A heterogeneous-agent model with district-level constraints: an application to livestock development in Gansu, China

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Abstract

This paper develops a heterogeneous-agent model to assess the impacts of removing lucerne growing subsidies, increasing livestock numbers and including district-level equilibrium conditions on optimal farm plans in the Qingyang district of Gansu Province, China. The model is a five-year dynamic linear program that solves across 96 farm households whilst incorporating district-level constraints. The approach used allows us to observe seasonal variations in incomes, infer the distribution of a policy shock among households and highlight trade patterns at the district level. The results suggest that without lucerne growing subsidies the total area of lucerne grown by all modelled households falls by 18%. Increasing livestock numbers by 25% reduces net household incomes by 17% as changes to labour allocations reduce off-farm employment opportunities. When external trade in forages is included in the model, total livestock numbers held by all 96 households rise from 502 to 838, this highlights the benefits of integrated feed markets. Shadow prices for crop production rise when livestock numbers increase, implying that benefits exist to improving crop yields.

Keywords: Heterogeneous-agent model; district-level constraints; livestock; China.

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1. Introduction

Modelling the responsiveness of rural households to different agricultural development policies has advanced beyond using representative household models to incorporate modelling multiple households simultaneously. Such modelling techniques include heterogeneous-agent models (Berger, 2001; Johnson *et al.*, 2006) and approaches that integrate individual agricultural households models into village economy-wide models (Taylor *et al.*, 2005; Dyer *et al.*, 2006; Heerink *et al.*, 2007; Shi *et al.*, 2010; Taylor *et al.*, 2010). Heterogeneity among households, interactions among households, or high levels of transactions costs may make it appropriate to incorporate district-level constraints into household modelling approaches. For example, if high transaction costs or low levels of market participation isolate a township market for credit, labour or food from outside markets, capturing local equilibrium feedbacks on household decision making becomes critical (Holden *et al.*, 1999).

Village economy-wide models often examine the income, land price and wage price effects of changing crop prices and government income support programs. One market that has not received much attention in the literature is the role of township-level livestock feed markets.[1] This is partly because previous studies examining the responsiveness of multiple households to alternative policies have tended to focus on cropping systems, not integrated crop-livestock systems. At the two extremes, either no livestock feed markets exist (feeding draught cattle own-produced crop residues) or perfect competition exists, where different feed stocks can be easily sourced from alternative markets (a poultry farmer close to an

[1] In this analysis, multiple villages aggregate into a township, and multiple townships aggregate into a district.

urban centre). The most common situation in developing nations appears to be somewhere in between these two extremes. High transaction costs potentially render inter-township or inter-district trade of some feed stocks unviable (for example, Parthasarathy and Hall (2003) find local markets exist for stover in mixed systems in India).[2] Accounting for feed trade constraints may be important, especially given that Komarek et al. (201X) find that owning more livestock raises net incomes only when feed can be sourced from different districts.

This paper presents a multi-period heterogeneous-agent model that incorporates township-level and district-level constraints. The model is used to analyse the impacts of livestock development policies on 96 farm enterprise mixes and incomes in two different townships in western China. We examine three scenarios: 1) the role of subsidies in promoting lucerne production 2) removing livestock feed trade barriers and 3) raising livestock numbers. Previous studies of policy developments in this region have focused on econometrically estimating the effect of crop subsidies and compensation payments on land usage and off-farm employment (Uchida *et al.*, 2005; Uchida *et al.*, 2009). Other relevant studies have used linear programs to assess meeting environmental objectives at a regional level (Lu and van Ittersum, 2004) and used scenario analysis tools to examine the income effects of increasing livestock numbers (Komarek *et al.*, 201X). This article complements these studies by using an alternative modelling technique to provide additional empirical evidence on the performance of different development policies.

Compared with earlier studies our model incorporates the following advances in analytical methods. First, our model builds on previous heterogeneous-agent models (Berger, 2001;

[2] Stover is the part of the crop left in the field after grain harvest and includes leaves and stalks.

Johnson *et al.*, 2006) as it incorporates district-level constraints for the trade of livestock feeds, labour and land. Second, our model differs from static village computable general equilibrium models (Holden *et al.*, 1999; Taylor *et al.*, 2005; Dyer *et al.*, 2006; Heerink *et al.*, 2007) and previous heterogeneous-agent models as it covers multiple years. This allows households to have a planning horizon that extends beyond the current year, a more realistic representation of reality than a static 'states of nature' model.[3] This is important for livestock producers as changes in flock dynamics occur between years. This links to the third difference; a large portion of farmers in Asia have integrated crop-livestock production systems (Devendra and Thomas, 2002). The previous village economy-wide models listed above don't assess livestock systems in detail.[4] We contribute by modelling integrated crop-livestock systems.

2. Study site and livestock development scenarios

Livestock are an important component of many rural household enterprise mixes, and are especially important in parts of western China (Brown *et al.*, 2008). To illustrate the model, three villages (Mengjiazhai, Xujiayuan and Xigou) within the Quzi township and the three villages (Xinzhuang, Shangzui and Shifeng) within the Shishe township of the Qingyang district in Gansu Province, China are chosen as case studies. Within each township, the villages are in a 5km radius of each other. The townships are approximately 100km apart. Quzi has lower rainfall, and hence lower crop yields, than in Shishe (Li *et al.*, 201X). Shishe households are closer to agricultural markets and non-agricultural off-farm employment

[3] The model, even though it has five years (and different years), is still a single state of nature i.e. a single sequence of years.
[4] Heerink et al. (2007) incorporate pigs and chickens into their model, although the main focus is on rice production and crop input usage.

opportunities, as Shishe is located closer to Qingyang's major city, Xifeng. In 2007, the average rural income in Qingyang was one half of the national rural average (Brown *et al.*, 2009).

Qingyang authorities are actively pursuing livestock intensification through policies designed to increase the area of lucerne and to increase livestock numbers (Brown *et al.*, 2009). The livestock and lucerne development push pose a number of areas for investigation. However, this paper focuses on three scenarios namely:

- Removal of lucerne growing subsidies. Lucerne subsidies are linked to government aims of reducing environmental externalities. In 2000, the Chinese government commenced a program converting cropland to forest and grassland (Cao *et al.*, 2009). In Qingyang, this program involves providing farmers with a subsidy of 2400RMB/ha/annum to plant and maintain lucerne.[5] These payments have large fiscal costs, and are subject to changes in government funding. In addition, farmers have reported payments to be sporadic. Evidence from other parts of western China suggests that without these subsidies households will reconvert land back to annual crops (Uchida *et al.*, 2005; Zhang *et al.*, 2008). In Qingyang, subsidies for lucerne are also related to developing feed sources for the push into ruminant livestock industry development. Removing the subsidies can test how farm enterprise mixes change and how this affects incomes.

[5] At the time of research US$1≈ 6.3 Chinese Renminbi (RMB).

- Removal of township and district forage trade constraints. Forages refer to maize stover, wheat stover and lucerne. Stover cannot be purchased from outside each township. Lucerne cannot be purchased from outside the two townships. In Qingyang, stover is traded between villages within a township, but not between towns, and lucerne is traded between towns. The rationale is that lucerne has a higher nutritional value to volume ratio, relative to stover (20% crude protein vs. 6% crude protein, respectively). Farmers display a willingness to travel within their township to obtain stover, and they often transport stover in a donkey-drawn cart or three-wheel motorcycle. Transportation constraints limit the distance farmers will travel to obtain this lower value to volume feed source, relative to grain or lucerne.

- Increasing total goat numbers at the aggregate level across both townships by 25% to reach government policy targets. The “Six Million” project policy’s objective is to increase the number of all goats in Qingyang district from 2.4 million (2008) to 3 million (2012) (Brown *et al.*, 2009). In this scenario, the township and district forage trade constraints still apply. This scenario is a “what if” scenario to assess what if there is no change to forage trade restrictions and livestock numbers need to rise to meet government targets. There is a concern that the socio-economic consequences of this scenario have not been fully explored. Neglecting socio-economics in crop-livestock research is common in Asia (Paris, 2002).

3. Model

Diversity exists among rural households in western China, with pastoral, semi-pastoral and agricultural households all existing (Brown *et al.*, 2008). The model developed in this study is centred on agricultural household farms. Improving the incomes of these households is important as governments are trying to reorientate households away from being subsistence producers (Li *et al.*, 2008). Analysing these agricultural households is relevant in Qingyang as the government has introduced grazing bans to combat over-grazing problems (Brown *et al.*, 2008; Han *et al.*, 2008). This has forced many households to shift from being semi-pastoral households to agricultural households. These agricultural households produce crops, raise goats and often buy and sell livestock feed. They are also involved in off-farm migration. The key decision variables are allocating land, labour and cash to different crop and livestock activities, buying and selling livestock feed stocks and allocating labour to working off farm.

The model's objective is to maximise the net present value of all 96 household net incomes from 2004 to 2008.[6] The model is solved simultaneously as a series of multi-year linear programming problems, with township-level and district-level constraints existing for specific activities. This is not identical to optimising individual discounted net incomes within each agricultural household. However, an aggregate objective function (normative approach) is used as modelling each farm individually (positive approach) does not allow township-level and district-level constraints to become relevant. There are 100,609

[6] The model is written and solved in the general algebraic modelling system (GAMS) (Brooke *et al.*, 1992). The complete GAMS code and data files are available from the authors on request.

variables (4,128 are discrete variables) and 53,936 equations in the model. The model is summarised in Appendix A. All households differ in their area of arable land, available starting cash and family size. Households within a township share identical crop yields and face the same market prices.

The model accounts for changes in livestock inventories, feed and cash supplies. This specification better represents household decision making, as opposed to a static model for representative years. Static models ignore linkages between years such as the carryover of livestock feed stocks and cash. Decisions regarding the buying, selling and retaining of goats in one year impact on future years, and a dynamic model best captures flock dynamics. A perennial crop (lucerne) is included in the model and its yields vary depending on the crop's age. Therefore, a dynamic model that incorporates different lucerne crop ages is used.

3.1 Activities and constraints

The main activities in the model are as follows:

- Livestock activities. Three breeds of goats are modelled: Liaoning, Inner Mongolian and native goats. Within each breed there are different classes of goats, including starting breeders, purchased breeders, culled breeders and kids retained for breeding or sale. Each breed and class produces different outputs (cashmere and meat) and has different energy requirements, gross margins, kidding rates and mortality rates. Goats can be housed in a warm shed or in a common shed. Temperatures inside a warm shed are approximately 10°C warmer than inside a common shed. This reduces goat energy requires by approximately 15% (minimum winter temperatures often reach –20°C).[7] The gross margin for a goat varies between each year (Table 3), but is the same across households.

- Crop activities. Maize, wheat and lucerne can be grown. Crop production is simulated from 2004 to 2008 using APSIM (Keating *et al.*, 2003).[8] APSIM has been previously used in the Qingyang district (Chen *et al.*, 2008; Shen *et al.*, 2009). Maize (a summer crop) and wheat (a winter crop) are always grown in a rotation and these crops can be cultivation using either machinery or draught power.

- Subsidies. Government subsidises lucerne planting at a rate of 2400 RMB/ha/annum in fieldwork sites, which is similar to payments for the Grain-for-Green scheme (Uchida *et al.*, 2005). Government also subsidises 50% of the cost to purchase breeder goats and build a warm shed, consistent with field observations and discussions with government officials.

- Labour. Households allocate their time to four activities: agricultural activities on the household's farm, agricultural activities on other households' farms (hired out labour), full year migration to an urban centre and 6 months migration over winter to an urban centre.[9] In each month, agricultural labour can be hired in and hired out.

[7] The growth of goats with and without a warm shed was estimated using local meteorological data, fieldwork data and the growth equations in CSIRO (2007). Temperature differences between inside and outside a warm shed were obtained from Wan et al. (2009).
[8] APSIM simulates crop, forage and soil-related processes and the influence of climate and management activities on these processes using local climate and soil data.
[9] Full employment in the off-farm sector is available in the model. Although, in reality under employment or unemployment may occur.

Daily wages for agricultural work are 27 RMB in the harvest season and 20 RMB in the slack season (Zhang *et al.*, 2010).

- Land. Land can be rented in and rented out at a rate of 1800RMB/ha/annum.

The main constraints for each household are as follows:

- Land constraint. The area of arable land available for a household is equal to the amount observed in the 2009 survey. Additional land can be rented, up to a maximum amount of 25% of a household's observed cropped area. This constraint occurs as fields are scattered and transport and labour costs increase with additional rented area.

- Livestock feed. Goats must obtain a set amount of megajoules and crude protein each month from stover, lucerne, grain or pasture. Goat energy demands were calculated using NRC (1981), Paten (2008) and local field observations. Livestock feed can be sourced from home-grown crops or market purchases. As ruminants, goats need a minimum proportion of coarse fodder in their feed, and therefore, the annual volume of grain that livestock consume must not exceed the volume of stover and lucerne consumed. Livestock feed can be stockpiled and carried forward to future months, with a 10% storage loss. The pen feeding of livestock rather than free grazing is currently mandatory in the six villages, although cutting native pastures from common areas occurs. To accommodate this reality, an area of native pasture that is no more than 10% of a farm's total size is available as an additional source of livestock feed.

- Labour constraints. Activities have monthly labour requirements that must be balanced with available household labour. The amount of labour available to conduct agricultural activities is limited by the number of people living on the farm in any month. Technical input-output coefficients for seasonal labour requirements per unit of activity are fixed and are based on survey data. They are the same across all households. Family labour can be supplemented with hired labour. Hired labour is constrained at the township level. Labour used in each township equals labour available in each township.

- Cash. In 2004, the amount of cash that can be spent on agricultural activities is set equal to one-third of observed net incomes from the survey. In following years, the amount of spending on agricultural activities is limited to one-third of the previous year's net income. The basis for this constraint is that households prefer to spend their profits on education and non-agricultural activities (De Brauw and Rozelle, 2008; Snyder and Chern, 2009), a finding consistent with fieldwork discussions. Cash that is left over each December can be carried forward to the following January.

- Crop equilibrium conditions. Within each year, for lucerne, maize stover, wheat stover, maize grain and wheat grain, the amount produced, plus stored from the previous year equals the amount fed to animals, consumed by humans, sold and stored for future usage.

- Livestock equilibrium conditions. The number of goats at the start of a year plus the number purchased equals the amount sold plus those kids retained for breeding (i.e.

natural increases). The number of breeder goats at the start of a year is equal to 95% of the previous year's ending stock plus kids retained (local livestock officials report a 5% mortality rate). Breeder goats are culled after 6 years.

A feature of the model is the incorporation of trade conditions at different levels of aggregation (Table 1).

Table 1: Base-case trade conditions.

Commodity	**Intra-town trade allowed**	**Inter-town trade allowed**	**Inter-district trade allowed**
Maize and wheat stover	Yes	No	No
Lucerne	Yes	Yes	No
Maize and wheat grain	Yes	Yes	Yes
Agricultural labour	Yes	No	No
Arable land	Yes	No	No

Note: When the no forage trade condition is relaxed, inter-town and inter-district wheat and maize stover trade can occur as can inter-district lucerne trade.

Township and district level constraints are as follows:

- Each year, the sum of all household wheat and maize stover purchases must not exceed sales within each individual township. Local markets exist for stover and intra-township trade occurs. However, unlike lucerne, inter-township trade does not occur for stover, which cannot be purchased from outside each township. This constraint ensures that stover consumed in a town is sourced from within town production, and not from other towns.

- Each year the sum of lucerne purchased by all surveyed households in Shishe and Quzi equals the sum of all purchases in Quzi and Shishe. This implies lucerne can be traded between the townships but not with other districts. Fieldwork interviews revealed a significant inter-town trade of lucerne but not of stover. Although lucerne markets are developing inter-district trade is not common.

- Each year aggregate grain supply for all 96 households must be enough to cover home consumption needs of 220 kg of grain/capita/annum (FAO, 2001) for all households, although grain can be stored from previous seasons. This implies that inter-township trade of grain can occur. Despite grain markets existing in China, households in Qingyang are still conservative towards meeting consumption needs from home production. In the model, if cumulative production is greater than cumulative own consumption needs, the surplus can either be sold or retained for future years.

- The sum of all the time spent across the households within a township in wage earning agricultural activities on other households equals the time that all households hire in labour for agricultural activities. Travel times restrict workers to staying within their township to work on other local farms.

- The sum of the total area cropped across all households within a township must be less than the sum of the available land for all households. This ensures that the area of land rented in equals the area of land rented out.

4. Data

Data to estimate the model are from three sources: a household survey conducted in 2009, APSIM crop simulations and data from research trials conducted by the Huanxian Animal Husbandry Bureau. The 2009 surveys provide data on land usage, socio-demographic characteristics, agricultural production and consumption, income and migration for a representative sample of rural households (Li *et al.*, 201X). The target population for this study consists of farm households that live below or close to the national rural average income in the two townships of Qingyang. The sample frame was constructed based on two townships located in different rainfall locations within Qingyang. Within the sample frame six villages were selected with three villages being in each township, and in each township 48 households were interviewed.

Households differ in their ability to generate income as they have access to different amounts of land and labour. Therefore, to investigate how household resource allocations vary under different scenarios, different household types are developed based on Principal Component Analysis and subsequent Cluster Analysis. Two major clusters formed and the major distinguishing feature between the clusters was the land to labour ratio (LLR). The LLR ratio is the number of hectares of land per working family member (aged 15 to 65 years). In Shishe, there are 46 low LLR households and two high LLR households, whilst in Quzi there are 23 low LLR households and 25 high LLR households. Shishe is a higher rainfall location, agricultural production is more intensive and population density is greater. These factors all results in lower LLRs in Shishe. The high LLR households have more land and less family members, relative to the low LLR households. Both household types are reliant on remittances (Table 2). Remittances are the portion of off-farm earnings that are sent back to family members living on the farm.

Table 2: Characteristics of household groups. Mean with standard deviation in brackets.

Variable	Low LLR (n=65)	High LLR (n=31)
Area cropped (ha)	0.99 (0.62)	1.53 (0.63)
Household size (all people)	4.9 (1.05)	4.4 (1.28)
Land to labour ratio	0.4 (0.18)	0.63 (0.18)
Income from crops (%)	15	19
Income from livestock (%)	10	19
Income from remittances (%)	75	62

Source: Authors' survey data.

Note: Areas cropped and land to labour ratios differ between the groups (P=0.00). Household size also differs between the groups, but at a lower level of significance (P=0.06).

The gross margin of goats varies between years as cashmere and meat prices change (Table 3). Breeder gross margins include the sale of cashmere and the sale of culls which are sold on a liveweight basis. The kid gross margins are derived from liveweight sales. Native goats are small-framed but attract a premium of 2RMB/kg liveweight because of consumer preferences for their meat. They have a low cashmere yield and the price of the cashmere is discounted because of its' dark colour. The cashmere of the Inner Mongolian breed is fine (15 micron) and attracts a price premium over Liaoning cashmere (16.5 micron). However, Liaoning goats have a high cashmere yield and heavier frames, and therefore generate the highest gross margins of the three breeds (Table 3).

Table 3: Distribution of goat gross margins in RMB per year.

Year	**Breeder**			**Kid**		
	Native	**Liaoning**	**Inner Mongolian**	**Native**	**Liaoning**	**Inner Mongolian**
2004	79	228	215	398	513	426
2005	88	254	239	403	526	438
2006	95	273	257	506	660	547
2007	106	301	283	591	774	640
2008	48	139	130	422	518	424

Source: Authors' survey data and Huanxian Animal Husbandry Bureau.

Note: The gross margin of breeders does not account for the value of kids produced. The model has a separate category for retained kids.

Crop yields are higher in Shishe village as annual average rainfall is higher (530mm vs. 403mm). These APSIM yields are similar to long-term averages reported in CSP (2006). Insufficient rainfall led to no grain crop yield being obtained in 2008 in Quzi. Prices of wheat stover exceed maize stover as maize stover has higher moisture content (Table 4). Wheat and maize prices are similar and increased over the study period.

Table 4: Distribution of crop prices (RMB/kg) and yields (t/ha).

	Crop prices					Crop yields					
	Wheat grain	Wheat stover	Maize grain	Maize stover	Lucerne	Wheat grain yield		Maize grain yield		lucerne biomass yield	
Year						S	Q	S	Q	S	Q
2004	1.24	0.24	1.26	0.10	0.9	2.9	2.4	5.6	2.4	6.8	4.6
2005	1.24	0.30	1.24	0.12	0.9	1.9	1.6	5.4	1.8	5.4	3.7
2006	1.26	0.30	1.30	0.13	0.8	2.3	1.9	5.5	1.6	5.4	2.5
2007	1.40	0.34	1.44	0.14	0.5	2.7	0.0	5.6	0.0	5.8	0.1
2008	1.66	0.40	1.52	0.15	0.8	2.9	3.1	6.6	3.1	6.8	2.5

Source: Authors' survey data and authors' APSIM simulation results.

Note: S= Shishe and Q=Quzi. Stover yields ranged from 1 to 1.6 times the grain yields.

5. Results

In each optimisation, the model yields the estimated impacts of each scenario on every household in the sample. Although the model is solved for all 96 households, results are reported for the two different household types. Results of the base-case model are reported in Table 5 (viewed as maximizing equation 1 subject to satisfying equations 2–15 in Appendix A). The household effects of removing lucerne subsidies, removing forage trade barriers and increasing livestock numbers are reported in Table 6. Shadow prices (Table 7) and opportunity costs are calculated to illustrate the impact on profits of introducing sub-optimal goat activities and also the impact of relaxing, at the margin, the no forage trade deficits condition. The distributions of incomes among households when different scenarios occur are presented in Figs. 1 and 2. The distribution of net agricultural income (in the base case) among households in different years is presented in Fig. 3. To test if incomes among different scenarios and different years are significantly different from each other multiple Analysis of Variances are conducted, and their P-values are reported.

5.1. Base-case results

Agricultural activities comprise approximately 10% of predicted total net household incomes (Table 5). This does not include the value of own consumption or the value of changes in livestock, grain or forage inventories. Total per capita net incomes do not differ between the farm types (P-value=0.29) in the base case, although net per capita agricultural incomes differ between farm types in the base case (P-value=0.00). Of the three breeds of goats available, households choose to raise Liaoning goats in a warm shed. The average household has 5.3 Liaoning goats, with low LLR households having 6.0 Liaoning goats and high LLR household having 3.5 Liaoning goats (Table 5). The average household spends approximately 23 person-months working away from the farm each year, with each household having on average 4.8 members. Area planted to lucerne exceeds grain area planted (Table 5). Three tonnes of stover is traded in the base case from high LLR to low LLR households. In an average year, 42 tonnes of grain are purchased from other districts, of which half is used for human consumption. In the base case, low LLR households purchase 48 tonnes of lucerne and 411 days of hired labour from high LLR households (Table 5).

5.2. Scenario results

Removing lucerne subsidies reduces total incomes. Lucerne production and goat numbers all decrease leading to a 30% fall in agricultural incomes (Table 6). Labour requirements for farm activities do not change enough to cause a shift in the amount of time spent in off-farm employment, therefore, off-farm incomes do not change. It may be expected that a decline in agricultural activities will see a rise in migration from farms to urban centres. This is not the case as there is a limit in the model as to how much time can be spent working in non-farm off-farm employment. Households must always have two people present on the farm, after this requirement is meet then migration can occur. Due to the shift away from lucerne production into grain production, grain purchased for human consumption falls by 51% at the district level.

Removal of the constraint on having a zero stover or lucerne trade deficit increases incomes because it facilitates the purchase of feed for larger goat flocks (Table 6). Total goat numbers owned by all households rise from 502 to 838. At the aggregate level, net stover traded (sales minus purchases) from other towns and districts changes from zero to –922 tonnes, implying that purchases exceed sales by 922 tonnes. Net lucerne traded from other districts changes from zero to –333 tonnes, implying that purchases exceed sales by 333 tonnes. Purchasing stover and lucerne from outside the individual townships reduces the aggregate planted area of lucerne, a labour intensive crop. The amount of labour allocated to off-farm employment does not change as the increase in labour requirements to maintain increased goats is offset by a reduction in lucerne harvesting labour requirements.

In the increased goat numbers scenario total net household incomes fall (Table 6). In this scenario there is no major change in land allocation. Liaoning goats are replaced with native goats (which have lower energy requirements) to help achieve the government target. In this scenario, feed for goats must be met from grain, from stover grown with each township or from lucerne grown within the two townships. For nutritional requirements, grain quantity intake cannot exceed stover and lucerne quantity intake. In this situation, the increased labour required to maintain extra goats without a reduction in crop harvesting labour requirements results in an increased agricultural labour allocation, at the expense of migration work and income.

Komarek et al. (201X) find that increased goat numbers increase incomes as households purchase feed stocks. However, this finding is based on an assumption of inter-township trade in stover. When inter-township stover trade and inter-district lucerne trade are not permitted, total net incomes fall. As the model is an optimisation program, as opposed to a model that examines set scenarios, results also differ to Komarek et al. (201X) where, for example, an increase in goat numbers inhibits off-farm work.

Table 5: Results for base-case model simulated variable levels for the whole sample in an average year and for the two household groups for an average year and average household.

Variable	Units for base model	Total	Low LLR	High LLR
Total per capita net income	RMB (000)	11.8	11.9	11.1
Per capita net agricultural income	RMB (000)	1.2	1.0	1.7
Off farm employment	Years	1.9	2	1.8
Total goat numbers	Number	502	392	110
Total area lucerne: grain	Ha	81:23	46:21	35:2
Total net stover traded	Tonnes	0	–3	3
Total net grain traded	Tonnes	–42	–13	–29
Total net lucerne traded	Tonnes	0	–48	48
Total net farm labour traded	Days	0	–411	411
Total grain purchased for home consumption	Tonnes	22.1	12.2	9.9

Note: All goats are Liaoning goats raised in a warm shed. Total net stover, total net grain and total net lucerne traded=sales–purchases. Total net farm labour traded=hired in–work off-farm. No land is traded in the base case.

Table 6: Model simulation results for the whole sample and the two household groups for an average season and average household, percentage changes from the base case for the three experiments.

Variable	**No lucerne growing subsidy**			**No local livestock feed market**			**Increased goat numbers**		
	Total	**Low LLR**	**High LLR**	**Total**	**Low LLR**	**High LLR**	**Total**	**Low LLR**	**High LLR**
Total per capita income	–3.0	–1.9	–5.9	6.1	7.0	3.7	–16.9	–19.2	–10.9
Per capita agricultural income	–29.7	–22.7	–40.0	59.7	84.2	23.8	–5.7	–6.5	–4.4
Off farm employment	0	0	0	0	0	0	–21	–25	–16
Total goat numbers	–9.2	–9.3	–9.1	167	163	178	26	19	50
Total area lucerne: grain	–18:64	–14:32	–22:384	–10:1	–14:–4	–4:61	–1:2	0:0	–2:2
Total net stover traded	0	215	215	**	22751	–6835	0	60	60
Total net grain traded	–103	–144	–85	–179	–335	–109	14	112	–30
Total net lucerne traded	0	–38	–38	**	503	–184	0	–32	–32
Total net farm labour traded	0	24	24	0	–109	–109	0	–0.5	–0.5
Total grain purchased for home consumption	–51	–46	–56	–4.8	0.8	–11	20	32	5

Note: ** In these scenarios, the base case value is zero so the percentage increase is undefined. No land is traded in any of the scenarios.

5.3. Opportunity costs and shadow price results

Introducing one native goat or one Inner Mongolian goat into the average farm's base-case enterprise mix reduces net income in an average year by 138 RMB (range from 0–901 RMB) and 96 RMB (range from 0–518 RMB), respectively. These are the opportunity costs of altering breeds away from Liaoning goats.

In the base-case model, the no lucerne subsidy and the increased goat number scenarios have restrictions that maize stover purchases cannot exceed sales within each township, that wheat stover purchases cannot exceed sales with each township and that lucerne purchases cannot exceed sales for both townships combined. These conditions ensure that livestock are fed from local production, matching field observations. Relaxing each of the three constraints by one unit implies that sales exceed purchases by one kilogram. One extra kilogram of sales implies that production has risen by at least one kilogram, therefore relaxing the constraints by one unit implies that production of the crop has risen by at least one kilogram. The shadow price of increased crop production rises when increased livestock numbers occur (Table 7). This suggests that with increased livestock numbers higher yielding crops are vital. Wheat has a higher shadow price than maize as its yields are lower so scarcity increases its value. Shadow prices are greater in Quzi than in Shishe meaning that yield improvements in Quzi could be beneficial to household incomes. The government's target of increasing goat numbers could be more easily met if it stover and lucerne could be sourced from outside the townships.

Table 7: Shadow prices of forages in different townships (in RMB/kg).

Scenario	Wheat stover		Maize stover		Lucerne
	Quzi	Shishe	Quzi	Shishe	
Base case	0.74	0.21	0.42	0.19	0.22
No lucerne subsidy	0.32	0.20	0.31	0.19	0.22
Increased livestock numbers	0.52	0.28	0.46	0.25	0.42

5.4. Distributional effects of scenarios and their statistical significance

When the forage trade condition is removed, total per capita net income and net agricultural income per capita significantly rises (P-value =0.02 and P-value=0.00), compared to the base case (Fig. 1–2). Total per capita net income significantly falls in the increased livestock numbers scenario (P-value=0.00), although net agricultural income per capita does not fall significantly (P-value=0.41) (Fig. 1–2). Total per capita net income does not significantly fall when lucerne subsidy payments are removed (P-value=0.19), although net agricultural income per capita does (P-value=0.00) (Fig. 1–2). Heterogeneity exists among households with a large distribution of total net incomes existing (Fig. 1). The coefficient of variation is 0.23 in the base case, no lucerne subsidy and no forage barrier scenario, and the coefficient of variation rises to 0.25 for the increased livestock numbers scenario.

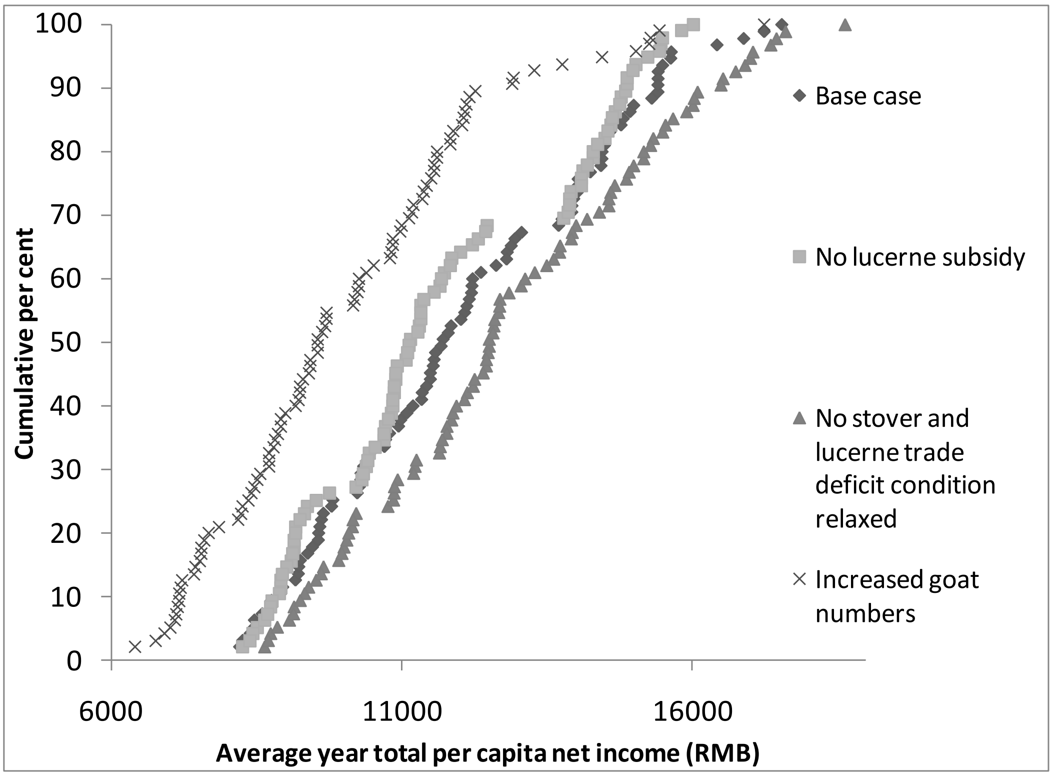

Fig. 1: Shifts in the distribution of total per capita income for the three scenarios. Individual points represent households. Incomes are the average across the 5 years.

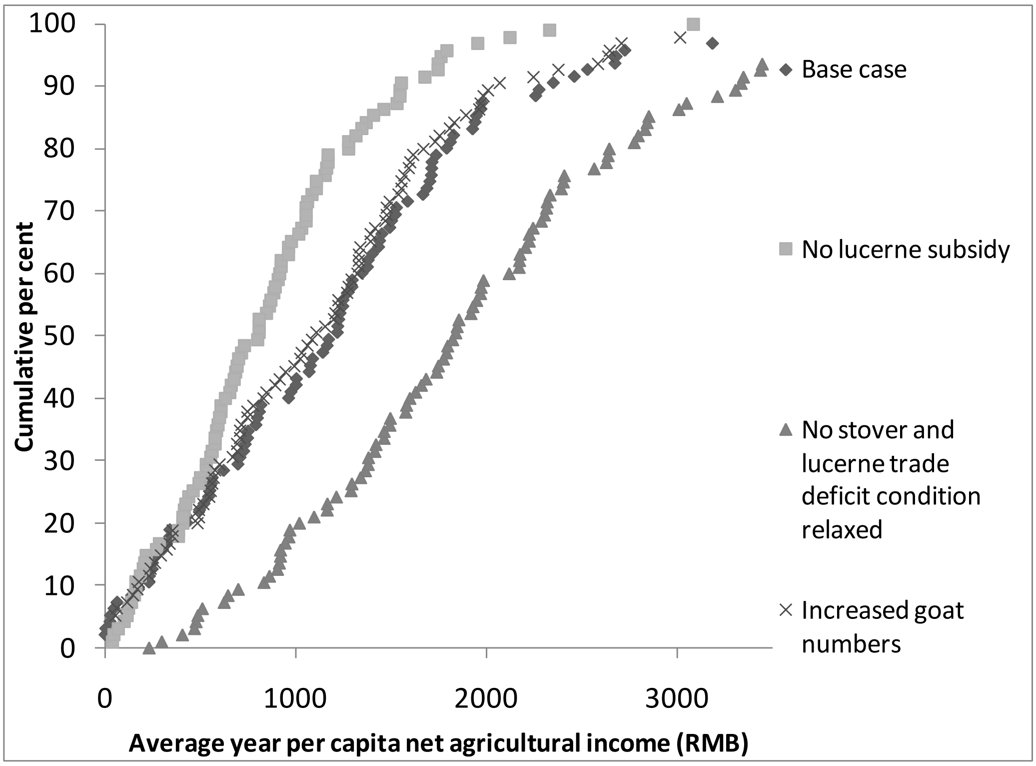

Fig. 2: Shifts in the distribution of per capita net agricultural income for the three scenarios. Individual points represent households. Incomes are the average across the 5 years.

Net agricultural income per capita significantly varies between years (P-value=0.01) (Fig. 3). Total per capita net income does not significantly vary between years (P-value=0.82). Off-farm earnings appear to stabilise total net incomes. Income in each year is dependent on prices and climatic conditions but is also a function of flock dynamics and so it is dependent not only on current year conditions but also on previous year conditions.

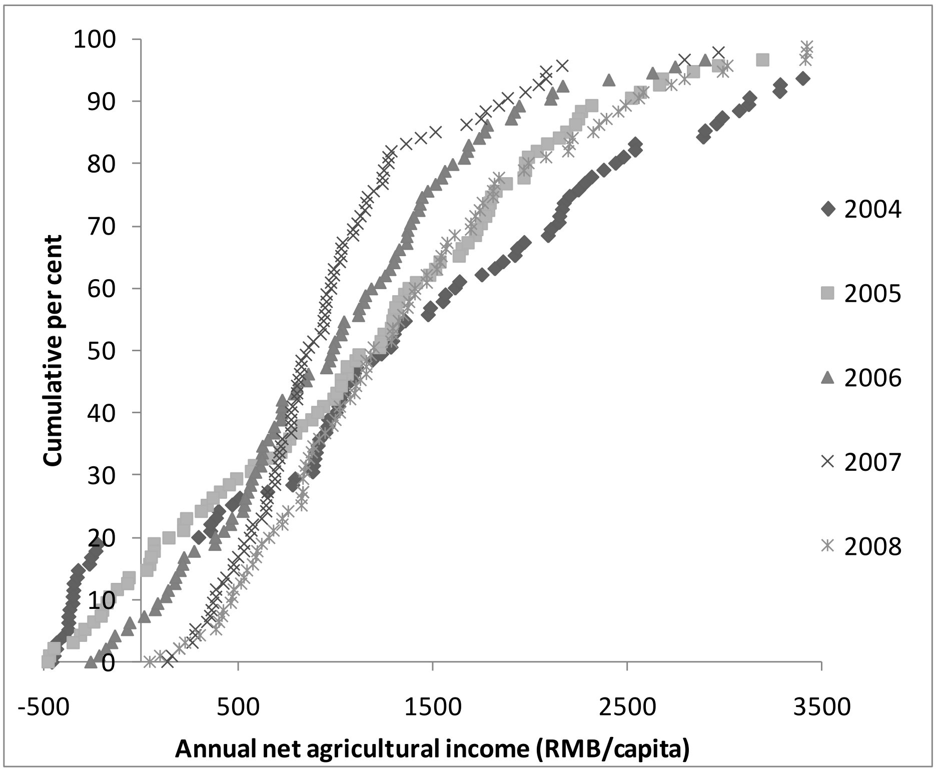

Fig. 3: Yearly shifts in the distribution of per capita from agricultural activities due to changing prices and climatic conditions. Individual points represent households in a specific year.

6. Conclusion

This analysis has several policy-relevant conclusions. Firstly, without inter-township trade in stover or inter-district trade in lucerne, increasing goat numbers to meet government targets reduced household net incomes as households switch breeds and spend less time in off-farm migration. To achieve this increase, native goats replaced Liaoning goats. Although the government target is to introduce improved goat breeds, not native breeds, introducing these breeds as opposed to native goats will reduce incomes even further if alternative feed sources are not available (as Inner Mongolian and Liaoning goats are not in the basis solution in the increased livestock numbers scenario). There appears to be a risk in increasing numbers without viable feed systems in place or an ability to source feed from outside the study region. A trade-off exists between increased livestock numbers and increased incomes as increasing goats numbers without better crop yields or without being able to source feed from other districts reduced migration. Realistic discussions on increasing rural household incomes could benefit from better integrating crop and livestock sector policies with more broad-scale economic development policies. Despite the government shifting some focus from increasing numbers towards adopting improved breeds, reconsidering the focus on ruminant livestock industry policies towards increasing numbers rather than value appears valuable.

Secondly, our results imply that increased access to crop forages—either through increased yields (shadow price calculations) or an ability to purchase stover from other townships or districts or purchase lucerne from other districts (lifting the no forage trade restriction)—can help increase livestock numbers (of Liaoning goats, an improved breed) and improve incomes. This highlights the importance of improved agronomic practices. More tightly integrated markets with improved transportation systems can help unlock the benefits of trading forage crops.

Without lucerne growing subsidies, the area of lucerne grown falls by 18%. To maintain high levels of lucerne areas and obtain the corresponding environmental benefits, subsidies are needed. Despite reduced area planted, lucerne still has a large role to play on the studied farms as it is an important source of energy for livestock, but its attractiveness falls under non-subsidised conditions.

In terms of methodology, the study demonstrates how the heterogeneous-agent modelling technique (Berger, 2001; Johnson *et al.*, 2006) can be scaled up to the district level, in a multi-year setting. Despite this analysis focusing on one particular region, it is reasonable to argue that the approach used could be applied to other agricultural household situations in the developing world where there is a diversity of households and where collective township conditions are important.

In the current approach prices for livestock feeds, land renting and off-farm wages are exogenous. Incorporating endogenous prices into the model would lead to a village computable general equilibrium model that has a planning horizon greater than one season. As long-term crop production data are not available at the household level, the model relied on using APSIM simulations and this led to all households within a township having the same crop yields within a year. Using observed farmer yields could better represent reality. This could affect land trading opportunities as higher productivity households may be more willing to rent land. To do this and maintain a dynamic element in the model data collection over multiple years will be required.

Appendix A: Summary of equations in model

The model's objective is to maximise the net present value of total net household income across all households:

$$Z = \sum_{h=1}^{H} \sum_{y=2004}^{Y} \sum_{\substack{i=wheat \\ (machine\ \text{produced})}}^{I} \frac{x_{h,i,y} GM_{h,i,y} + FYM_{h,y}\ \mathrm{FW_{h,y}} + WM_{h,y}\ \mathrm{WW_{h,y}}}{\left(1+d\right)^{r}} + V_{h,2008} \tag{1}$$

where *h*=1,…, H (index of households, with H=96); *i*=wheat (machine produced),…,I (index of agricultural activities); *y*=2004,…,Y (index of years, with Y=2008); Z =total aggregate net income (2009 RMB); $x_{h,i,y}$= level of agricultural activity *i* conducted by household *h* in year *y*; $GM_{h,i,y}$= the gross margin of agricultural activity *i* conducted by household *h* in year *y*; $FYM_{h,y}$= an integer variable representing whether or not a family member migrates away from household *h* in year *y*; $FW_{h,y}$= the wage paid to work one year in off-farm employment for a family member of household *h* in year *y*; $WM_{h,y}$= an integer variable representing whether or not a family member migrates away from household *h* for a 6 month period over winter in year *y*; $WW_{h,y}$= the wage paid to work over winter in off-farm employment for a family member of household *h* in year *y*; d= the discount rate, set at 6%; and $V_{h,2008}$ is the value of livestock at the end of 2008. To discount the objective function, r=0 in 2004, and increases sequential to r=4 in 2008. Households 1-48 are in Shishe and 49-96 are in Quzi.

Equation (1) is maximised subject to constraints A1 to A7, where A1 to A6 are household-level constraints and A7 are township-level and district-level constraints:

A1: Land

$$\sum_{y=2004}^{Y} \sum_{\substack{i=wheat \\ (machine\ produced)}}^{I} x_{cr,y} - RO_y \le FS + RI_y \tag{2}$$

$$cr \subseteq i$$

$$RO_y \le FS \times 0.25, \forall y \tag{3}$$

$$RI_y \le FS \times 0.25, \forall y \tag{4}$$

Where cr = area of wheat (machine produced), area of maize (machine produced), area of wheat (draught power), area of maize (draught power) and area of lucerne; RO_y = area of land rented out in year y; RI_y = area of land rented in year y; and FS = total observed land area available under cultivation in survey year. Wheat and maize are grown in rotation, therefore their area's planted in year y are equal (eqtn 5).

$$\sum_{y=2004}^{Y} x_{wheat(\text{machine produced}),y} + x_{wheat(\text{draught power}),y} = x_{maize(\text{machine produced}),y} + x_{maize(\text{draught power}),y} \tag{5}$$

A2: livestock energy

$$\sum_{f \in GCP,MJ} \sum_{m=1}^{M} \sum_{y=2004}^{Y} \sum_{\substack{i=wheat \\ (machineproduced)}}^{I} x_{i,y} D_{f,m,i,y} + T_{f,m,y} + TD_{f,y} \le x_{i,y} S_{f,m,i,y} + T_{f,m-1,y} + TD_{f,y-1} + B_{f,m,i,y} \tag{6}$$

Where m=1,…,M (index of monthly periods, with M=12); where f= grams of crude protein (GCP), megajoules (MJ); $D_{f,m,,i,y}$ = livestock activity *i* demand for *f* in month *m* in year *y*; $S_{f,m,,i,y}$ = supply of *f* by cropping activity *i* in month *m* in year *y*; $T_{f,m,y}$ = net transfers of *f* from month *m* to *m*+1; $TD_{f,y}$ = net transfers of *f* from December in year *y* to January in year y+1; $B_{m,f,i,y}$ = supply of *f* by buying crop *i* in month *m* of year *y*.

A3: labour

$$\sum_{m=1}^{M}\sum_{y=2004}^{Y}\sum_{\substack{i=wheat\\(machine\ \text{produced})}}^{I} x_{i,y}LD_{m,i,y}-HI_{m,y}\le HL_{m,y}-FYM_{m,y}-WM_{m,y}-HO_{m,y} \tag{7}$$

Where $LD_{m,i,y}$=technical input-output coefficients for activity i's labour requirements in month *m* of year *y*, expressed in days; $HI_{m,i,y}$ and $HO_{m,i,y}$ = the days of labour hired in and out in month *m* of year *y*, respectively; $HL_{m,y}$= the days of family labour available in month *m* of year *y* (based on total household size); $FYM_{m,y}$= the days of family labour used in full year migration in month *m* of year *y* (an integer variable); and $WM_{m,y}$= the days of family labour used in winter migration in month *m* of year *y* (winter migration lasts 6 months).

A4: Cash

$$\sum_{\substack{i=wheat\\(machine\ \text{produced})}}^{I}\sum_{y=2005}^{Y} x_{i,y}c_{i,y}\le \frac{NAI_{y-1}}{3}+CO_{y-1} \tag{8}$$

Where $c_{i,y}$ = the cost in RMB of activity *i* in year *y*; NAI_{y-1} is net agricultural income in year y-1; and CO_{y-1} is unused cash in year y-1.

A5: Crop material balance

$$\sum_{y=2004}^{Y} \sum_{\substack{i=wheat \\ (machineproduced)}}^{I} x_{cr,y} P_{cr,y} + St_{cr,y-1} = Dl_{cr,y} + Se_{cr,y} + St_{cr,y} + Dh_{cr,y} \qquad (9)$$

$$cr \subseteq i$$

Where $P_{cr,y}$ = the yield of cr in year *y*; $St_{cr,y-1}$ and $St_{cr,y}$ = amount of *cr* retained in years y-1 and y, respectively; $Dl_{cr,y}$ = the amount of *cr* fed to livestock in year *y*; $Se_{cr,y}$= amount of *cr* sold in year y; and $Dh_{cr,y}$ = the amount of *cr* consumed by humans in year *y.*

A6: Livestock breeder equilibrium

$$\sum_{b=CCS}^{B} \sum_{y=2004}^{2008} x_{b,eb,y} + x_{b,rk,y} = 1.05 \times x_{b,sb,y+1} \qquad (10)$$

$$eb, rk, sb \subseteq i$$

Where eb=end breeder, rk=retain kid, sb=starting breeder, b= Inner Mongolian goats common shed (CCS), Inner Mongolian goats warm shed, native goats common shed, native goats warm shed, Liaoning goats common shed, Liaoning goats warm shed; $x_{b,eb,y}$= number of ending breeders in class b in year *y*; $x_{b,rk,y}$= number of kids retained in class *b* in year *y*; and $x_{b,sb,y+1}$= number of starting breeders in class *b* in year *y*+1.

A7: Township and district equilibrium constraints

The amount of lucerne sold across all 96 farms equals the amount purchased. This means that lucerne can be traded between the two different townships.

$$\sum_{h=1}^{H}\sum_{y=2004}^{Y} x_{h,buylucerne,y} - x_{h,selllucerne,y} = 0 \quad (11)$$

$$\sum_{h=1,49}^{48,96}\sum_{y=2004}^{Y}\sum_{i=bs}^{I} x_{h,bs,y} - x_{h,ss,y} = 0 \quad (12)$$

$bs, ss \subseteq i$

Where bs= maize stover purchased, wheat stover purchased and ss= maize stover sold, wheat stover sold. Within each township stover purchases cannot exceed sales.

$$\sum_{h=1,49}^{48,96}\sum_{y=2004}^{Y}\sum_{\substack{cr=wheat\\(machineproduced)}}^{CR} x_{h,cr,y} + RO_{h,y} + RI_{h,y} \le FS_{h,y} \quad (13)$$

The area of all land cropped with a township cannot exceed the amount of land available in that township.

$$\sum_{h=1,49}^{48.96}\sum_{m=1}^{M}\sum_{y=2004}^{Y} HI_{h,m,y} - HO_{h,m,y} = 0 \quad (14)$$

Within a township, the amount of labour hired in for local agricultural employment equals the amount supplied.

$$\sum_{h=1}^{H}\sum_{y=2004}^{Y}\sum_{i=1}^{I} x_{h,i,y} P_{h,i,y} \ge Dh_{h,i,y} \quad (15)$$

The total amount of maize and wheat produced must exceed the sum of total household demand.

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