt, A4/mlt/pota/mlt, A4/mlt/corn/flax/wht, A4/corn/mlt/corn/mlt/flax, A5/mlt/corn/flax
Yield levels	3	Three levels: attainable irrigated yield; attainable rainfed yield; N-limited yield
Soil conservation measures	4	Two tillage options: contoured tillage; furrow-ridging tillage Two residue management options: crop residue removed; crop residues left on field
Mechanization levels	3	Two levels: semi-mechanized; non-mechanized (hand labor and animal traction)
Terracing types	2	Two types: level bench terracing; spaced terracing

[a] A# = alfalfa with # growing years; wht = winter wheat, mlt = millet, soy = soybean, pota = autumn potato, and pots = summer potato.

(production situations) and agro-techniques for water and soil conservation. Here, a description is only given of the remaining two criteria, mechanization levels and terracing options.

Mechanization levels were distinguished based on power sources. The semi-mechanization level refers to the fact that farm operations, transportation and harvests are carried out by powered and small-scale machines. Weeds are controlled by herbicides, and application of insecticides, pesticides and herbicides is carried out by hand with powered knapsack sprayers. The non-mechanization level implies that animal traction is used for farm operations instead of machinery. Transportation of manure and harvested products are carried out with animal traction (donkeys and oxen), and weeding is done manually without herbicides. Two representative terracing types were selected: bench terracing with the slope land fully terraced, and spaced terracing with the slope land partly terraced. Further, each of the two terracing types could be built by either a bulldozer or manually.

Not all combinations of the six design criteria were feasible. Irrigation was considered possible only on the floodplains, and mechanized farming was applied only on the floodplains and on gently and moderately sloping land units. For the N-limited cropping activities, machinery use was not considered. In total, 118 feasible combinations of the suitable land units and production techniques were applied to each of the 17 representative monocultures/rotations, resulting in a total number of 2006 cropping activities.

3.2.2. Identification of other production activities

Fruit production was represented by apple, and six activities were defined, i.e. one for each land unit. Livestock activities were based on the animal species including cashmere goats, fine-wool sheep, small-tail sheep, pigs, cattle and donkeys. The main aims of livestock production were: goats for producing meat and cashmere, fine-wool sheep for mutton and wool, small-tail sheep for lamb and pigs for pork. Cattle were used to produce oxen for farm operations, while donkeys produced traction. Dairy and beef production were not considered. They may have limited development potential since the steep terrain is not suitable for grazing. Furthermore, the rural people do not consume dairy products, and the market is limited because Ansai is far away from urban areas. Grasslands and shrub-lands included the existing (natural) and newly planted ones. The new grasslands were defined only for the four sloping land units, and the new shrub-lands only for two land units (steeply sloping and very steeply sloping).

3.3. Technical coefficients of production activities

Production activities were quantified using a ‘target-oriented approach’ (Van Ittersum and Rabbinge, 1997), in which the set of minimum inputs to realize a production target was calculated by assuming use of the ‘best technical means’. Basic information for quantifying the production activities was obtained from results of the quantitative land evaluation (Lu, 2000; Lu et al., 2003) using the EPIC model (Mitchell et al., 1998) and from literature and expert knowledge.

Target yields of cropping activities were based on the potential, water-limited and nutrient-limited yields simulated with EPIC, taking into account unavoidable yield-reductions due to climatic hazards (hail, frost and rainstorms), soil-borne diseases and pests (due to narrow rotations and particular cropping sequences), and crop management imperfections (fertilizers, weeding, biocides and irrigation may not always be timely and evenly applied). Table 2 presents summarized results of target yields for each of the eight crops, and the yields achieved in experiments and on relatively well-managed farms for comparison. The target yields represented a broad spectrum, reflecting the effects of different physical environments, production techniques and rotations (Table 1).

Nutrient requirements (N, P and K) to realize the target yields were determined by balancing the total removal through economic products and harvested crop residues plus the losses. We assumed a nutrient use efficiency which was based on experiments and literature and which was equal for nutrients from fertilizers and from manure. N-losses included gaseous losses by volatilization and denitrification, losses by leaching and surface runoff, and loss of organic N by soil erosion. Pesticide inputs were derived from literature data and expert knowledge, taking into account effects of crop rotations and yield levels. Labor requirements for farming operations were estimated using a task-time approach (Van Heemst et al., 1981), for transportation of agricultural products and manure as a function of the amount and distance, and for terracing as a function of earthwork movement. Production costs included those for seeds, nutrients (N, P and K), biocides, irrigation water, farm equipment (sowing machines, knapsack sprayers, plough, hoes, cutters and threshers), labor, animal traction and tractors, and were calculated based on their prices in 1997–1998. Net return was calculated as the difference between gross production value (summation over all marketable products multiplied by their prices in 1997–1998) and

Table 2
Target yield ranges (minimum–maximum yield, t DM ha^{-1}) of the eight crops in the irrigated, rainfed and N-limited cropping activities, and yields achieved in experiments and on relatively well-managed farms

Crops	Irrigated yield	Rainfed yield	N-limited yield	Experimental yield reported[a]	Present yield[b]
Corn	9.6–12.7	3.8–9.2	2.4–6.5	13.5/8.5	4.0–8.5
Millet	7.7–10.1	2.9–6.6	1.5–4.9	7.9/6.6	3.5–5.5
Soybean	2.8–3.2	1.3–2.1	1.1–1.8	2.2/na[c]	1.2–2.0
Winter wheat	4.1–5.5	1.4–4.2	0.9–2.3	5.5/na	1.5–3.5
Autumn potato	8.4–10.7	3.0–6.8	1.4–4.9	na/5.5	3.0–6.5
Summer potato	6.6–7.6	1.6–3.1	1.4–2.6	na	2.5–5.5
Seed flax	2.1–2.8	0.6–1.5	0.5–1.2	na	0.6–1.2
Alfalfa	15.4–21.1	8.1–15.0	8.1–15.1	na/13.5	na

[a] Maximum yields achieved in experiments and by farmers (in Ansai and similar areas) based on available literature (Hou and Cao, 1990; Hou et al., 1990; Jiang et al., 1992; IWSC, 1992; Yang, 1996; Gao, 1997; Wu, 1997). Figures before and after the slash are irrigated and rainfed yields, respectively.

[b] Yields generally achieved on relatively well-managed farms/fields in Ansai, which are estimated from the statistical data of Ansai (yearbook) in 1990, 1992 and 1998, and interviews of farmers in 1997.

[c] na = not available.

total costs. No price was given to crop residues and manure or to grazed grasses, but costs were considered for their transportation and/or application or for the inputs to the sown grassland (activities). Technical coefficients of fruit, grassland and firewood activities were estimated using literature data. A simplified animal model based on a stable herd structure (Lu, 2000) was developed and used to determine the input–outputs of animal activities. Feed requirements were expressed in terms of digestible energy and digestible crude protein and calculated as a function of the metabolic weight.

Production activities were future-oriented and their quantification was based on well-defined assumptions and procedures, which integrated fragmented data from Ansai and areas with similar conditions. The production activities and their input–output coefficients generally differed from present systems, particularly in terms of resource use efficiency (nutrients, labor, water and land). The input-output coefficients of the cropping activities (Table 3) show the wide range of possibilities, with target yields ranging from 1.6 to 12.2 t GE ha^{-1}. Because of the low rainfall, deep soils and an assumed timely and proper incorporation of fertilizers, N leaching and denitrification are low in this semi-arid region, and N losses are mainly due to volatilization, soil erosion and surface runoff (Lu et al., 2003). As a result, total N losses are low (Table 3). Currently in Ansai N losses are much higher due to the

Table 3
Ranges (minimum–maximum) of major input–output coefficients in the irrigated, rainfed and N-limited cropping activities with and without alfalfa, respectively

Items	Unit	No-alfalfa cropping activities			With alfalfa cropping activities		
		Irrigated	Rainfed	N-limited	Irrigated	Rainfed	N-limited
Yield[a]	t GE ha^{-1}	4.7–12.2	1.6–7.6	1.2–5.2	3.4–7.1 (10.8–6.1)[b]	1.3–4.3 (5.5–4.6)	1.0–2.1 (5.4–5.9)
N-input	kg ha^{-1}	140–304	61–188	19–110	116–204	20–92	na[c]
Biocide input	kg ha^{-1}	1.3–4.7	1.0–3.3	0.4–1.5	0.4–1.7	0.3–2.0	0.1–0.7
Labor input, non-mechanized[d]	Manday ha^{-1}	65–121	47–137	37–121	73–98	50–122	52–108
Labor input, mechanized[d]	Manday ha^{-1}	12–37	9–37	nc[e]	15–25	11–50	nc
Oxen input, non-mechanized[f]	Oxday ha^{-1}	17–36	11–68	12–62	25–35	16–39	11–45
N-loss	kg ha^{-1}	32–58	12–45	3–29	28–41	4–25	0.1–16
Soil loss	t ha^{-1}	0.1–1.3	0.1–55	0.1–70	0.1–0.1	0.1–15	0.1–16

[a] Yield was expressed in Grain Equivalents (GE), as calculated based on energy contents of different crop products, assuming that the energy content of a GE is 16 MJ kg^{-1} (close to the energy content of wheat).

[b] Figures between brackets were production of alfalfa in dry matter per year.

[c] na, not applied, i.e., no external N from fertilizers and manures was applied.

[d] The data do not include labor required for transportation and application of manure and terracing, which was calculated separately (see Lu, 2000).

[e] nc, not considered.

[f] The data do not include oxen required for transportation and application of manure and terracing, which were calculated separately (see Lu, 2000). For the semi-mechanized level, no oxen were used.

surface application of urea and poor soil management, and estimated at more than 50% of the applied fertilizer-N, based on literature (IWSC, 1992; Yang and Yu, 1992) and the statistical data of Ansai. The labor inputs for the cropping activities without use of machinery are estimated at ca. 30–70% of those reported in the 1998 yearbook of Ansai, but have higher oxen inputs.

3.4. Constraints incorporated for the scenarios

Constraints included available land area, labor forces and draught animals, and driving constraints concerning the self-sufficiency requirements for agricultural products. The county was divided into six sub-regions, and constraints were imposed at regional (county) or sub-regional scale.

3.4.1. Agricultural land area and labor

Agricultural land resources included suitable land (slope gradient $<47\%$) for growing crops/apples or planting grass/shrubs, natural grassland for grazing animals and natural shrub-lands for firewood collection. The maximum available area for the three land uses was 10.6, 44.1 and 13.0 10^3 ha, respectively, based on land survey data (Chen et al., 1988; Chen, 1988). Due to steep slope, poor infrastructure and small size of land parcels, not all suitable land units were accessible for machinery or irrigation. Table 4 presents the areas of the land units and their fraction suitable for mechanized or irrigated cropping activities, and those considered for planting grass/shrubs. In view of the limited markets and poor road systems, a maximum growing area of 1000 ha for apples in Ansai was assumed in the present scenario analysis. In addition, a limit of 15 t ha^{-1} (often suggested by Chinese scientists) for soil loss was added in the model to exclude cropping activities with soil loss exceeding this limit. Water availability for irrigation on the floodplains was considered sufficient because of limited land area accessible to irrigation.

The labor force was based on the projected rural population in 2020 and the fraction of population that is economically active (aged from 20 to 60). The

Table 4
Slope gradient and total area of suitable land units, and the upper limit (fraction) of each land unit used for different groups of production activities

Group of production activities	Floodplains	Existing terraces	Gently sloping land	Moderately sloping land	Steeply sloping land	Very steeply sloping land
Slope gradient (%)	<5	<5	<9	10–18	19–27	28–47
Total area (ha)	5123	3186	5923	11 380	40 650	39 528
Irrigated	0.8	nc[a]	nc	nc	nc	nc
Semi-mechanized	0.8	nc	0.8	0.8	nc	nc
Non-mechanized	1.0	1.0	1.0	1.0	1.0	1.0
Fruit (apple)	0.15	0.1	0.1	0.1	0.1	0.1
Sown grass	nc	nc	1.0	1.0	1.0	1.0
Firewood	nc	nc	nc	nc	1.0	1.0

[a] nc, not suitable or not considered.

requirement and supply of labor and draught animals (oxen and donkeys) were calculated for each of five labor-demand periods over the year, as determined by the major farm operations (e.g., land preparation, harvesting). The total number of oxen or donkeys that could be maintained for agricultural production was set to one quarter of the total rural population, assuming that one family could have a maximum of one ox and one donkey. Per labor period and per sub-region, the needs of labor and draught animals could not exceed the total availability.

3.4.2. *Food and feed*

Food requirements were calculated as a function of the projected rural population, per capita requirement of food energy and protein and a dietary structure. Based on Luyten (1995), a base diet was defined with a daily energy intake of 11 kJ and 75 g protein per capita, assuming that 15% of the food protein was from animal meat, and at least 35% of the food energy was from wheat. In addition, requirements for vegetable oil, potatoes and apple in the diet were specified and set to 14.5, 15–20 and 1.5% of the total energy, respectively. Firewood requirement was set to 400 kg SCE (standard coal equivalents) per capita per year, the mean annual home consumption of the rural population in the Loess Plateau/China in the mid 1980s (Peng et al., 1991). Four feed types were used to meet feed requirements, including (grazing) grass, crop residues, agricultural by-products, and main crop products (corn, alfalfa and potatoes).

Food self-sufficiency was ensured by an imposed production of various individual agricultural products (food crops, meat and apple). Considering annual variability of crop production due to climatic variation and importance of food crops for survival, it was assumed that per sub-region, total crop production expressed in grain equivalents (GE) should exceed 150% of the total requirements (food and feed), and total meat production in terms of pork equivalents and apple production should meet the requirements. For Ansai as a whole, self-sufficiency requirement for each of the marketable crop products (e.g., corn, wheat, potato) had to be met, but for individual sub-regions the deficit could not exceed 50% of the total requirement. Further, it was assumed that per sub-region at least 50% of the requirement for food oil was produced from soybean and flax, and the remaining part was bought at external markets. Grasslands (the natural and newly sown for animal grazing), crop residues (as feedstuffs or firewood), shrub-wood, alfalfa and manure were used only within a sub-region. Available husks of wheat and millet for feed, and cakes from seed flax and soybean were determined by the amounts of wheat, seed flax and soybean used as food and for food oil. Constraints were incorporated in the MGLP model for imposing indoor feeding and grazing for a ruminant animal and for calculating manure production (see Lu, 2000).

3.4.3. *Terracing*

Terrace building requires high labor and capital inputs and may be restricted due to high cost or other problems such as the small farm size. Therefore, it may be helpful to the stakeholders to show the consequences of terracing on the regional objectives. This study considered two terracing options for each of the four scenarios, named ‘with-terracing’ and ‘non-terracing’, assuming that a maximum of 60% of the area could be terraced in the first option, while no *new* terraces were built in the second option.

3.5. Procedure for generating policy scenarios

Each of the four scenarios was defined by different priority settings of several objectives and by the same assumptions regarding requirements of agricultural products, as described in Section 3.4. An iterative procedure has been developed for the scenario generation, in which an objective variable was treated as a constraint with a goal value that was in line with the policy priority when it was not optimized. For each of the objectives used in a policy scenario, a priority order was given according to policy preferences, with an allowed deviation (‘sacrifice’) from the optimum of that objective (Table 5). The objective variable with the highest priority (major goal) was firstly optimized without imposing restrictions on other objectives. The optimized value plus (for a minimization objective) or minus (for a maximization objective) the allowed deviation was imposed as a target for the first objective variable, and then the second objective variable was optimized. In the next run, the third objective variable was optimized with restrictions imposed on the first two objectives. Using the same procedure, the remaining objectives were optimized sequentially. The essence of this procedure is to release some solution space through a small sacrifice of the optimal value of the higher priority objective, for the sake of the lower priority objective. This procedure can be mathematically described as:

Table 5
Priority setting and the deviation (α_i) of objective variables for scenarios *Nat*, *Loc*, *Farm* and *Envir*[a]

Optimization of objective variables[b]	Priority order (i)				Deviation fraction (α_i)			
	Nat	Loc	Farm	Envir	Nat	Loc	Farm	Envir
Min. total soil loss	1	7	6	4	0.2	G[c]	G	0.1
Min. total cropping area	2	nc[d]	nc	nc	0.15	nl[e]	nl	nl
Max. total employment	3	1	5	2	0.15	0.2	0.1	0.15
Max. total net return	4	4	1	5	0.1	0.1	0.2	0.1
Min. total production costs	5	2	2	6	0.1	0.15	0.15	0.5
Min. fertilizer N use	6	5	3	3	0.05	0.1	0.15	0.15
Min. biocide use	7	6	4	1	G	0.05	0.05	0.2
Max. crop production	nc	3	nc	nc	nl	0.15	nl	nl
Min. total N loss	nc	nc	nc	7	nl	nl	nl	G

[a] *Nat*: soil conservation and ecological restoration; *Loc*: employment and food security; *Farm*: agricultural profit; *Envir*: low use of agro-chemicals for environmental protection. Further details refer to Sections 2.2 and 3.5.

[b] Min., minimization and Max., maximization.

[d] nc, not considered.

[c] G, final solutions.

[e] nl, no limitations imposed.

Let n = total number of objective variables considered in a scenario, i = priority order of an objective, e.g., $i = 1$, the objective with the highest priority; O_i = optimization value of objective i under restrictions imposed on the first (i–1) objective variables, G_i = goal value of objective i, and α_i = deviation fraction from the optimum value of objective i.

When $i = 1$, the optimal value ($O_{i=1}$) of the first objective variable can be obtained by minimization or maximization without imposing restrictions on other objectives. When $i = 2$ to n, the optimal value (O_i) of objective i can be obtained by minimization or maximization, along with the first i–1 objectives as constraints with the following upper or lower bounds:

$$G_{i-1} \leqslant (1+\alpha_{i-1}) \cdot O_{i-1}, \quad \text{if the } O_{i-1} \text{ is a minimized value; or} \tag{1}$$

$$G_{i-1} \geqslant (1-\alpha_{i-1}) \cdot O_{i-1}, \quad \text{if the } O_{i-1} \text{ is a maximized value.} \tag{2}$$

For the last objective, i.e., $i = n$, the goal value $G_i = O_i$. Results of the last optimization are final solutions for the scenario.

This procedure can be further illustrated with the generation of scenario *Nat*. In this scenario, seven objective variables were selected, and their assumed deviation fractions (α_i) are given in Table 5. First, total soil loss was minimized under the restrictions given in Section 3.4, and then total cropping area was minimized by imposing the total soil loss not to exceed 1.2 times ($\alpha_1 = 0.2$) its minimized value. Next, the goal values of both objective variables [$G_1 \leqslant (1+0.2) \cdot O_1$, $G_2 \leqslant (1+0.15) \cdot O_2$] were added to the MGLP model as constraints for maximizing total employment in the third run ($i = 3$). In the next four runs, total net return was maximized, and total production cost, total fertilizer N use and total biocide use were minimized sequentially with restrictions imposed on the higher priority objectives. Results of the last run, the minimization of total biocide use, were the final solutions of *Nat*.

4. Model results

The model results (Table 6) are presented for the four scenarios and the two terracing options, with-terracing and non-terracing, respectively.

4.1. Land use allocation

Land use allocation differed greatly among the scenarios. Area allocated to arable farming in *Loc* was similar to the current cropland area, to meet the employment and food production aims. By contrast, cropping area was greatly reduced in the other scenarios compared with the present cropland area, associated with a considerable decrease in employment in agriculture (Fig. 3). Area allocated to crops in *Nat* was only around 30% of that in *Loc* at a great loss of employment, reflecting distinct conflicting objectives between both scenarios. The areas not used for croplands were largely used for growing shrubs to produce firewood for self-sufficiency requirement, rather than for growing grass (Table 6). This implies that the imposed firewood requirement for meeting the rural energy demands heavily affected the regional land use.

All scenarios gave a high priority to arable farming, and *Loc* and *Farm* also to fruit (apple) production, to meet aims of food self-sufficiency, employment and benefits (per unit area). Since only a small area (14.7 10^3 ha) was deemed suitable for mechanization, labor-intensive cropping activities with animal traction dominated all scenarios, and hence the high requirement of oxen. A large number of draught animals required for arable farming (Table 7) restricted the amount of forage available for sheep and goats, and priority regarding livestock production was therefore more often given to pigs, rather than to sheep and goats in all scenarios (Table 6).

Table 6
Optimization results for the four scenarios and the two terracing options

	With-terracing				Non-terracing			
	Nat[a]	Loc	Farm	Envir	Nat[a]	Loc	Farm	Envir
Area under agriculture (10^3 ha)	56.4	105.8	105.8	93.8	78.6	105.8	105.8	105.8
Crops	26.7	97.8	74.0	50.8	29.3	97.6	62.2	58.2
Apples	0.51	1.0	1.0	0.14	1.0	1.0	1.0	0.14
Sown grasses	0	0	5.4	0	2.7	0	1.4	0
Planted shrubs	29.2	7.0	25.4	42.9	45.7	7.2	41.3	47.5
Crop production								
Total (10^3 t GE)	128	440	282	139	116	368	244	174
Mean (t GE ha^{-1})	4.8	4.5	3.8	2.7	3.9	3.8	3.9	3.0
Meat and apple production (10^3 t)								
Pork (carcass)	8.0	21.8	8.5	6.8	4.8	24.7	13.3	8.2
Mutton (carcass)	2.3	1.0	4.0	7.1	4.0	1.7	2.3	6.3
Apple (fresh Weight)	18.3	25.6	25.6	4.9	23.5	23.5	23.5	4.9
Net return and production costs								
Total net return (10^6 yuan)	183	462	443	126	205	382	349	163
Total production cost (10^6 yuan)	212	582	372	387	206	615	350	407
Ratio total net return to total costs	0.86	0.79	1.19	0.32	0.99	0.62	1.0	0.40
Employment								
Total (10^3 man-years)	22.3	69.3	44.9	44.0	20.6	58.7	34.0	36.3
% of total available labor	21	66	43	42	20	56	33	35
Mean soil loss of agricultural area (t km^{-2})	51	271	237	74	199	696	365	250
Biocide use								
Total (t a.i.)	61	137	153	33	56	124	128	44
Mean (kg a.i. ha^{-1})	2.2	1.4	2.0	0.7	1.9	1.3	2.0	0.8

[a] See footnotes in Table 5.

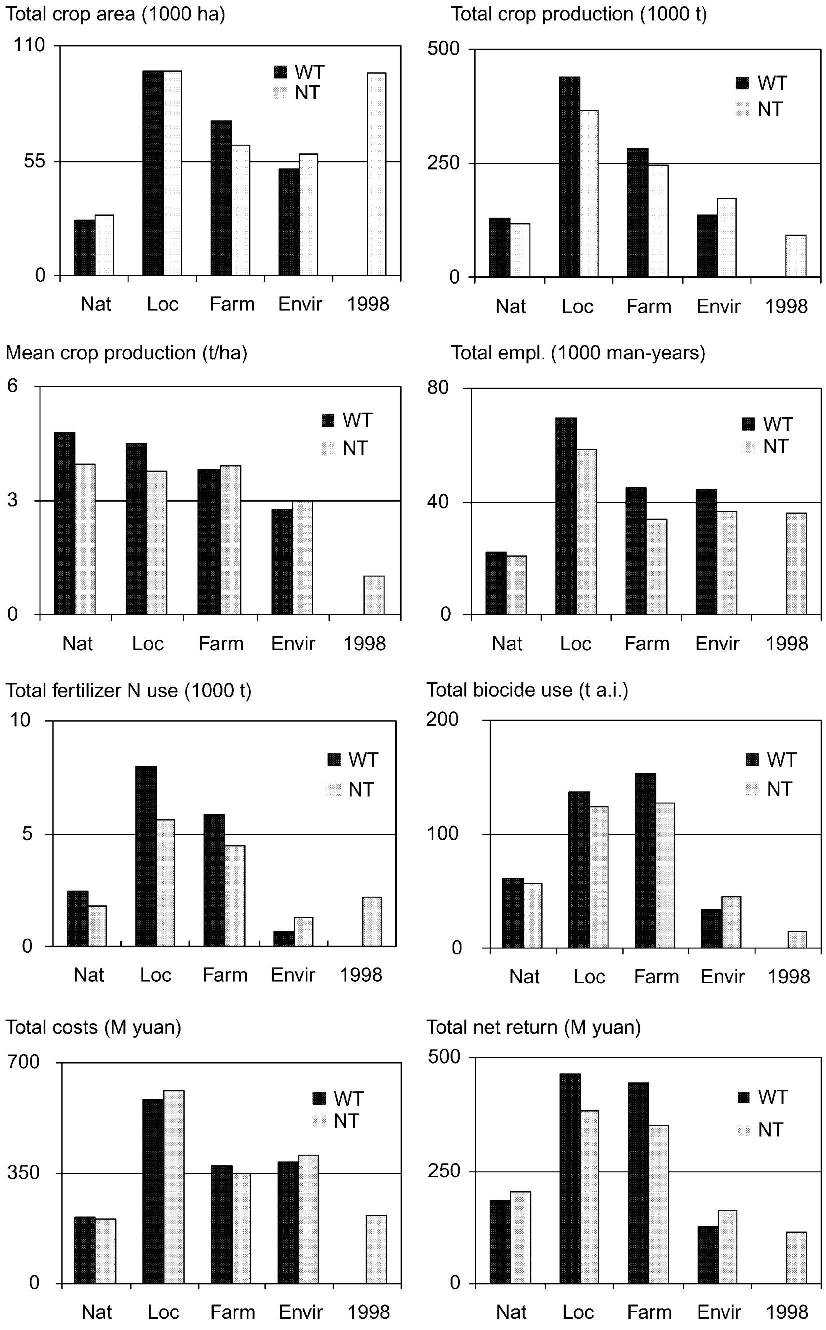

Fig. 3. Goal values of the selected objectives in the four scenarios. Total and mean crop production is in Grain Equivalents, and total biocide use is in active ingredients, but the current use is in commercial formulation. *Nat*, *Loc*, *Farm* and *Envir* refer to footnotes in Table 5. 1998: actual data for Ansai from 1998; WT: with-terracing option, and NT: non-terracing option.

Some crop rotations dominated the selected cropping activities, particularly in *Loc* and *Farm* of the with-terracing option (Fig. 4). Rotations including corn were selected most often because of high yield potential of corn. In *Nat* and *Envir*, particularly when terracing was not applied, the selected crop rotations were much more diversified than those in other scenarios, satisfying the aims of soil conservation and environmental protection.

4.2. Food self-sufficiency and crop production

Meeting the food requirement for self-sufficiency seems not a problem from a biophysical point of view. Even if the current cropland area is reduced by 70%, enough food for self-sufficiency could be produced (*Nat*) by selecting cropping activities that are most productive and meet the requirements for specific food products as indicated in Section 3.4. If targeted to achieve a high crop production (*Loc*), more than fourfold of the food requirements for the projected rural population in 2020 could

Table 7

Number of oxen and transport donkeys and their actual working time expressed as a percentage of 365 days per year assuming 8 h a day

	Current (1998)[a]	With-terracing				Non-terracing			
		Nat[b]	Loc	Farm	Envir	Nat[b]	Loc	Farm	Envir
Total oxen (10^3 oxen unit)	9.2	4.8	29.0	10.9	13.3	11.1	40.7	20.0	26.5
Total donkey (10^3 donkey unit)	6.5	5.8	23.2	14.7	13.0	7.0	19.4	9.8	12.6
Actual working time of oxen (%)	na[c]	28.3	24.9	33.4	34.8	27.0	24.9	33.5	26.2
Actual working time of donkey (%)	na	26.4	19.0	17.9	33.3	27.1	19.2	23.7	29.9

[a] current numbers of draught animals are estimated based on 1998 Ansai Yearbook data.

[b] see footnotes in Table 5.

[c] na, not available.

Table 8

Total N use and loss, share of manure N, and mean N use and N loss per ha agricultural land (total lands allocated to cropping, apple and sown grassland activities)

	With-terracing				Non-terracing			
	Nat[a]	Loc	Farm	Envir	Nat[a]	Loc	Farm	Envir
Total N use (10^3 t N)	3.6	10.8	7.8	3.3	3.3	9.0	6.5	4.0
% of total N use covered through manure[b]	33	26	25	81	46	38	31	68
Mean total N use (kg per ha agric. land)	128	107	96	58	94	90	97	63
Mean fertilizer N use (kg per ha agric. land)	90	81	73	12	54	57	70	22
Total N loss (10^3 t N)	1.4	3.9	2.9	2.3	1.7	3.9	2.7	2.8
% of total N loss covered by livestock[c]	47	41	41	73	53	48	41	66
Mean N loss (kg per ha agric. land)	24	37	27	25	22	37	26	26

[a] See footnotes in Table 5.

[b] 100 minus this percentage is covered through chemical fertilizers.

[c] 100 minus this percentage is from cropping, apple and sown grassland activities.

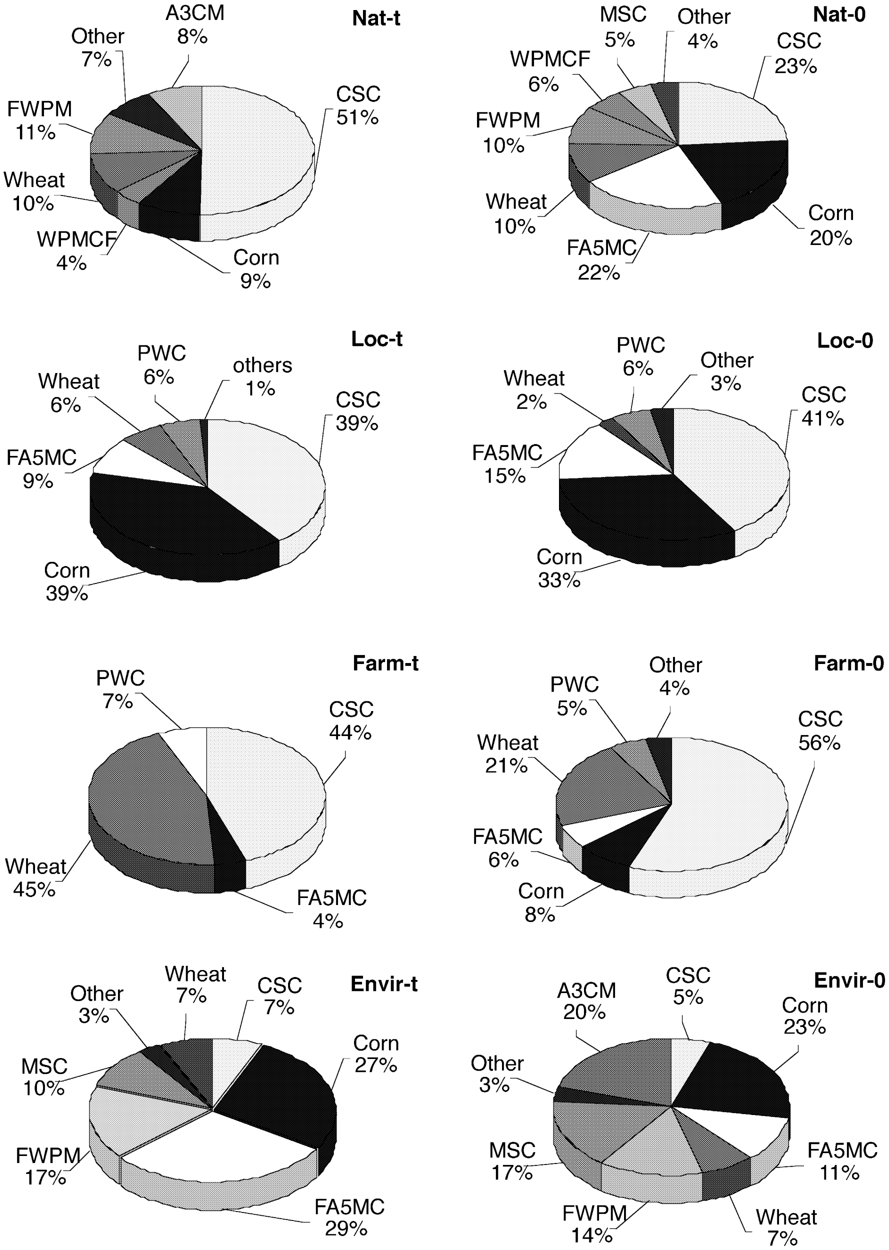

Fig. 4. Main crop rotations selected and the area (as a percentage of the total area allocated to crops) in the four scenarios. CSC: corn/soybean/corn, MSC: millet/soybean/corn, CMP: corn/millet/autumn potato, PWC: summer potato/wheat/corn; FWPM: flax/wheat/autumn potato/millet; A3CM: alfalfa (3 years)/corn/millet; FA5MC: flax/alfalfa (5 years)/millet/corn. *Nat, Loc, Farm* and *Envir* refer to footnotes in Table 5. t: with-terracing option, and 0: non-terracing option.

be produced. To realize these goals, arable farming must be substantially intensified. For instance, the mean crop production in *Nat* was 4.8 and 3.9 t GE ha^{-1}, with a mean input of 90 and 54 kg ha^{-1} for fertilizer N, and 2.2 and 1.9 kg a.i. ha^{-1} for biocides, respectively, for the two terracing options. These inputs are much higher than those in current practices (Fig. 3).

Results of *Envir* indicate that it is also possible to produce enough food for self-sufficiency at low inputs of fertilizer N (Table 8). In this case, the required fertilizer N was only 30 and 45% of that used in Ansai in 1998, respectively, for the two terracing options. This low use of fertilizer N can be explained by the selection of cropping activities with N-limited yields (Table 9), a relatively high share of alfalfa-based crop rotations (Table 10, Fig. 4), and a high share of manure in the total N use (Table 8).

4.3. Soil loss and soil conservation

The model results indicate that soil loss can be greatly reduced. The average soil loss from the agricultural land uses (cropland, orchard, sown grass and planted shrubs) was 0.5–2.7 t ha^{-1} in the four scenarios when terracing was used, and 2.0–7.0 t ha^{-1} when no additional terracing was applied (Table 6). These soil losses are estimated to be less than 10% of the current rate of soil losses in Ansai (CAAC, 1993).

Several options exist for achieving the soil conservation aims. One choice is conversion of marginal farmlands and restricting cropping to the most suitable land units. This has been strongly promoted by the government in recent years through the implementation of the program '*conversion of croplands into forests/grass*'. This option seems highly possible but may increase unemployment, as revealed in *Nat* (Fig. 3). Building terraces on slope lands could be an alternative. Terracing is not only effective in soil loss control, but also increases crop yield and utilizes the large rural labor resource. Therefore, terracing was highly selected in the four with-terracing

Table 9
Land area allocated to different yield levels in the four scenarios

	With-terracing				Non-terracing			
	Nat[a]	Loc	Farm	Envir	Nat[a]	Loc	Farm	Envir
Total area (10^3 ha)								
Nitrogen-limited yield level	1.8	14.4	3.1	44.7	7.8	38.7	3.7	45.6
Rainfed yield level	20.6	79.1	66.5	4.6	17.1	54.6	54.2	8.5
Irrigated yield level	4.4	4.4	4.4	1.6	4.4	4.4	4.4	4.0
Percent of total cropping area								
Nitrogen-limited yield level	6.8	14.7	4.2	87.9	26.7	39.6	5.9	78.5
Rainfed yield level	76.9	80.8	89.9	9.0	58.5	55.9	87.1	14.7
Irrigated yield level	16.3	4.5	5.9	3.1	14.9	4.5	7.0	6.9

[a] See footnotes in Table 5.

scenarios (Table 10). An increase of labor inputs by terracing did not affect the benefit much, because terraces were built during the fallowing period, and thus efficiency of labor use was enhanced. Both the scenarios *Loc* and *Farm* even obtained a higher profit per unit production costs in the with-terracing option than in the non-terracing option (Table 6). Without terracing, agro-technical measures of furrow-ridging and crop residue left as mulch were most often selected for soil conservation (Table 10), and next the alfalfa-based crop rotations with 6–32% of the total cropping area.

4.4. Employment

Labor was not a binding constraint for the scenarios, i.e., available labor was abundant, even during the periods with a peak labor demand. Reducing the area for cropping greatly decreased employment. In the extreme case of *Nat*, only 20% of the available rural labor was employed in agriculture (Table 6). Total employment in *Loc* was 66 and 56% of the total available rural labor, respectively, for the two terracing options, but, to achieve this, all present farmlands should be maintained. Prioritizing employment in agriculture stimulated the selection of labor-intensive cropping activities (without use of machinery), and thus reduced profit as a result of increased costs for labor and draught animals per unit area. The net return per unit production cost was markedly lower in *Loc* than in *Farm* and *Nat*, largely because of the higher amount of labor and draught animals involved in agriculture (Tables 6 and 7).

Table 10
Cropping area with specific soil conservation measures in the four scenarios. The figures in each column cannot be added up, as some measures are applied simultaneously, for example, furrow-ridging and residue left on-field

	With-terracing				Non-terracing			
	Nat[a]	Loc	Farm	Envir	Nat[a]	Loc	Farm	Envir
Area allocated to different soil conservation measures (10^3 ha)								
Alfalfa-based crop rotations	2.8	8.5	3.1	15.8	6.8	15.0	4.1	18.6
Residue left on-field	2.6	47.4	42.1	4.5	3.8	42.8	37.2	36.7
Furrow-ridging	2.8	31.8	4.9	4.6	21.2	89.5	48.0	50.4
Bench terracing	19.0	35.8	33.5	42.4	nc[b]	nc	nc	nc
Spaced terracing	0.0	22.7	25.0	1.0	nc	nc	nc	nc
Area allocated to different soil conservation measures (% of the total cropping area)								
Alfalfa-based crop rotations	10.5	8.7	4.2	31.1	23.1	15.3	6.5	32.0
Residue left on-field	9.5	48.4	56.9	8.9	12.8	43.9	59.9	63.2
Furrow-ridging	10.5	32.5	6.6	9.1	72.5	91.7	77.2	86.6
Bench terracing	71.0	36.6	45.3	83.4	nc	nc	nc	nc
Spaced terracing	0.0	23.2	33.8	2.0	nc	nc	nc	nc

[a] See footnotes in Table 5.

[b] nc, not considered.

4.5. Net return and production costs

Total net return from agriculture increased greatly with an increase of production inputs (Fig. 3). For instance, total net return in *Farm* was increased 2- to 3-fold at an increase of production costs with around 60–70% compared to that in 1998.

Total net return in the various scenarios was composed of 48–71, 20–42 and 6–22%, respectively, from arable farming, livestock and fruit production. Total production costs was composed of 32–43 from labor, 8–16% from fertilizers and biocides, and 40–59% from draught animals, feeds, seeds, irrigation, small farm equipment, machinery and terracing. The low share of agro-chemicals in the total production costs was because a significant part of the nutrient requirements was covered by manure (nutrients from manure were not priced) (Table 8). The use of oxen and donkeys was high in comparison with that in 1998, particularly in the scenarios without use of terracing (Table 7). This high demand of oxen largely resulted from the use of the furrow-ridging technique for soil conservation (Table 10). Use of this technique caused a high need of oxen during the land preparation, however, oxen requirement was low during the growing period, and hence the low use rate for oxen (Table 7). This resulted in high needs of feed to keep this large number of draught animals, and therefore increased production costs.

5. Discussion and conclusions

5.1. Achievements and limitations of the study

The study presents methodical and operational ways of applying explorative land use studies and MGLP to a county with soil conservation, food self-sufficiency and rural employment objectives. The study revealed relationships between components of the system, e.g., between plant and animal production, and trade-offs between economic, social and environmental objectives, that could not be revealed without such a quantitative system analysis. Section 5.2 summarizes the major findings for Ansai county.

The scenario results were generated with explicit assumptions regarding e.g., the self-sufficiency requirement of agricultural products and prices, to indicate the biophysical and agro-technical potentials for future agricultural development. Results may be strongly affected when any of these assumptions is changed. Particularly assumptions regarding prices may have important implications. If deemed desirable, variable prices using price elasticity could be implemented in the LP model (Hazell and Norton, 1986).

The study presented in this paper should be considered as an input to a policy design procedure, not providing blue-prints for future land use, but rather as a means to learn about the regional potentials and limitations and about possible conflicts between objectives (Rossing et al., 1999). Note, that the study only addresses the regional and sub-regional scale. Many decisions regarding land and resource use are taken by farmers or communities. Farm level studies are required to explore farm scale opportunities and constraints.

The scenarios presented here are relevant to the main problems as perceived by the local government and rural communities, based on current knowledge and understanding of the regional development issues. However, these scenarios should not be considered as the only possible options, as numerous other possibilities can be formulated according to preferences of stakeholders. Different scenarios can be easily generated with the MGLP model when other priorities and goal values are specified by stakeholders.

5.2. Highlights of the results

The results of this study provide stakeholders with the following perspectives, if alternative land uses and production activities are adopted:

1. Food requirements for self-sufficiency can be guaranteed from a bio-physical point of view. There is a large potential to reduce the area currently used for crop production. To meet the estimated food requirement of the rural population in 2020, a cropping area of ca. 30% (*Nat*) of the cultivated area in 2000 would be sufficient.
2. Arable farming may continue to play a key role in meeting the regional objectives, although there are possibilities to considerably reduce the area of marginal croplands. Livestock production may, to some extent, replace cropping. However, this change seems to be strongly constrained by the large labor ‘surplus’ in the rural areas, because livestock have lower labor requirements. Given the limited available lands and abundant rural labor force, animal husbandry should focus on indoor feeding, rather than on grazing. This conclusion is in line with the planned development direction of livestock in the local development plan (OPGS, 2001).
3. Several options exist to mitigate the problems of land degradation as induced by slope cultivation. Conversion of slope farmlands into more sustainable land uses such as shrubs or grasslands seems a most cost-efficient way of soil conservation and ecological restoration, but this requires alternatives for the large rural labor force. Alternatively, terracing could be a promising choice, not only because of the high efficiency in soil loss control, but because terracing can increase crop yield and utilize rural labor. Another option is the use of agro-techniques for soil conservation, such as furrow-ridging tillage, leaving crop residues on field and growing crops in rotations with alfalfa. It should be noted that although furrow-ridging is efficient in preventing soil loss, its preparation needs traction from oxen. Due to the low need of oxen in the crop-growing period, this results in a low use-efficiency of the oxen, while putting heavy pressure on the limited feed resources. Growing crops in rotations with alfalfa may be a promising alternative because of its efficiency in controlling soil losses with low fertilizer N and capital inputs.

4. There is a relatively strong trade-off between agricultural employment and labor productivity in terms of net return per laborer (see also Lu and Van Ittersum, submitted for publication). The large rural population and the need for employment could be crucial factors affecting sustainable agricultural development in the long run.

5.3. Implications for policy development and on-farm innovations

This study suggests that many possibilities exist for stakeholders to make choices for future agricultural development, and to break the unsustainability spiral by an efficient use of land resources. A prerequisite for adoption of alternative land use systems, and agro-technical and soil conservation measures such as those suggested in this study, is development of appropriate policies that stimulate further reforms of the land tenure system, and investment in infrastructure, soil conservation and education. Fig. 5 presents key measures that may promote an efficient resource use and contribute to the regional development goals.

Land is legally owned by the villager's collective and subject to state regulations. This land tenure system restricts farmer's investment in soil conservation and agriculture, due to insufficient protection of the ownership or interests of the investment. The introduction of household-based farming on the land rented from the state for a long term has alleviated this problem, however, further reforms are necessary (Heilig, 1999). Education is another important issue in this region because of shortage of teachers and finances and the isolation of villages due to the natural conditions. The state has recognized this problem and increased the financial supports to improve education and infrastructure, being an important component of the Development Program for the West China Region as recently implemented. An improvement

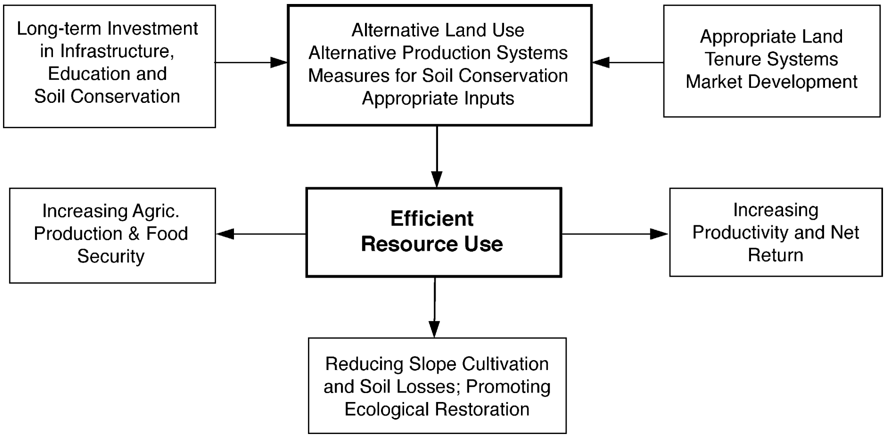

Fig. 5. A schematic illustration of main agro-technical and policy measures to stimulate efficient resource use for breaking the unsustainability spiral and meeting various goals of regional development in the Loess Plateau.

of infrastructure can promote the development of markets, and thus the growth of cash crops such as apple. In the long run, development of non-agricultural employment opportunities to absorb the large surplus rural labor and education related to effective family planning are very important for the sustainable development in this region.

The present study may also be used as a starting point for targeted development and testing of innovations at farm and community scale. Alternative crop rotations, management systems and integration of plant and animal production, such as those suggested in this study, need on-farm development, testing and evaluation. Targeted experimental and model-based research may support such innovation, but strong participation of farmers and communities through on-farm training and pilot demonstrations are essential.

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