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Towards a spatially and socially explicit agricultural policy analysis for China: specification of the Chinagro models

by

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Abstract

The Chinagro-project has developed a series of single-commodity, spatially explicit partial equilibrium models covering China with around 94000 grid cells of 10-by-10 kilometer surface, as well as one 17-commodity, 8-region general equilibrium welfare model with 6 income groups per region and agricultural supply represented separately for as much as 2433 counties (virtually all), and describing, for every county, 14 land use types in cropping and livestock production, with 28 aggregate outputs. Both models are run in parallel. The present paper describes the structure of the general equilibrium model and its relation to the partial versions. It also shows how to compute the solution of this very large model, and how to calibrate it. The model is formulated as a welfare program of an open economy with transportation costs between regions and with tax distortions. It operates on an annual basis, evaluating a solution under given scenario-trends with respect to land availability, demography, economic growth, technological progress, international prices and government policies. Regarding validation, the Chinagro-model fully replicates for every county and region of China at 1997 base-year conditions, adequately mimics changes over the period 1997-2003 and provides interpretable results until 2030. It has fully integrated software that efficiently runs from basic data, via solution algorithms and simulation, to automatic production of detailed county-level maps and tabulation of results. The Chinagro-model is programmed in GAMS. Maps and other tabulations are controlled in GAMS or in user-friendly menus, even though they actually run in DOS, Fortran and SAS.

1. Introduction[1]

Until the early eighties the question how China could feed its people was a primary concern but nowadays, the puzzle is how the country can feed its livestock. This in itself reflects the impressive success achieved during this period. More specifically, from a trade perspective the policy question is whether, in the light of the fast-rising demand for animal proteins by Chinese consumers as per capita incomes rise dramatically, and the sustained rural to urban migration, the country should aim at (i) selfsufficiency in cereals, protein feeds and meat, including animal feed; or (ii) at importing feed; or (iii) at importing meat. These questions are to be answered in the context of the WTO-accession, the Doha Round, and more generally China's opening to world trade. Distributional issues constitute a second group of policy concerns, as the fast changes in income and the persistent migration generate major income disparities between rural and urban across the country and between regions. A third group of issues relates to the policy responses in the sphere of natural resource management, changes in land use, the scope for expanding irrigation in the areas that can produce animal feeds, and the scope for improved rangeland management.

Chinese specificity?

The Chinagro-project has been studying these three issues in a multidisciplinary research effort involving natural scientists and economists, in which natural scientists provide the basic information on natural resources productivity and potential for incorporation by economists into dedicated decision support tools. Even though the issues under consideration are unmistakably typical for China, one might expect that they are not sufficiently specific to warrant departure from well- established tools from econometrics and computable general equilibrium (CGE-) modeling. Yet, we argue that application of existing software tools would not be a fruitful exercise. In a nutshell, China is not Luxembourg or Monaco. The country is too large to possess any specific set of features. In fact, it possesses them all. Dealing with the basic fact that the scale of a country should be accounted for has taken a prominent place in the research within the Chinagro-project. Indeed, a distinctive feature of this project is that it seeks to due justice to the enormous spatial and social diversity of China. We find this detail essential in the analysis of Chinese agriculture and its scope for transformation, because the food economy of the country is so diverse, and through its fast economic growth becoming ever more so. Obviously, population densities differ tremendously throughout China, consumers have different lifestyles, the cropping pattern and yields vary dramatically, and the unused potentials differ as well. Furthermore, the distances spanned by the country are large, and imply that a policy change say, at the border, will affect consumers and producers very differently, depending on their location. Finally, the self-sufficiency ratios of various regions show an uneven pattern, in particular with regard to the shipment of grains to consuming regions.

Consequently, the Chinagro-project has chosen to accommodate a maximum of geographic detail both socially and spatially, thereby accounting for the country's immense diversity and allowing for incorporation of essential agro-ecological information on land use, suitability and development potentials, jointly with information on feed requirements and changing food consumption habits as incomes rise and urbanization proceeds. At the same time, the project has sought to embed this information on the current situation, on fundamental technological relationships and on the nation's resource base within the established economic framework of welfare analysis, while accommodating major price, trade and income redistribution policies. This is not possible within existing decision support tools. Hence, an investment in refinement

[1] Ninghui Li and Huanguang Qiu provided useful comments on earlier drafts.

and extension of available methodology was necessary. In fact, this innovative element also justified the funding under the INCO-program of the EU.

The research strategy has been to develop and implement models of two kinds, on the one hand a series of single-commodity, spatially explicit partial equilibrium models covering China with around 94000 grid cells of 10-by-10 kilometer surface, and on the other hand a single 17-commodity, 8-region general equilibrium welfare model with 6 income groups per region and agricultural supply represented separately for as much as 2433 counties (virtually all), and describing, for every county, 14 land use types in cropping and livestock production, with 28 aggregate outputs. Both models are run in parallel and have relative strengths of their own.[2]

The spatial detail of the partial equilibrium models provides a transparent geographical representation of supply, demand, and commodity flows between cells, and also of price transmission through the delivery chain, while accounting for border measures such as tariffs and quotas, as well as specific producer and consumer subsidies. This in particular makes it possible to calculate the density distribution of consumer as well as producer prices within every county and to infer average transport margins from there, for subsequent use in the general equilibrium welfare model.[3]

The major reason for constructing a general equilibrium model besides the partial equilibrium one is to achieve a proper multi-commodity, multi-agent representation, for example to reflect the diversity of the resource basis and cropping patterns of farms and the non-tradability of some of the feed, fertilizer and traction power inputs between them. At the same time, we want to account for the substitutability on the demand side, and perhaps most importantly, for the technological interactions between the livestock and the crop sector, through feed requirements, draft power, and availability of manure, within the limits of the prevailing agro-ecological conditions. The welfare approach offers a transparent way to incorporate these relationships, because it merely consists of a social welfare function as an objective that depends on the consumption of the various income groups, and the technological relations, a commodity balance and a national balance of payments restriction as constraints. In the general equilibrium welfare model, whose classifications are given in Appendix B, the regions trade with one another and with the world market. Hence, this welfare model is also very large comprising around 50,000 truly endogenous variables including prices, as well as consumption by every consumer group in every region and agricultural production and input demand for every land use type in every county, as well as another 50,000 variables that directly depend on exogenous trends. The welfare model is static and solved at exogenously given values of parameters for the years 1997, 2003, 2010, 2020 and 2030.

The present paper is of a methodological nature and presents the mathematical formulation of both the partial and the general equilibrium welfare models, focusing on the latter, for which we also detail the decentralization into surplus maximizing consumer programs and profit maximization farm models, connected via commodity balances and a trade balance, while prices and tax rates adjust so as to clear these balances.

The following methodological results are obtained. First, we prove that the model possesses a solution that is, moreover, unique, and maximizes social welfare once all distortions are eliminated.

Second, we specify a modular calibration procedure through which it can be assured that the base year (1997) equilibrium solution of the full welfare program exactly replicates the base-year data. Agricultural supply is calibrated, in a modular way as well, for every county so that

[2] The GIS-database management and preparation of maps is executed in SAS. Further database management operations are conducted in GAMS (see Van Veen et al., 2005).

[3] New globally convergent algorithms were developed for solving these very large partial equilibrium welfare models, and implemented in Fortran (see Keyzer, 2004).

production as well as factor and non-factor input use are fully replicated and maximize county revenue. For interregional trade, we present a new dual programming technique to calibrate flows so as to meet given net export positions of each regions at prices that are sufficiently close to the observed ones and cover the associated transportation costs. Non-agricultural stock changes are treated as a closing item to fit the balance of payments. We note that such a modular decomposition of the calibration process is essential for the future maintenance of this very large model, as it makes it possible to keep database operations fully separate from the modeling work, while improvements in the database are in a transparent way transmitted to the model outcome and future replacements in specific model components can be implemented without requiring a new calibration full of surprises of the complete model. Moreover, initialization at a fully calibrated base-year solution provides a large number of checks and clues for detecting programming errors in the debugging phase of model building, as will be explained in more detail below, and also speeds up computation.

Third, we specify a globally convergent algorithm to solve this very large model. This algorithm decomposes the problem in two components, one an 8-region exchange component that maximizes social welfare of consumers while treating the output and input of the 2433 counties as given and is solved as a regular medium-sized convex program (via a Minos-solve statement in GAMS), the other an agricultural supply module consisting of a series of county-specific farm-income maximization programs that takes prices as given and is solved with a tailor-made algorithm that terminates in a finite number of iterations and has an exact solution . This property of finite and exact termination makes it possible to embed both components within a price-adjustment loop (implemented through parameter adjustments in GAMS) and to prove global convergence. The algorithm proves to be remarkably fast and precise.[4]

The paper proceeds as follows. Section 2 introduces the partial equilibrium welfare model; section 3 discusses spatial aggregation to county and region level, preparing for the specification in section 4 of the general equilibrium welfare model. This section also describes the calibration of the trade flows. Section 5 deals with specification and calibration of agricultural supply at county level. Section 6 concludes with a discussion on scenario design. The convergence of the price adjustment process to achieve equilibrium between the exchange and the supply module is established in Appendix A. Appendix B presents the classifications, Appendix C a list of main symbols and Appendix D describes the job-flow in GAMS.

[4] Numerical performance is as follows. Starting from given data files and estimates of the consumer demand system, the model calibration and preparation of GAMS-input files for simulation take about 5 minutes, on a regular laptop (Pentium®, 4-M CPU, 512MB RAM, 1.70 Ghz). A five-period simulation (1997, 2003, 2010, 2020, 2030) plus tabulation, is completed within 20 minutes, at a precision of .08% for every regional commodity price in every year.

2. Single-commodity partial equilibrium welfare model with given production

The present section describes the version of the model that was so far implemented for wheat and rice. A more general multi-commodity version with endogenous production is currently under development that will describe the interactions between livestock, animal feeds and the environment (Keyzer, 2004).

We represent the territory of China as a grid of S cells or sites ($94{,}024$ cells forming a 10x10 km grid) indexed s and represent the economy through a welfare maximization program. We initially abstract from any impediments to trade such as tariffs, quotas or other forms of taxation and represent the rest of the world by cells that denote ports and border crossings, whose net supply is, when positive, the import into China, and when negative, the export from the country. We suppose that every grid cell consists of homogeneous consumers, in number equal to the population living within the cell, who maximize their consumer surplus (utility minus expenditures). Traders maximize profit from shipping the commodity from one site to the next under a constant to scale transport technology with a strictly quasiconvex (CES/Leontief-type) technology (transformation function). Specifically, if prices at two neighboring destinations whose prices are higher than at the origin are very different the shipment will be to the most rewarding destination only but if they lie close, both destinations will receive positive inflows.

A competitive equilibrium on such a market can be represented by means of a social welfare maximization program, that actually maximizes the sum of trader's surplus, and consumer surplus measured as the sum of money metric utilities $u_s(x_s)$, strictly concave increasing functions expressed in money metric, minus trade-and-transport costs $T_s(v_{s1},...,v_{sS})$, a strictly quasiconvex increasing function, by commodity. The maximization is subject to a commodity balance that equates the local endowment (production) ω_s, which is here treated as given, plus inflows $\sum_{s'} \frac{1}{1+\rho_{s'}} v_{s's}$, where ρ_s is a fixed physical loss rate, with consumption x_s, and outflows $\sum_{s'} v_{ss'}$, which are all variable, subject to a fixed bound $\bar{\upsilon}_s$ on outflows:[5]

$$
\begin{aligned}
V^* = \; & \max_{v_{ss'} \geq 0; x_s \geq 0} \sum_s u_s(x_s) - \sum_s T_s(v_{s1},...,v_{sS}) \\
& \text{subject to} \\
& x_s + \sum_{s'} v_{ss'} = \sum_{s'} \frac{1}{1+\rho_{s'}} v_{s's} + \omega_s \qquad (p_s) \\
& \sum_{s'} v_{ss'} \leq \bar{\upsilon}_s \qquad (\xi_s)
\end{aligned}
\tag{2.1}
$$

This is the usual partial equilibrium form. Note that the maximization assumes comparability of utilities across sites, and that this is achieved by expressing utility in money metric, that is in the same unit as the costs of transportation. Now the first-order conditions imply that the constraints are met, and that

[5] Social welfare usually refers to economic value in general but in a transportation context it could also refer to a more focused concept such as average traveling time. It may be noted that the commodity is dealt with as perfectly homogeneous, like water in the river, and no record is kept of time already spent in transportation. Hence, the transport time is not being minimized for the individual shipment.

$$\frac{1}{1+\rho_s} p_{s'} - p_s - \frac{\partial T_s}{\partial v_{ss'}} - \xi_s \leq 0 \quad \textit{with equality if} \ v_{ss'} > 0 , \tag{2.2a}$$

where since the marginal cost of transportation $\frac{\partial T_s}{\partial v_{ss'}}$ is positive it follows that:

$$v_{ss'} = 0 \text{ whenever } p_{s'} \leq p_s . \tag{2.2b}$$

In other words, goods do not flow to sites with lower price. In theory, the problem is simple, but when the number of sites is large, say, about 100000, the number of variables becomes, even for this single commodity model, of the order of 10^{10}, which obviously exceeds our computational capabilities with regular software. However, for the analysis of Chinese agricultural policy, a single-commodity model is not satisfactory. Hence, there is a need for a multi-commodity approach, but this only makes the problem more daunting. Dedicated software was developed to deal with this problem.

However, the availability of data is insufficient to pursue this approach, which is also very demanding in terms of manpower resources. Therefore, we consider a series of single-commodity partial equilibrium models in conjunction with a spatially more aggregated general equilibrium welfare model, noting that spatial aggregation necessarily implies a loss of information.

3. Aggregation from site to county and region level

We aggregate to county level, with counties indexed *c*, $c=1,...,2433$ and from counties to regions indexed *r*, $r=1,...,8$. These indices appear as subscripts and are also taken to distinguish between the site-, region- and county-level for both variables and functions, e.g. x_s from x_r and ω_s from ω_c.

To introduce the issues at stake, we first apply this spatial aggregation in the partial equilibrium welfare model, as a preparation for the extension to general equilibrium. This essentially means that we apply the welfare program for larger sites. For ease of exposition we abstract from the income group distinction in consumption. Now the welfare program reads:

$$V^* = \max_{v_{rr'}\geq 0; x_r \geq 0} \sum_r u_r(x_r) - \sum_r T_r(v_{r1},...,v_{rR})$$
$$\text{subject to} \qquad (3.1)$$
$$x_r + \sum_{r'} v_{rr'} = \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + \sum_{c\in C_r} \omega_c \qquad (p_r)$$

where C_r is the set of counties in region *r*. This formulation implies in terms of the earlier disaggregated model that we assume in the aggregation that:

(a) All trade within the region is captured as an input v_{rr} in production. If $v_{rr}=0$ is feasible, it will be chosen.

(b) Endowments are:

$$\omega_c = \sum_{s\in S_c} \omega_s, \qquad (3.2a)$$

where S_c are the sites in county *c*.

(c) Consumer utility is obtained as

$$u_r(x_r) = \max_{x_s \geq 0}\{\sum_{s\in S_r} u_s(x_s) | \sum_{s\in S_r} x_s = x_r\}, \qquad (3.2b)$$

where S_r are the sites in region *r*.

(d) Transport costs are measured in the same money metric as utility and obey

$$T_r(v_{r1},...,v_{rR}) = \min_{v_{ss'}\geq 0} \sum_{s\in S_r} T_s(v_{s1},...,v_{sS})$$
$$\text{subject to} \qquad (3.2c)$$
$$\sum_{s\in S_r} \sum_{s'\in S_{r'}} v_{ss'} = v_{rr'}$$
$$\sum_{s'} v_{ss'} \leq \overline{\upsilon}_s$$

Formulation (a)-(d) is not adequate, though, since it abstracts from price differences between sites *s*, and essentially allows supply and demand of every sites to move along the cheapest route, to supply neighboring regions, irrespective of the location of supply and demand within the region.

Therefore, we opt for a different approach, where we assume fixed price differentials within the unit. Furthermore, the spatial aggregation applied to construct the general equilibrium welfare model is somewhat more elaborate. First, the general equilibrium model distinguishes eight regions indexed *r*. Second, within every region consumers are classified as being either rural or urban depending on the population density in the site *s* they live in. The superscripts *u* and *v* distinguish between urban and rural variables and functions (*v* for village to avoid the confusion if we were to use *r* for both rural and regional). Urban consumers are dealt with at regional level, rural consumers at county level.

For the county the gross commodity inflow into rural areas is represented by flows z_c^+ with transport costs τ_c^+ , the outflow by z_c^- with costs τ_c^-. This can be represented through an additional cost term in the objective.

$$V^* = \max_{v_{rr'} \geq 0; x_c^v, x_r^u \geq 0; z_c^-, z_c^+ \geq 0} \sum_r u_r^u(x_r^u) + \sum_r \sum_{c \in C_r} u_c^v(x_c^v)$$
$$- \sum_r T_r(v_{r1},...,v_{rR}) - \sum_r \sum_{c \in C_r} (\tau_c^+ z_c^+ + \tau_c^- z_c^-)$$

subject to (3.3)

$$x_r^u + \sum_{r'} v_{rr'} + \sum_{c \in C_r} z_c^+ = \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + \sum_{c \in C_r} z_c^- + \omega_r^u \qquad (p_r)$$

$$x_c^v + z_c^- = \omega_c^v + z_c^+, \qquad c \in C_r. \qquad (p_c)$$

This specification, which still applies to a single-commodity only and is, therefore, not a general equilibrium form, has the advantage that it maintains a realistic price distribution between counties within the same region. In particular, we have:

$$\frac{1}{1+\rho_r} p_{r'} - p_r - \frac{\partial T_r}{\partial v_{rr'}} \leq 0 \quad \text{with equality if } v_{rr'} > 0, \qquad (3.4)$$

and

$$p_c \leq p_r + \tau_c^+ \qquad \text{with equality if } z_c^+ > 0,$$
$$p_c \geq p_r - \tau_c^- \qquad \text{with equality if } z_c^- > 0.$$

It is important to note that the solution to this partial equilibrium welfare program can also be obtained in a decentralized way. Indeed, on the basis of the Lagrangean of the program it may be verified that it can be obtained when every consumer solves for village counties:

$$\max_{x_c^v \geq 0} u_c^v(x_c^v) - p_c x_c^v, \text{ for } c \in C_r \qquad (3.5a)$$

and for urban regions:

$$\max_{x_r^u \geq 0} u_r^u(x_r^u) - p_r x_r^u, \qquad (3.5b)$$

while prices adjust at every site to let markets clear. The coefficients τ^- and τ^+ will be obtained from welfare program (2.1) as mean price margins, which we approximate as:

$$\tau_c^+ = \tau_c^- = max(\frac{\Omega_r^u}{\omega_r^u} - \frac{\Omega_c^v}{\omega_c^v}, 0) \;\; if \;\; X_c^v < \Omega_c^v \;\; and \;\; max(\frac{X_c^v}{x_c^v} - \frac{X_r^u}{x_r^u}, 0) \; otherwise \qquad (3.6)$$

for $c \in C_r$, $X_c^v = \sum_{s \in S_c^v} p_s x_s$, $\Omega_c^v = \sum_{s \in S_c^v} p_s \omega_s$, $X_r^u = \sum_{s \in S_r^u} p_s x_s$, $\Omega_r^u = \sum_{s \in S_r^u} p_s \omega_s$.

In other words, we use differences in unit values of consumption in case the county is a net purchaser and of production in case it is a net seller, since a net purchasing county faces a consumer price, and a net seller a producer price. An immediate extension allows for agricultural production (in rural counties only), allowing for a transformation function that uses current inputs e_c at fixed price p_c^e, to produce outputs q_c, supposing that producers maximize their profit:

$$\begin{aligned} & max_{e_c, q_c \geq 0} \; p_c q_c - p_c^e e_c \\ & subject \;\; to \qquad . \\ & F_c(q_c, e_c) \leq 0. \end{aligned} \qquad (3.7)$$

The associated partial equilibrium welfare program extended with production now reads:

$$\begin{aligned} V^* = \;\; & max_{v_{rr'} \geq 0; e_c, q_c, x_c^v, x_r^u \geq 0, z_c^-, z_c^+ \geq 0} \sum_r u_r^u(x_r^u) + \sum_r \sum_{c \in C_r} u_c^v(x_c^v) \\ & \qquad - \sum_r T_r(v_{r1}, \ldots, v_{rR}) - \sum_r \sum_{c \in C_r} (\tau_c^+ z_c^+ + \tau_c^- z_c^-) \\ & \qquad - \sum_c p_c^e e_c \\ subject \;\; to & \qquad (3.8) \\ & x_r^u + \sum_{r'} v_{rr'} + \sum_{c \in C_r} z_c^+ = \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + \sum_{c \in C_r} z_c^- + \omega_r^u \qquad (p_r) \\ & x_c^v + e_c + z_c^- = q_c + \omega_c^v + z_c^+, \qquad c \in C_r \qquad (p_c) \\ & F_c(q_c, e_c) \leq 0. \end{aligned}$$

This program comes close to Chinagro's general equilibrium welfare model but the important further step is obviously to allow for multiple commodities. The most direct way to try this is to reinterpret all the variables of this program as vectors and product forms such as $\tau_c^+ z_c^+$ as inner products. However, as this does not achieve the full transition, we make the transition in separate steps.

4. General equilibrium and the Chinagro-welfare model

4.1 Welfare and competitive equilibrium

Recall that a competitive equilibrium is an allocation of commodities, in which consumers maximize their utility subject to a budget constraint, producers maximize profits subject to a technology constraint, all take prices as given, and total demand does not exceed total supply.

The main properties of the competitive equilibrium are laid down in the two Welfare Theorems. The First Welfare Theorem states that a competitive equilibrium is Pareto efficient. The Second Welfare Theorem states that any Pareto efficient allocation can be achieved as a competitive equilibrium with transfers. Hence, distributional considerations can be met through transfers, and there is no need to use the price mechanism for this. Consequently, there is room to let the price mechanism operate freely.

An important result that forms the bridge between both fundamental theorems says that any Pareto efficient allocation can, if utility functions are well behaved, be expressed as a welfare optimum with given welfare weights on individual utilities. Finally, the Negishi Theorem says, that there exist weights, such that the solution of the welfare program corresponds to a competitive equilibrium without transfers.

As Pareto efficiency has become such a high-prized property, the conditions of competitive equilibrium have gradually been transformed from a theoretical construct to a policy recipe, witness the so-called Washington consensus as well as the transition to the market economy in China. We note that these conditions are non-trivial in terms of the institutional requirements they impose. In particular, the fact that consumers should take budgets as given, and that producers maximize profits at given prices is important, since it implies, among others:

(1) all goods in the economy are priced (no free use)
(2) no one can manipulate prices (no monopoly)
(3) all consumers pay the price of what they use, and receive the price for what they sell (no crime).
(4) producers maximize profits independently of the preferences of the shareholders who own the firm.
(5) income transfers, if any, should be given (and if negative, levied) lump-sum, that is in such a way that individual consumers cannot by any choice of their own affect the amount they receive or pay.

The Chinagro-welfare model implements a welfare optimum, distorted by prevailing indirect taxes and tariffs. Hence, it assumes that compensating income transfers are provided that maintain fixed welfare weights among consumers. We abstain from imposing budget constraints with given transfers for every household or consumer group separately for the following reasons. First, our description of the non-farm sector in the Chinese economy is rudimentary at best. This makes it difficult to derive a realistic distribution of primary income over household groups. Second, data on income distribution within regions are only available for total expenditure and not by source of income. Information on the distribution of savings is not available either. Third, several public redistribution mechanisms are currently in place that would have to be analyzed as well. Finally, but this is not a major reason, calculations are somewhat easier with fixed welfare weights.

4.2 The multi-commodity welfare model

We are now ready to present the Chinagro general equilibrium welfare model, in its static version for a single calendar year. The generalization that is introduced to formulate a general equilibrium version consists of the following steps:

(1) We consider all goods simultaneously, but some, such as the good used in transport can be purchased at a fixed price. Hence, the variables of this program are now *K*-dimensional vectors with commodities indexed $k = 1,...,K$ as elements. We write $'$ for the vector transpose. The transport costs are represented through the *K*-dimensional vectors $\theta_{rr'}$ of inter-regional transport requirements, i.e. demand for non-agriculture as input, and the *K*-dimensional vector of intra-regional transport requirements τ_c^-, τ_c^+. Hence, products terms become inner products such as $\tau_c^{+\prime} z_c^+$. Similarly, ζ_r^+ and ζ_r^- denote the transport and processing requirements for international trade from the border to the region and vice-versa. The total input demand g_r for inter- and intraregional transport is:

$$g_r = \sum_{r'} \theta_{rr'}{}' v_{rr'} + \sum_{c \in C_r} (\tau_c^{+\prime} z_c^+ + \tau_c^{-\prime} z_c^-) + \zeta_r^{+\prime} m_r^+ + \zeta_r^{-\prime} m_r^- \tag{4.1}$$

(2) The economy is an open economy that trades with the outside world at given prices. By contrast, in the partial equilibrium model, the outside world is represented through separate offshore sites, just across the border. Hence, the partial equilibrium model is a simplified world model with endogenous prices, and is in this respect more complete than the general equilibrium form. We can also use the partial equilibrium model to inform simulations with the general equilibrium model about price responses on the world market.

(3) The general equilibrium model imposes a balance of payments constraint: at given import prices $\bar{p}_r^+$, and export prices $\bar{p}_r^-$, such that $\bar{p}_r^- < \bar{p}_r^+$, the value of imports from the outside world m_r^+ should not exceed the value of exports m_r^- incremented by a given, possibly negative trade deficit:

$$\sum_r (\bar{p}_r^{+\prime} m_r^+ - \bar{p}_r^{-\prime} m_r^-) \le \bar{B} \tag{4.2}$$

We note that regions without direct access to foreign markets through seaports or border crossings have $\bar{p}_r^- = 0$ and $\bar{p}_r^+ = +\infty$.

(4) The general equilibrium model requires utility to be in money metric. The welfare function now performs the conversion from site-specific utility to money metric through given, positive welfare weights α_r^u, α_c^v which make utilities comparable across consumers:

$$W = \sum_r \alpha_r^u u_r^u(x_r^u) + \sum_r \sum_{c \in C_r} \alpha_c^v u_c^v(x_c^v) \tag{4.3a}$$

Here x_r^u and x_r^v denote total consumptions, and welfare weights are equal to the inverse of individual marginal utilities of income λ_r^u and λ_c^v :

$$\alpha_r^u = 1/\lambda_r^u \tag{4.3b}$$
$$\alpha_c^v = 1/\lambda_c^v$$

implying that individual consumers maximize the consumer surplus as in (3.5a), (3.5b):

$$x_r^u = arg\,max_{x\geq 0}\, u_r^u(x) - \lambda_r^u p_r^u{}'x \tag{4.3c}$$
$$x_c^v = arg\,max_{x\geq 0}\, u_c^v(x) - \lambda_r^v p_c^v{}'x\,. \tag{4.3d}$$

This formulation has the shortcoming that it does not make the population size explicit. This will be addressed below.

(5) The general equilibrium model has a detailed component for agricultural production. This component is developed further in section 5 below. Here we merely represent it by replacing the production function through a strictly quasiconvex transformation function $F_c(q_c, e_c) \leq 0$, where q_c is the output and e_c the input vector.

Consequently, the general equilibrium welfare model reads:

$$\begin{aligned}
V^* = \quad & max_{v_{rr'}\geq 0; e_c, m_r^-, m_r^+, q_c, x_c^v, x_r^u \geq 0; z_c^-, z_c^+ \geq 0, g_r} \sum_r \alpha_r^u u_r^u(x_r^u) + \sum_r \sum_{c\in C_r} \alpha_c^v u_c^v(x_c^v) \\
& subject\ to \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (4.4) \\
& x_r^u + \sum_{r'} v_{rr'} + \sum_{c\in C_r} z_c^+ + g_r \delta^n + m_r^- = \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + \sum_{c\in C_r} z_c^- + m_r^+ + \omega_r^u \qquad (p_r) \\
& g_r = \sum_{r'} \theta_{rr'}{}' v_{rr'} + \sum_{c\in C_r} (\tau_c^+{}' z_c^+ + \tau_c^-{}' z_c^-) + \zeta_r^+{}' m_r^+ + \zeta_r^-{}' m_r^- \\
& \sum_r (\overline{p}_r^+{}' m_r^+ - \overline{p}_r^-{}' m_r^-) \leq \overline{B} \qquad (\rho) \\
& x_c^v + e_c + z_c^- = q_c + \omega_c^v + z_c^+ \qquad (p_c) \\
& F_c(q_c, e_c) \leq 0, \qquad c \in C_r\,.
\end{aligned}$$

Here δ^n is a vector with a unit entry in the row corresponding to the non-agricultural good. This almost is, in its static version, the full model we are concerned with. Indeed, the formulation illustrates the major practical advantage of the welfare approach that it can accommodate a complex economic system in a transparent way, for example, through its first-order conditions the price relationships:

$\frac{1}{1+\rho_r} p_{r'} \leq p_r + p_{rn}\theta_{rr'}$ with equality if $v_{rr'} > 0$

$p_c \leq p_r + p_{rn}\tau_c^+$ with equality if $z_c^+ > 0$

$p_c \geq p_r - p_{rn}\tau_c^-$ with equality if $z_c^- > 0$

$p_r \leq \rho\overline{p}_r^+ + p_{rn}\zeta_r^+$ with equality if $m_r^+ > 0$

$p_r \geq \rho\overline{p}_r^- - p_{rn}\zeta_r^-$ with equality if $m_r^- > 0$.

The last step is to apply a further simplification that enables us to decompose the program into an exchange component in which production and input demand are taken as given, and a supply component that determines these variables at county level depending on prevailing prices.

Since we have no data available on consumption at county level, we represent demand by rural consumers at regional level, supposing that a fraction Γ_r (a diagonal matrix) of total consumption is from net purchasing rural counties. These fractions are only used to determine the processing requirements, and associated to these the price margins.

The county level prices for production are obtained from regional selling and purchasing prices, $p^{\bullet}_{rk}$ and p^{o}_{rk} depending on whether the county is a net seller ($c \in C^{\bullet}_{rk}$) or a net buyer ($c \in C^{o}_{rk}$) of the product concerned.

The exchange component deals with given input $\bar{e}^{\bullet}_{rk} = \sum_{c \in C^{\bullet}_{rk}} e_{ck}$, $\bar{e}^{o}_{rk} = \sum_{c \in C_r} e_{ck} - \bar{e}^{\bullet}_{rk}$, and output $\bar{q}^{\bullet}_{rk} = \sum_{c \in C^{\bullet}_{rk}} q_{ck}$, $\bar{q}^{o}_{rk} = \sum_{c \in C_r} q_{ck} - \bar{q}^{\bullet}_{rk}$, and similarly for endowments $\omega^{\bullet}_{rk}$ and ω^{o}_{rk}. Hence, the exchange component of the Chinagro welfare program reads:

$$V^* = \max_{v_{rr'} \geq 0; m^-_r, m^+_r, x^u_r, x^v_r \geq 0; z^-_r, z^+_r \geq 0, g_r} \sum_r \alpha^u_r u^u_r(x^u_r) + \sum_r \alpha^v_r u^v_r(x^v_r)$$

subject to (4.5)

$$x^v_r + x^u_r + \sum_{r'} v_{rr'} + g_r \delta^n + m^-_r + \bar{e}^{\bullet}_r + \bar{e}^{o}_r = \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + m^+_r + \omega^u_r + \bar{q}^{\bullet}_r + \omega^{\bullet}_r + \bar{q}^{o}_r + \omega^{o}_r \qquad (p_r)$$

$$g_r = \sum_{r'} \theta_{rr'}{}' v_{rr'} + \tau^+_r{}' z^+_r + \tau^-_r{}' z^-_r + \zeta^+_r{}' m^+_r + \zeta^-_r{}' m^-_r$$

$$\sum_r (\bar{p}^+_r{}' m^+_r - \bar{p}^-_r{}' m^-_r) \leq \bar{B} \qquad (\rho)$$

$$\Gamma_r x^v_r + \bar{e}^{o}_r = \bar{q}^{o}_r + \omega^{o}_r + z^+_r \qquad (\psi^{o}_r)$$

$$(I - \Gamma_r) x^v_r + \bar{e}^{\bullet}_r + z^-_r = \bar{q}^{\bullet}_r + \omega^{\bullet}_r \qquad (\psi^{\bullet}_r)$$

Input and output prices p^{o}_{rk} and $p^{\bullet}_{rk}$ can be retrieved from this solution as:

$$p^{o}_{rk} = p_{rk} + \psi^{o}_{rk} \qquad (4.6a)$$
$$p^{\bullet}_{rk} = p_{rk} - \psi^{\bullet}_{rk},$$

that satisfy $\psi^{o}_{rk} \leq p_{rn} \tau^+_{rk}$ if $z^+_{rk} > 0$, and $\psi^{\bullet}_{rk} \geq p_{rn} \tau^-_{rk}$ if $z^-_{rk} > 0$. Furthermore, we introduce county-specific factors $\breve{\kappa}_{ck}$ and $\hat{\kappa}_{ck}$ that can be positive or negative. The county prices for outputs are now determined as:

$$\breve{p}_{ck} = p^{\bullet}_{rk} - \breve{\kappa}_{ck} p_{rn} \text{ if } c \in C^{\bullet}_{rk} \text{ and } p^{o}_{rk} - \breve{\kappa}_{ck} p_{rn} \text{ otherwise,} \qquad (4.6b)$$

and for inputs as

$$\hat{p}_{ck} = p^{\bullet}_{rk} + \hat{\kappa}_{ck} p_{rn} \text{ if } c \in C^{\bullet}_{rk} \text{ and } p^{o}_{rk} + \hat{\kappa}_{ck} p_{rn} \text{ otherwise.} \qquad (4.6c)$$

Since we only measure either $\hat{\kappa}_c$ or $\breve{\kappa}_c$ we make the assumption that $\hat{\kappa}_c = -\breve{\kappa}_c$. This means that, apart from the producer tax, the same county prices are applied to production and input demand. The margins may be negative as they actually reflect differences in composition, i.e. differences in quality and making of the commodity as well as differences in location inside the region. These prices enter the model of the representative producers in each county *c*, who solve:

$$\Pi_c(\breve{p}_c, \hat{p}_c) = \max_{e_c, q_c \geq 0} \breve{p}_c' q_c - \hat{p}_c' e_c \quad \text{subject to} \quad F_c(q_c, e_c) \leq 0. \tag{4.6d}$$

and collectively form the supply component.

Three qualifications are in order. One is that, for simplicity, we have assumed here that all transportation costs within site are truly incurred. In fact, this is an unwarranted assumption, as differences in mean prices are not fully attributable to transport cost. The second qualification is that in what follows the characterization of counties as net selling or net buying is kept fixed unless changed exogenously. Allowing for an endogenous transition would require an explicit representation of consumer demand by county. Finally, we need to assume that

$$(1-\Gamma_{rk})\tau_{rk}^{-} = \Gamma_{rk}\tau_{rk}^{+}, \tag{4.7}$$

in order to maintain the interpretation of p_r as mean consumer price for rural areas, i.e. as $p_{rk} = \Gamma_{rk} \overset{\circ}{p}_{rk} + (1-\Gamma_{rk}) \overset{\bullet}{p}_{rk}$. Further producer margins can be covered via (4.6a) and (4.6b).

Tariffs, quotas and committed trade

Finally, regional tariffs $\xi_{rk}^{+}, \xi_{rk}^{-}$ and quotas $\bar{m}_{rk}^{+}, \bar{m}_{rk}^{-}$ on international trade, and other taxes on domestic trade are still to be incorporated in (4.5), for agricultural products only. This is readily achieved by additional tariff terms in the objective $\sum_r \sum_k (\xi_{rk}^{+} m_{rk}^{+} + \xi_{rk}^{-} m_{rk}^{-})$ and upper bounds on flows $m_{rk}^{+} \leq \bar{m}_{rk}^{+}$, $m_{rk}^{-} \leq \bar{m}_{rk}^{-}$, respectively. Indirect taxes and subsidies on consumption, production, or input use can be incorporated in a similar way (as in Ginsburgh and Keyzer, 2002, chapter 5). In addition, we also allow for lower bounds $\underline{m}_{rk}$ on exports, to represent export commitments. Hence, exports may co-exist with imports. Such commitments can also serve to address inevitable problems of heterogeneity of trade flows within a single commodity *k*. To represent investment and public consumption, we also introduce a vector of exogenous final demand $\bar{g}_r$. Thus, program (4.5) is extended into:

$$V^* = \max_{v_{rr'}\geq 0; m_r^-, m_r^+, x_r^u, x_r^v \geq 0; z_r^-, z_r^+ \geq 0, g_r} \sum_r \alpha_r^u u_r^u(x_r^u) + \sum_r \alpha_r^v u_r^v(x_r^v) - \sum_r (\xi_r^+{}' m_r^+ + \xi_r^-{}' m_r^-)$$

subject to (4.8)

$$x_r^v + x_r^u + \sum_{r'} v_{rr'} + g_r \delta^n + m_r^- + \bar{e}_r^\bullet + \bar{e}_r^o$$
$$= \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + m_r^+ + \omega_r^u + \bar{q}_r^\bullet + \omega_r^\bullet + \bar{q}_r^o + \omega_r^o \qquad (p_r)$$

$$g_r = \sum_{r'} \theta_{rr'}{}' v_{rr'} + \tau_r^+{}' z_r^+ + \tau_r^-{}' z_r^- + \zeta_r^+{}' m_r^+ + \zeta_r^-{}' m_r^- + \bar{g}_r$$

$$\sum_r (\bar{p}_r^+{}' m_r^+ - \bar{p}_r^-{}' m_r^-) \leq \bar{B} \qquad (\rho)$$

$$m_r^+ \leq \bar{m}_r^+$$

$$\underline{m}_r^- \leq m_r^- \leq \bar{m}_r^-$$

$$\Gamma_r x_r^v + \bar{e}_r^o = \bar{q}_r^o + \omega_r^o + z_r^+ \qquad (\psi_r^o)$$

$$(I - \Gamma_r) x_r^v + \bar{e}_r^\bullet + z_r^- = \bar{q}_r^\bullet + \omega_r^\bullet \qquad (\psi_r^\bullet)$$

Keeping the price of non-agriculture fixed

A further extension is to ensure that the Lagrange multiplier ρ on the balance of payments constraint remains fixed. There is no theoretical reason for requiring this, but the practical difficulty in working with (4.8) is that the non-agricultural sector, which contributes the lion's share to the Chinese economy is largely treated exogenously, on the supply side as well as on the demand side, where only (uncommitted) private consumption, intermediate deliveries to agriculture, and trade and transportation of agricultural produce are endogenous. Consequently, scenarios that treat $\bar{g}_r$ as given might generate gaps on the balance of payments that cannot be accommodated by agriculture. Note that the equilibrium domestic price of a domestic good without any processing costs and commodity-specific taxes becomes $p_{rk} = \rho \bar{p}_{rk}^+$. Hence, expressed in the monetary unit of the foreign prices, the price becomes $\hat{p}_{rk} = \frac{p_{rk}}{\rho} = \bar{p}_{rk}^+$, implying that the effect is fully neutralized for a traded good. However, the factor ρ also applies to non-traded goods, and may cause significant instability in these prices. To avoid this, and because of the limited importance of agriculture in the overall economy, we make the model more partial by allowing for upward adjustment of non-agricultural consumption c_n, in regional shares η_r, with fixed marginal utility $\bar{p}_n = \bar{p}_{rn}^+ = \bar{p}_{rn}^-$ equal to the foreign price of non-agriculture that is assumed to be equal across regions and between import and export. This uniform foreign price also leads to a uniform domestic price, since, as mentioned earlier, we abstract from any taxes and transportation margins on non-agriculture, taking these to have been netted out already in the exogenous regional demand $\bar{g}_{rn}$. The variable c_n acts as a closure rule, and as long as it is positive in the optimum, maintains a fixed value for ρ. To make sure that c_n remains positive we should keep a sufficient part of public demand under this item as opposed to treating it as exogenously given.

The complete Chinagro welfare program

We complete the presentation in this section by writing the full Chinagro welfare program, including production, and summarizing some of its basic properties in a proposition.

As final extensions we introduce two additional features:

(i) Population numbers n_{ir}^{v} and n_{ir}^{u} and (LES) utility functions u_{ir}^{v}, u_{ir}^{u} by income groups *i*, (low, middle and high income) of rural and urban population separately, by region *r*, while x_{ir}^{v} and x_{ir}^{u} will now denote the associated per capita consumption vectors.

(ii) Producer tax per quantity unit ξ_c^q, by county.

This leads to the following welfare program:

$$V^* = \max_{v_{rr'}\geq 0; e_c, e_r^{\circ}, e_r^{\bullet}, m_r^-, m_r^+, q_c, q_r^{\circ}, q_r^{\bullet}, x_r^u, x_r^v \geq 0; z_r^-, z_r^+ \geq 0, c_n \geq 0, g_r} \sum_r \sum_i \alpha_{ir}^u n_{ir}^u u_{ir}^u(x_{ir}^u) + \sum_r \sum_i \alpha_{ir}^v n_{ir}^v u_{ir}^v(x_{ir}^v)$$
$$- \sum_r (\xi_r^{+}{}' m_r^+ + \xi_r^{-}{}' m_r^-) - \sum_c \xi_c^{q}{}' q_c + \bar{p}_n c_n$$

subject to (4.9)

$$\sum_i x_{ir}^u n_{ir}^u + \sum_i x_{ir}^v n_{ir}^v + \sum_{r'} v_{rr'} + g_r \delta^n + m_r^- + e_r^{\bullet} + e_r^{\circ}$$
$$= \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + m_r^+ + \omega_r^u + q_r^{\bullet} + \omega_r^{\bullet} + q_r^{\circ} + \omega_r^{\circ} \qquad (p_r)$$

$$g_r = \sum_{r'} \theta_{rr'}{}' v_{rr'} + \tau_r^{+}{}' z_r^+ + \tau_r^{-}{}' z_r^- + \zeta_r^{+}{}' m_r^+ + \zeta_r^{-}{}' m_r^- + \sum_{c \in C_r} (\breve{\kappa}_c{}' q_c + \hat{\kappa}_c{}' e_c) + \bar{g}_r + \eta_r c_n$$

$$\sum_r (\bar{p}_r^{+}{}' m_r^+ - \bar{p}_r^{-}{}' m_r^-) \leq \bar{B} \qquad (\rho)$$

$$m_r^+ \leq \bar{m}_r^+$$

$$\underline{m}_r^- \leq m_r^- \leq \bar{m}_r^-$$

$$\Gamma_r \sum_i x_{ir}^v n_{ir}^v + e_r^{\circ} = q_r^{\circ} + \omega_r^{\circ} + z_r^+ \qquad (\psi_r^{\circ})$$

$$(I - \Gamma_r) \sum_i x_{ir}^v n_{ir}^v + e_r^{\bullet} + z_r^- = q_r^{\bullet} + \omega_r^{\bullet} \qquad (\psi_r^{\bullet})$$

$$e_r^{\circ} = \sum_{c \in C_r^{\circ}} e_c$$

$$q_r^{\circ} = \sum_{c \in C_r^{\circ}} q_c$$

$$e_r^{\bullet} = \sum_{c \in C_r^{\bullet}} e_c$$

$$q_r^{\bullet} = \sum_{c \in C_r^{\bullet}} q_c$$

$$F_c(q_c, e_c) \leq 0$$

This is the full specification of the Chinagro welfare model with the qualification that the transformation functions F_c will be made explicit in the next section.

Proposition 1 (general properties of welfare equilibrium): Suppose that (i) the per capita consumer utility functions u_{ir}^u and u_{ir}^v are strictly concave, differentiable; (ii) the transformation functions at county level are strictly quasiconvex, homogeneous, non-decreasing in $(q_c, -e_c)$; (iii) total endowments support positive production of all goods.

Then, for $\bar{B}$ sufficiently large, the welfare equilibrium of model (4.9) generates bounded prices p_r, supporting an equilibrium in which consumers maximize their surplus according to (4.3c), (4.3d) and producers maximizing their profits according to (4.6d), exists, is unique, and once all distortions are eliminated yields a Pareto efficient solution.

Proof. Under assumptions (i)-(iii) program (4.9) is a convex program that is feasible for $\bar{B}$ large enough and has, by strict concavity of the utility functions and strict quasiconvexity of the transformation function a unique solution for consumption, inputs, and outputs. Moreover, for $\bar{B}$ large enough its commodity balance satisfies Slater's constraint qualification, implying that the Lagrange multipliers p_r are non-negative and bounded. The decentralization into surplus maximization and profit maximization follows from the Second Welfare Theorem. Pareto-efficiency is ensured by construction. ■

As mentioned earlier, the model is solved by decomposition into a supply component that takes prices as given and generates net supply, and an exchange component that takes net supply as given and generates prices as Lagrange multipliers. The prices are adjusted iteratively on that basis. In Appendix A, the global convergence of this process is shown.

4.3 Calibration of the exchange component

The calibration process is an adjustment of a subset of model parameters to ensure that the optimum of model (4.9) will, for levels of exogenous variables that coincide with base year values, fully replicate the carefully constructed and internally consistent data set for this base year, also at county level. The calibration can also be looked at as an inclusion of fixed (county-specific) effects in earlier regressions, so as to eliminate regression errors while ensuring that the first-order conditions of the welfare program are met at (and, since the program is strictly convex, only at) a point that agrees with base year data.

The Chinagro general equilibrium welfare program has its exchange component calibrated separately from its supply component (cf. section 5.7). The exchange calibration reproduces the base year data set for consumer demand, trade flows, and prices at given levels of farm production and farm input demand and processing margins, as specified in the database of the base year. It proceeds in three stages: (i) the calibration of consumer demand; (ii) calibration of trade routing; (iii) calibration of foreign trade and nonagricultural demand.

For a model as large as Chinagro, we consider full calibration to be essential, among others because, as mentioned in the introduction, it provides several logical checks to detect programming errors. First, it offers a transparent check that the database used to feed the model is internally consistent. Second, since the optimal solution to be found by the optimization algorithm is known beforehand, it also provides a thorough error check on the computer program and the algorithms used for solving this program. Third, as all initial values are known, the calibration also gives an error check for the post-optimal calculations to generate the tables.

Nonetheless, calibration only is a trick. Eventually, the modeler should base all coefficients on statistical procedures with more degrees of freedom than one, and errors in regression should be accepted, once sufficient cross-section and time-series data have become available, but the Chinagro-database has not reached that stage.

Calibrating consumer demand

Utility functions are supposed to be Cobb-Douglas for per capita consumption by regional income group *i* (low, medium and high income, for rural and urban separately), in excess of a given commitment. The associated linear expenditure system is calibrated with marginal budget shares adjusted to ensure that at the base-year consumer prices every group demands the base-year per capita observed quantity. Furthermore, the given base-year prices define the marginal utility of expenditure, equal to the inverse of the welfare weights α, needed as a multiplication factor of per capita utility to money metric.

These budget shares and commitments are adjusted in scenario simulation, jointly with the population numbers of every group.

Calibrating trade flows

Specifically, the calibration step (ii) for trade routing serves to ensure that first-order conditions of internal flows $v_{rr'}$ and foreign trade m_r^-, m_r^+ should be such that the tax/tariff inclusive price received by a trader at the destination is higher than at the origin, so as to cover transportation costs. For foreign trade prices $\overline{p}_k^+, \overline{p}_k^-$, it is relatively straightforward to meet this requirement by shifting the unit value of a flow in between the commodity *k* and non-agriculture (processing) reflecting a difference in commodity composition by means of a complementary input of processing. For example, if the import price (c.i.f.) $\overline{p}_k^+$, incremented by a positive tariff ξ_k^+, falls above the observed regional trade price p_{rk}, while import z_{rk}^+ is positive, then the calibration will reduce the import price and deal with the import value on the balance of payment, as an additional inflow of non-agricultural product.

The calibration of the internal trade routing in the exchange component is more complex. It serves to ensure that for zero loss rate the equivalent of first-order conditions (3.4) holds:

$$p_{r'k} - p_{rk} - p_{rn}\theta_{rr'k} \leq 0 \quad \textit{with equality if } v_{rr'k} > 0, \tag{4.10}$$

which now relates the regional urban trade prices. Flows that are physically impossible can be represented either through prohibitively high transport coefficients $\theta_{rr'k}$ or by dropping the associated variable $v_{rr'k}$ from the program altogether. Here we represent all restrictions via the transport coefficients. For calibration, the key restriction is that:

$$p_{r'k} > p_{rk} \quad \textit{if } v_{rr'k} > 0.$$

Calibration now starts with observed values p_{rk} on prices and observed net outflows of every region:

$$\textstyle\sum_r v_{r'rk} - \sum_r v_{rr'k} = \overline{v}_{r'k}, \tag{4.11}$$

where $\sum_{r'} \overline{v}_{r'k} = 0$, and that can serve as the constraints of the transport cost minimization problem by commodity:

$$min_{v_{rr'k}\geq 0}\{\sum_r \sum_{r'} p_{rn}\theta_{rr'k}v_{rr'k} \mid \sum_r v_{rr'k} - \sum_r v_{r'rk} \geq -\bar{v}_{r'k}\}. \tag{4.12}$$

To impose the flow restrictions implied by the observed prices p_{rk}, we may insert the additional constraints:

$$v_{rr'k} = 0 \;\; if \;\; p_{rk} > p_{r'k}, \tag{4.13}$$

where, to maintain feasibility, we must allow for a slack import into each region, at high cost. A positive external import reflects an infeasibility in routing the goods to that particular region.

One might consider curing this infeasibility by raising the urban trade price of that region. However, this is only possible up to the minimum of the given level of the urban consumer price, p^c_{rk} and the prices net of transport costs at the most rewarding destination the region delivers to. This illustrates that the calibration may require adjustment of transport costs $\theta_{rr'k}$. To perform this adjustment, we note that (4.12) has as dual the linear program:

$$min_{p_{rk}\geq 0}\{\sum_r p_{rk}\bar{v}_{rk} \mid (p_{r'k} - p_{rk} - p_{rn}\theta_{rr'k}) \leq 0\}. \tag{4.14}$$

Defining (positive) lower bounds $\underline{p}_{rk}$ on prices we can view (4.14) as being embedded in a program with variable transport margin $\theta_{rr'k}$:

$$min_{p_{rk}\geq 0,\theta_{rr'k}\geq 0}\{\sum_r p_{rk}\bar{v}_{rk} \mid p_{r'k} - p_{rk} - p_{rn}\theta_{rr'k} \leq 0, \underline{p}_{rk} \leq p_{rk} \leq p^c_{rk}, \underline{\theta}_{rr'k} \leq \theta_{rr'k} \leq \bar{\theta}_{rr'k}\} \tag{4.15}$$

where the bounds on the margins should be kept sufficiently tight to ensure that if the optimal value of the margin is introduced in (4.14), the appropriate constraints will remain binding, i.e. with $v_{rr'k} > 0$ such that the primal constraints of (4.12) are met. For $\underline{p}_{rk}$ sufficiently low, this program (4.15) is feasible. It yields $p_{r'k} - p_{rk} - p_{rn}\theta_{rr'k} = 0$ for some pairs (r, r') and strict inequality for the other pairs, and dually associated to these pairs are the flows $v_{rr'k}$ that are zero whenever strict inequality holds. In case the bounds on prices are unbinding (zero Lagrange multipliers), except one lower bound, we are assured that the optimal transport costs $\theta_{rr'k}$ can be entered as fixed parameters into (4.14) to yield a solution that meets all requirements.

The key point to note in this connection is that it is possible to rank all prices p_{rk} obtained from (4.15) in decreasing order. As long as we maintain this order, we are assured that we can find transport margins $\theta_{rr'k}$ that support the observed routing sequence, and, therefore, can obtain the target net outflow $\bar{v}_{rk}$ of every commodity *k* from every market *r*.

However, to devise a constructive procedure the observed trade price $p^o_{rk} \leq p^c_{rk}$ must also be accounted for. The following program extends (4.15) by (weakly) penalizing deviations from this price:

$$
\begin{aligned}
& min_{p_{rk} \geq 0, \theta_{rr'k}, \varphi^+_{rk}, \varphi^-_{rk} \geq 0} \sum_r p_{rk} \overline{v}_{rk} + \beta_k \sum_r (\varphi^+_{rk} + \varphi^-_{rk}) \\
& subject \;\; to \qquad\qquad (4.16) \\
& \quad p_{r'k} - p_{rk} - p_{rn} \theta_{rr'k} \leq 0 \\
& \quad p_{rk} \leq p^c_{rk} \\
& \quad p_{rk} = p^o_{rk} + \varphi^+_{rk} - \varphi^-_{rk} \\
& \quad \underline{\theta}_{rr'k} \leq \theta_{rr'k} \leq \overline{\theta}_{rr'k}
\end{aligned}
$$

From this program follows, for β_k small enough, the same routing (set of positive flows) as from (4.15). Therefore, we can interpret (4.16) as a calibration procedure for every commodity separately, starting from the region with the highest price in (4.16). For this region the trade price will lie below the consumer price, and we can derive the processing margin on consumption residually. Then we turn to the region with the next highest price. If this region delivers to the previous one, the trade price exactly bridges the gap and will not exceed the consumer price. Otherwise, we can choose any trade price below the consumer price. The penalization will now shift it towards the observed price. Hence, the parameter β_k accounts for a trade-off. The smaller its value the closer the flows will reproduce the observed net flow and the larger it is, the closer the prices will be to the observed levels. In other words, the calibration will not fully replicate observed flows but the net outflows by region will be approximated, and it will not replicate fully the trade prices but an additional processing margin is introduced to ensure that consumer and producer prices are unaffected. In the implementation the value of β_k is kept low so as to let the procedure results in a full calibration of interregional trade flows supported by regional prices.

Calibration of international trade and non-agricultural demand

The trade flows generate a calibration for regional prices p_r. Next we must relate these to international prices and do this by treating the processing margins $p_{rn}\zeta^+_r$ and $p_{rn}\zeta^-_r$ on foreign exports and imports as closing items, for given explicit tariffs ξ^+ and ξ^-. However, the complications to be dealt with is that these margins should be kept non-negative. Hence, whenever $m^+_{rk} > 0$ we require the inequalities $\overline{p}^+_k + \xi^+_k \leq p_{rk}$ to hold for all *r*, *k*, and similarly, whenever $m^-_{rk} > \underline{m}^-_{rk}$ the inequalities $\overline{p}^-_k + \xi^-_k \geq p_{rk}$ must hold for all *r*, *k*. We impose these restrictions by adjusting world prices levels at the border, while adjusting non-agricultural exogenous demand $\overline{g}_r$ so as to maintain the balance of payments restriction as an equality.

4.4 Further details on implementation of the exchange component

This section ends with some details on the actual implementation of the exchange component in the GAMS-program.

Possibility of trade flows. A subset of regions is defined with the possibility to engage in foreign trade. Similarly, a network structure is imposed on interregional trade by defining arcs of regions with the possibility to trade directly.

Consumer group-specific processing margins on consumption. To account for more specific composition, processing and retail margins in consumption, the model allows for consumer group specific processing margins.

Indirect tax on consumption. A consumer tax is introduced because it is effective in the base year and allows to capture scenario trends in value added tax on food.

Endowments. The parameters ω_r^u for urban endowments measure net supplies of non-agriculture, forestry and fisheries (all exogenous and specified at regional level); rural endowments $\omega_r^{\bullet}$ and ω_r^{o} are kept at zero, as all supply emanates from county-level production.

Foreign prices. All prices on foreign trade are expressed in US dollar. Therefore, the objective coefficient $\bar{p}_n$ is actually multiplied with the dollar-to-Yuan conversion rate, so as to keep the multiplier ρ of the balance of payments equal to this conversion rate in the base-year, rather than equal to unity, as is the case in program (4.9). Furthermore, foreign prices are supposed to be equal across regions but this only is for lack of clear evidence to the contrary. The calibration can allow for any pattern.

Tariffs. For similar reasons, import and export tariffs are assumed to be equal across regions.

Losses. Post-harvest losses are represented as separate demand categories instead of through the loss factors ρ_r related to flows, because the aggregate treatment at regional level does not warrant using losses proportionate to the flows.

Stock changes agricultural goods. These changes appear as exogenous net demand categories on the commodity balances.

Non-agricultural commodity balances. As mentioned earlier, for the non-agricultural commodity we impose (i) no taxes on production, consumption or trade, (ii) no transportation margins, (iii) import prices equal to export prices. Hence, interregional flows are indeterminate and the model in fact only maintains a national commodity balance for this commodity.

Post-optimal revenue accounting. From the optimal outcomes of the welfare program, regional budget accounts are compiled that cover value added, taxes and final expenditures, whereas net transfers across regions are calculated residually. The resulting national income deficit is consistent with the exogenous balance of trade deficit $\bar{B}$, provided that the all domestic price equilibrium conditions taken into consideration, including, for example the effect of $c_n = 0$, $z_{rk}^{+} = 0$ and $z_{rk}^{-} = 0$.

5. The agricultural supply component: assumptions and exact solution algorithm

5.1 General approach

We return to the profit function (4.6d) at county level, disaggregating it further by distinguishing several land use types *j* each with a transformation function of their own, with as before output prices $\breve{p}_k$ and input prices $\hat{p}_k$, and maximizing profits subject to the transformation functions by land use type and an overall labor constraint:

$$\begin{aligned} &\Pi(\breve{p},\hat{p}) = \sum_j max_{e_{kj},q_{kj}\geq 0, L_j \geq 0} \sum_k \breve{p}_k q_{kj} - \sum_k \hat{p}_k e_{kj} \\ &\qquad subject\ \ to \\ &\qquad\quad F_j(q_{1j},...,q_{Kj},e_{1j},...,e_{Kj},L_j,\bar{A}_j) \leq 0 \\ &\qquad\quad \sum_j L_j \leq \bar{L} \end{aligned} \tag{5.1}$$

where henceforth the county index is dropped for ease of notation and where q_{kj} stands for the output of *k* from land use *j* and e_{kj} for input, where L_j is the labor applied to land use type *j* and $\bar{A}_j$ the given number of capacity units (area, number of stable units etc., depending on the land use type).

Land use types fall in three classes with index sets $J_p + J_g + J_o = J$, a price responsive class, grazing, and other land use activities (see Appendix B for the lists):

(i) *Price responsive class,* $j \in J_p$: yield is dependent on labor and equipment intensity per hectare for crops and per stable unit for livestock, and labor is allocated flexibly between different uses:

```
Irrigated cropping
Rainfed cropping
Specialized dairy farm
Traditional mixed nonruminant farm
Intensified nonruminant farm
```

(ii) Grazing, $j \in J_g$: for grazing, the aggregate yield index is price independent and depends on the given livestock density (herdsize per hectare) and on the supplementary feed provided per hectare. The sector's output is price responsive, nonetheless, in that we allow for substitution between the commodities entering the aggregate index. Labor use per unit $\bar{A}_j$ is fixed.

(iii) *Other land use types*, $j \in J_o$: these have fixed ε_{kj} input and output o_{kj} of various commodities *k* per unit $\bar{A}_j$; labor use per unit $\bar{A}_j$ is fixed as well:

```
Tree cropping
Draught animal system
Traditional mixed ruminant farm
```

```
Machine power
Household waste
Household manure
Green feed
Utilizable grass
```

These land use types supply or use local commodities only traded inside the own county, such as manure, crop residuals and animal power, in addition to the tradable commodities indexed *k*. Use of these local commodities follows fixed coefficients, bilaterally specified per unit of $\bar{A}_j$ in which *j* may refer either to the delivering or the receiving land use type (see section 5.7).

The exogenous capacities $\bar{A}_j$ play an important role in the model. In simulation, these capacities follow directly from scenario assumptions on resources that follow a slightly different classification *z*, also listed in Appendix B, which, however, is not essential for an understanding of the specification and operation of the supply module and is, therefore, not considered in the present section.

5.2 Separability

Revisiting the steps in Albersen et al. (2002), we further structure the transformation functions F_j that jointly make up the overall transformation function *F* in (4.6d). This overall function *F* can be constructed by maximizing the total output of, say, commodity 1, $q_1 = \sum_j q_{1j}$, for given total output $q_k = \sum_j q_{kj}, k \neq 1$ of other commodities, and total inputs $e_k = \sum_j e_{kj}$ of all commodities. Having established the connection between F_j and *F*, we further specify the functions F_j.

First, we impose separability between input and outputs:

$$F_j(q_{1j},...,q_{Kj},e_{1j},...,e_{Kj},L_j,\bar{A}_j) = H_j(q_{1j},...,q_{Kj}) - G_j(e_{1j},...,e_{Kj},L_j,\bar{A}_j). \tag{5.2}$$

With respect to the specification of the functions in (5.2) we assume, for the price responsive class as well as for grazing that the transformation functions satisfy:

Assumption TO (transformation function, outputs): Output function H_j is (i) strictly quasiconvex, convex; (ii) nondecreasing; and (iii) homogeneous of degree one.

Assumption TI (transformation function, inputs): Input function G_j is (i) concave; (ii) nondecreasing; and (iii) homogeneous of degree one, and (iv) strictly concave increasing in $(e_{1j},...,e_{Kj},L_j)$.

These separability assumptions make it possible to decompose program (5.1) into three parts, successively discussed in sections 5.3-5.5.

5.3 Optimal commodity basket: the revenue index

For the price responsive class and for grazing, homogeneity property TO.iii enables us to write the aggregate output value as the product of the aggregate quantity index Y_j and aggregate revenue index r_j, and to solve (5.1) in three parts, starting from the price or revenue index r_j :

$$
\begin{aligned}
& r_j(\breve{p})Y_j = max_{q_{kj}\geq 0} \textstyle\sum_k \breve{p}_k q_{kj} \\
& \quad subject\ \ to \\
& \qquad H_j(q_{1j},...,q_{Kj}) \leq Y_j .
\end{aligned}
\tag{5.3}
$$

For given aggregate output Y_j, by Gorman's rule (see e.g. Blackorby et al., 1978), we can derive the profit maximizing supply of the separate commodities as:

$$
q_{kj}(\breve{p},Y_j) = \frac{\partial r_j(\breve{p})}{\partial \breve{p}_k} Y_j . \tag{5.4}
$$

For each land use type we distinguish several activities indexed *h* and suppose that the revenue index expressed in the revenue of these activities is a *convex CES-function*:

$$
r_j(\breve{p}) = (\textstyle\sum_h a_{hj}(\breve{r}_{hj}(\breve{p}))^{\rho_j})^{\frac{1}{\rho_j}} , \tag{5.5}
$$

for $\rho_j > 1$, while gross revenue , $\breve{r}_{hj}(\breve{p}) = \sum_k max(B^j_{kh}\breve{p}_k, 0)$ from activity *h* in land use type *j* is non-negative. Recall from (4.6) that $\breve{p}_k$ could be negative because of processing but here we may assume free disposal of any negatively priced output *k* from activity *j*; here the matrix B^j transforms output commodity aggregates indexed *h* (e.g. milk cattle-meat cattle) into commodities (dairy, hides, meat), indexed *k*. The output price $\breve{p}_{ck}$ at county level is related to the market prices $p^{\bullet}_{rk}$ and p^{o}_{rk} of the corresponding region, according to price relationships (4.6a,b) from region to county.

Hence, for $j \in J_p$ and $j \in J_g$ the relation between aggregate output and commodities consists of two steps: a CES-type allocation from the aggregate output index to activity levels (commodity aggregates), with substitution elasticity $\rho_j - 1$, and fixed coefficients from activity levels to commodities. For the other land use types, $j \in J_o$, both steps are governed by fixed coefficients. For cropping the activities are defined in terms of crops that are subsequently processed into main products and byproducts, and for livestock in terms of animal types, also processed into main and by-products, according to a list given in appendix B.

5.4 Input demand per unit of aggregate output and profit per area/livestock unit

The revenue index (5.5) is scale-independent and mainly serves as an aggregator over commodities. Next, we turn to the demand for inputs associated to the aggregate output. In principle the only requirement is that the cost function of all purchased inputs for given yield $y_j = Y_j / A_j$, should be *convex non-decreasing* in y_j. However, to maintain a closed form solution we also take the cost function to be *piecewise linear in* y_j, which allows for an arbitrarily close approximation.

For simplicity of notation we also limit attention to a single purchased input, to be referred to as feed and purchased at the given price $p_j^f(\hat{p})$. In fact, the formulation applies to an arbitrary number of current inputs, complementary to y_j, and with fixed purchasing prices $\hat{p}_k$. The simplest way is to assume constant returns in input demand, by treating p_j^f as a concave differentiable unit cost function of input prices $\hat{p}$. In this case, the individual input demands at given y_j can be retrieved, by Hotelling's Lemma, via the derivative of the profit function. Specifically, the cost function defines the unit profit per unit of $\bar{A}_j$:

$$\tilde{\pi}_j(\breve{p},p_j^f,y_j)=r_j(\breve{p})y_j-c_j(p_j^f,y_j), \tag{5.6a}$$

for the piecewise linear cost function:

$$c_j(p_j^f,y_j)=min_{f_j\geq 0}\{p_j^f f_j \mid f_j\geq \eta_j^i y_j-\gamma_j^i, i=1,...,M\}. \tag{5.6b}$$

where the coefficients η_j^i and γ_j^i are the fixed coefficients; we only need to assume $\eta_j^1=0$, $\gamma_j^1=0$ (possibility of inaction), $\eta_j^i\geq 0$ (no free lunch), as the minimization will on this basis select the appropriate constraints on the boundary that lead to a piecewise linear cost function that is concave non-decreasing in prices, and convex non-decreasing in yield. However, to ease the calibration we actually specify the various segments by assuming that $\gamma_j^i>0$ and $\eta_j^i>0$ for $i=2,...,M$, while both the slope and the yield-intercepts are taken to rise with *i*: $\eta_j^i>\eta_j^{i-1}$ and $\frac{\gamma_j^i}{\eta_j^i}>\frac{\gamma_j^{i-1}}{\eta_j^{i-1}}, i=3,...,M$. These piecewise linear cost functions also define the input demand functions in commodity terms:

$$e_{kj}=\frac{\partial p_j^f(\hat{p})}{\partial \hat{p}_k}f_j. \tag{5.7}$$

It may be restrictive to assume a yield-independent composition of this purchased input but the chosen formulation has the advantage that it maintains continuity of the input demand curve. Nonetheless, extensions can be envisaged in which the input function p_j^f and its derivative to $\hat{p}$ depend on yield.

The intercept γ_j^i makes it possible to account for fixed or exogenous and free supply of the input as a given quantity (manure and natural soil fertility for crops, roughage and hey for ruminants, and household residuals for pork and poultry) and a switch point will occur once an additional input has to be purchased with rising output. This defines the indicator function:

$$i_j(y_j)=\{i\in\{1,...,M\} \mid \hat{y}_j^i\leq y_j\leq \hat{y}_j^{i+1}\}, \tag{5.8}$$

where $\hat{y}_j^1$ is the yield obtainable with zero feed and zero labor input beyond which labor will be required, $\hat{y}_j^2$ the yield with positive labor and zero feed beyond which feed will be required and , generally, beyond that $\hat{y}_j^{i+1}$ is the yield at the switch point between the branches i and $i+1$ Consequently, in between switching points the unit profit has a constant derivative w.r.t. y_j :
`

$$\pi_j^i = r_j(\breve{p}) - p_j^f \eta_j^i \tag{5.9}$$

5.5 Optimal labor allocation

The third and main step is to determine the aggregate yields y_j. In our model, these are actually yields per unit of capacity in land use type *j*, while capacity is measured in hectares and stable size depending on the type. We formulate a profit maximization model for the representative county farm, using a Mitscherlich-Baule (MB) yield function y_j, with given asymptote (yield potential) $\bar{y}_j$ and with labor as sole input equiped with animal and machine power. Land use types compete for labor. All other inputs are already dealt with as "feed" in (5.6): fertilizer and manure for crops and purchased or locally available animal feed for livestock. We use a Mitscherlich-Baule production function because it possesses, like the logistic curve, an asymptote that can accommodate information on the yield potential of each land-use type in every county.

Let A_j denote the capacity use, $\bar{A}_j$ its positive availability, both expressed in hectare or stable unit, hectare for short (land uses with $\bar{A}_j = 0$ are dropped from the outset) and ℓ_j the labor applied per hectare/stable unit (equipped with implements). However, since for the land use class grazing, the "harvesting labor" is essentially performed by the herds themselves the yield on grazing, with associated demand for supplementary feed, follows from the herdsize that is exogenously given. Moreover, the labor of herders cannot be considered substitutable for that of cropping activities because of the large distances involved. Hence, we only consider labor allocation between the price responsive sectors, noting that the specification for grazing allows, nonetheless, for price response of the commodity bundle on the output side, following (5.4).

Henceforth, this section only considers the price responsive sectors proper, $j \in J_p$. Labor is a local, non-tradable resource, and $\bar{L}$ is the fixed total labor available for these sectors. It is as the input feed f_j per hectare complementary to yield, but explicitly incorporates the yield potential. The profit maximizing labor allocation meets a land and labor constraint and is obtained from:

$$\Pi = max_{A_j, y_j \geq 0}\{ \sum_j \tilde{\pi}_j(\breve{p}, p_j^f, y_j) A_j \mid \sum_j A_j \ell_j(y_j) \leq \bar{L}, A_j \leq \bar{A}_j \}. \tag{5.10}$$

It remains to specify the labor requirement function $\ell_j(y_j)$. For this we use its inverse, the production functions $y_j(\ell_j)$. The yield potential $\bar{y}_j$ acts as an asymptote in the *Mitscherlich-Baule production function*:

$$y_j(\ell_j) = \bar{y}_j(1 - e^{\alpha_j - \beta_j \ell_j}), \tag{5.11}$$

where we assume that $\beta_j > 0$ as additional output requires additional labor. This function is increasing and therefore has a continuous inverse, in closed form. Clearly, $\ell_j(y_j)$ is convex increasing. If for some land use type, the net profit π_j remains positive for any y_j, all labor will be employed, and the marginal productivity or wage rate μ will be positive in the optimum. The sign of the intercept α_j is discussed in Assumption Y below. We remark that the zero-labor intercept $\hat{y}_j^1$ corresponds to $y_j(0) = \bar{y}_j(1 - e^{\alpha_j})$.

Assumption Y (first and second input regime): (i) output is positive with zero labor input: $\alpha_j < 0$; (ii) labor has positive marginal productivity; $\beta_j > 0$; (iii) no feed is required at the maximal yield attainable without labor: $\eta_j^1 = 0, \gamma_j^1 = 0, \gamma_j^2 \geq \eta_j^2 \bar{y}_j(1 - e^{\alpha_j})$.

These technical relationships are illustrated in Figure 1 below.

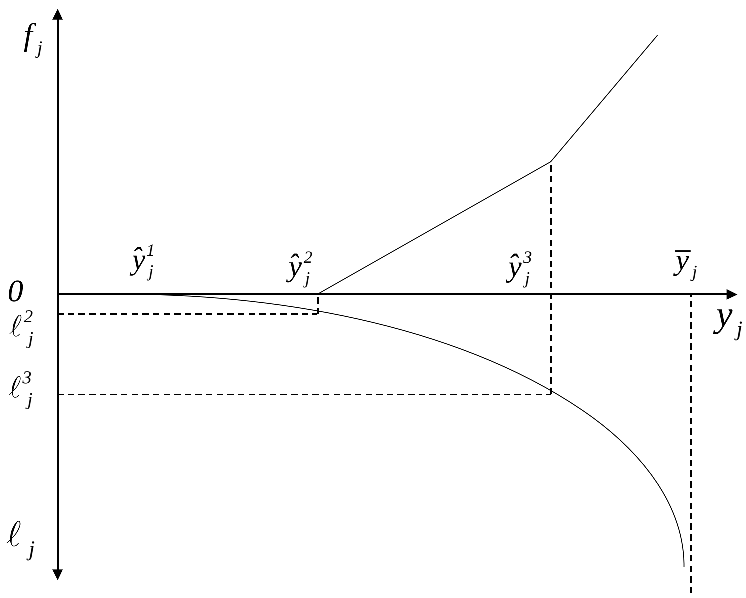

Figure 1. Technical relationships of land use type *j*

From Assumption Y follows that $A_j = \bar{A}_j$ is optimal, since production is possible without labor and feed, and the unit revenue $r_j(\breve{p})$ is non-negative by construction. Hence, program (5.10) reduces to the convex program:

$$\begin{aligned}
& max_{f_j,\ell_j,y_j \geq 0} \textstyle\sum_j (r_j(\breve{p}) y_j - p_j^f f_j) \bar{A}_j \\
& subject\ to \\
& f_j \bar{A}_j \geq (\eta_j^i y_j - \gamma_j^i) \bar{A}_j,\ i = 1,...,M \qquad (\theta_j^i) \\
& \textstyle\sum_j \ell_j \bar{A}_j \leq \bar{L} \qquad (\mu) \\
& y_j \bar{A}_j \leq \bar{y}_j (1 - e^{\alpha_j - \beta_j \ell_j}) \bar{A}_j
\end{aligned} \tag{5.12}$$

For positive μ, as labor will not be wasted the MB-restriction holds with equality. For zero μ, yields will for all j be at some threshold point $\hat{y}_j^i$, beyond which the marginal cost exceeds marginal revenue and not all available labor will be employed but the MB-restriction can be taken to hold with equality, nonetheless (if marginal cost happens to be equal to marginal revenue, inequality could be optimal as well). Hence, we have the first-order conditions:

$$
\begin{array}{llcl}
\text{(a)} & p_j^f \geq \sum_i \theta_j^i & \perp & f_j \geq 0 \\
\text{(b)} & f_j \geq (\eta_j^i y_j - \gamma_j^i) & \perp & \theta_j^i \geq 0 \\
\text{(c)} & \sum_j \bar{A}_j \ell_j \leq \bar{L} & \perp & \mu \geq 0 \\
\text{(d)} & \beta_j (r_j(\breve{p}) - \sum_i \theta_j^i \eta_j^i) \bar{y}_j e^{\alpha_j - \beta_j \ell_j} \leq \mu & \perp & \ell_j \geq 0
\end{array}
\qquad (5.13)
$$

with $y_j = \bar{y}_j (1 - e^{\alpha_j - \beta_j \ell_j})$.

Together conditions (a) and (b) determine the branch selected. In between switch points, we have, by (a) the equality $\theta_j^i = p_j^f$. By contrast, at a switch point between two branches, positive θ_j^i for two *i*-values can co-exist that sum to p_j^f. At such a point these values adjust on an interval of wage rates, so as to keep labor intensity fixed. Condition (d) shows that once the wage is given and the branch of the input function is known, the optimal labor demand follows for each land-use type separately. Moreover, every land use type has a wage-level of its own beyond which no labor is used and $\hat{y}_j^1$ prevails. These properties are used in the algorithm solving the farm model but for the algorithm computing the solution of the overall welfare model it also is important to establish continuity of farm supply and demand functions, as stated in the following proposition:

Proposition 2 (continuity of optimal labor allocation): If Assumption Y holds then program (5.10) defines continuous labor allocation functions $\ell_j(\breve{p}, p^f, \bar{L}, \bar{A})$, with associated to these, continuous yield functions $y_j(\breve{p}, p^f, \bar{L}, \bar{A})$ and input demand functions $f_j(\breve{p}, p^f, \bar{L}, \bar{A})$.

Proof. By strict concavity of the MB-functions, this program is strictly convex. Since it also is feasible and bounded, it solves uniquely for ℓ_j, and, therefore, by the Maximum Theorem, $\ell_j(\breve{p}, p_j^f, \bar{L}, \bar{A})$ is continuous. Then, continuity of the MB-function and the input functions ensures continuity of output and input demand functions. ■

Lastly, to prepare for the algorithm we note that (5.12) further reduces to:

$$
\begin{array}{l}
max_{\ell_j \geq 0} \sum_j \left[r_j(\breve{p}) \bar{y}_j (1 - e^{\alpha_j - \beta_j \ell_j}) - p_j^f \, max(max_i(\eta_j^i \bar{y}_j (1 - e^{\alpha_j - \beta_j \ell_j}) - \gamma_j^i), 0) \right] \bar{A}_j \\
subject \;\; to \\
\quad \sum_j \ell_j \bar{A}_j \leq \bar{L} \qquad\qquad (\mu)
\end{array}
\qquad (5.14)
$$

5.6 Exact solution

The exact solution is obtained by means of an algorithm with finite termination. As discussed earlier, we insist on this property because the outcome is to be used as a module within the algorithm solving the general equilibrium welfare program, and therefore, has to be evaluated often and with good precision. At the same time, the number of counties is large. An exact algorithm has the advantage that it tends to converge quickly, and, more importantly, with very high numerical precision.

The approach is to iterate over the wage rate μ while evaluating the excess demand for labor. The standard approach would be to adjust the wage rate in proportion to excess demand or straight bisection or following some Newton-Raphson rule. The latter would have to accommodate the non-differentiability of excess demand but more importantly, none of these techniques would offer finite termination. We obtain finite termination by exploiting the fact that, for given regimes *i* in every land use type *j*, the wage rate that balances supply and demand can be evaluated in closed form. Hence, once μ has reached sufficiently close to the optimum, this balancing value can be used and the procedure terminates.

To introduce this algorithm, we define for every land use type the wage rates at which regime switches occur, ranked in decreasing order:

$$\underline{\mu}_j^i = \beta_j \pi_j^i \bar{y}_j e^{\alpha_j - \beta_j \ell_j^i}, \; i = 1,...,M, \tag{5.15a}$$

$$\bar{\mu}_j^i = \beta_j \pi_j^{i-1} \bar{y}_j e^{\alpha_j - \beta_j \ell_j^i}, \; i = 2,...,M \;\; and \;\; \bar{\mu}_j^1 = \infty, \tag{5.15b}$$

with π_j^i defined as in (5.8), and where $\ell_j^i = \ell_j(\hat{y}_j^i)$ for $i = 2,...,M-1$, $\ell_j^1 = 0$ and $\ell_j^M > \frac{\bar{L}}{\bar{A}_j}$ the level with minimal wage, at which more than the available labor would have to be allocated, which, therefore, is never reached. Intermediate switch points occur at the labor intensities corresponding to the yield levels defined by the indicator function (5.8). Definitions (5.15) imply that $\underline{\mu}_j^{i+1} < \bar{\mu}_j^{i+1} < \underline{\mu}_j^i < \bar{\mu}_j^i$. Labor intensity is determined for all non-negative μ as the continuous function:

$$\ell_j(\mu) = \ell_j^i \;\; if \;\; \mu \in [\underline{\mu}_j^i, \bar{\mu}_j^i] \;\; and \tag{5.16a}$$

$$max\left(\frac{\alpha_j - ln\,\mu + ln(\beta_j \pi_j'(\mu)\bar{y}_j)}{\beta_j}, 0 \right) \;\; otherwise$$

where marginal profits (w.r.t. yield) obey:

$$\pi_j'(\mu) = \pi_j^i \;\; if \; \mu \in [\bar{\mu}_j^{i+1}, \underline{\mu}_j^i] \;\; and \; 0 \; otherwise. \tag{5.16b}$$

In other words, in (5.16a) labor intensity is constant at switching of the input demand functions and variable at points in between. In (5.16b), the marginal revenue with respect to yield is equal to the fixed value π_j^i on the given linear segment. The zero value attributed outside the segment is purely arbitrary and only serves as indicator to characterize values where marginal revenue is set-valued. This also defines the (non-differentiable) unit profit functions from (5.6a):

$$\pi_j(\mu)=r_j(\breve{p})y_j(\ell_j(\mu))-c_j(p_j^f,y_j(\ell_j(\mu)),\tag{5.17}$$

and enables us to specify the switch functions:

$$\delta_j(\mu)=1 \;\; if \;\; \pi_j^{'}(\mu)>0 \;\; and \;\; 0 \; otherwise,\tag{5.18a}$$
$$\kappa_j(\mu)=1-\delta_j(\mu).\tag{5.18b}$$

Figure 2 depicts the labor demand function $\ell_j(\mu)$ of land use *j*. The flat segments of this function correspond to $\kappa_j(\mu)=1$. The figure allows for the functions to intersect the vertical axis, at $\mu=0$. This supposes that the unit profit from this land use becomes negative beyond some yield.

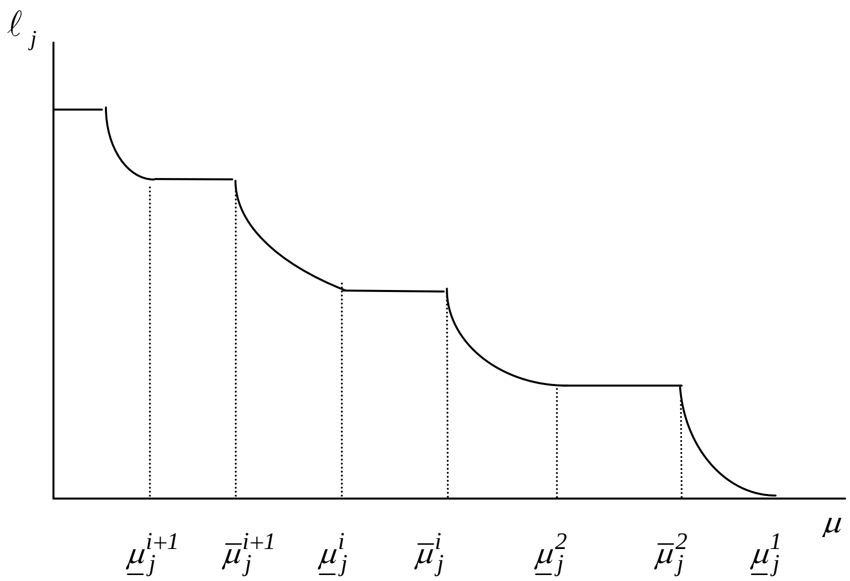

Figure 2. Labor intensity of land use type *j* as function of the wage rate

Now labor balance can, if it holds, be written:

$$\Sigma_j\kappa_j(\mu_t)\ell_j(\mu_t)\overline{A}_j+\Sigma_j\delta_j(\mu_t)\frac{(\alpha_j+ln(\beta_j\pi_j^{'}(\mu_t)\overline{y}_j)}{\beta_j}\overline{A}_j-ln(\mu_t)\Sigma_j\delta_j(\mu_t)\frac{\overline{A}_j}{\beta_j}=\overline{L}\tag{5.19}$$

from which a target value for μ_t can be obtained in closed form, at given regimes of the land use type.

On the basis of these functions, a bisection algorithm can be specified with iterations $t=1,2,...$, variable excess demand bounds initialized at $\underline{z}=-\overline{L}$, $\overline{z}=\overline{L}\sum_j\overline{A}_j/min_j\overline{A}_j$, variable wage bounds initialized at $\underline{\zeta} = max(min_j\, \overline{\mu}_j^M, 0)$, $\overline{\zeta} = \varepsilon_1 + max(max_j\, \underline{\mu}_j^1, 0)$, and some starting wage $\mu_t \in [\underline{\zeta}, \overline{\zeta}]$, say, in the middle of this interval. The algorithm proceeds as follows:

(i) Evaluate labor intensities (5.16) and excess demand

$$z_t = \sum_j \ell_j(\mu_t) A_j(\mu_t) - \overline{L}.$$

(ii) If $\underline{z} \le z_t < 0$ then

$\overline{\zeta} = \mu_t$

$\underline{z} = z_t$

else

if $0 \le z_t < \overline{z}$ then

$\underline{\zeta} = \mu_t$

$\overline{z} = z_t$

endif

endif.

(iii) Evaluate target value of market clearing wage rate:

if $\sum_j \delta_j(\mu_t) > 0$ then

$$\mu_{t+1}^o = exp\left(\frac{\sum_j \delta_j(\mu_t) \frac{\overline{A}_j}{\beta_j} \left(\alpha_j + ln(\beta_j \pi_j'(\mu_t) \overline{y}_j) \right) + \sum_j \kappa_j(\mu_t) \ell_j(\mu_t) \overline{A}_j - \overline{L}}{\sum_j \delta_j(\mu_t) \frac{\overline{A}_j}{\beta_j}} \right)$$

else

$z^o = \sum_j \kappa_j(\mu_t) \ell_j(\mu_t) \overline{A}_j - \overline{L}$

if $z^o \le 0$ then

$\mu_{t+1}^o = \underline{\zeta}$

else

$\mu_{t+1}^o = \overline{\zeta}$

endif

endif

(iv) If $\mu_{t+1}^o = \mu_t$ go to (vii).

(v) If $\underline{\zeta} \le \mu_{t+1}^o \le \overline{\zeta}$ then

$\mu_{t+1} = \mu_{t+1}^o$

else

$$\mu_{t+1} = \frac{\overline{\zeta} + \underline{\zeta}}{2}$$

endif.

(vi) $t := t + 1$,
go to (i).

(vii) End.

The excess demand function $z(\mu)$ is monotonically non-increasing, and flat on a segment only if all $\ell_j(\mu)$ are flat on that segment. In Figure 3 we give an illustration with two flat segments, one of them including $\mu = 0$.

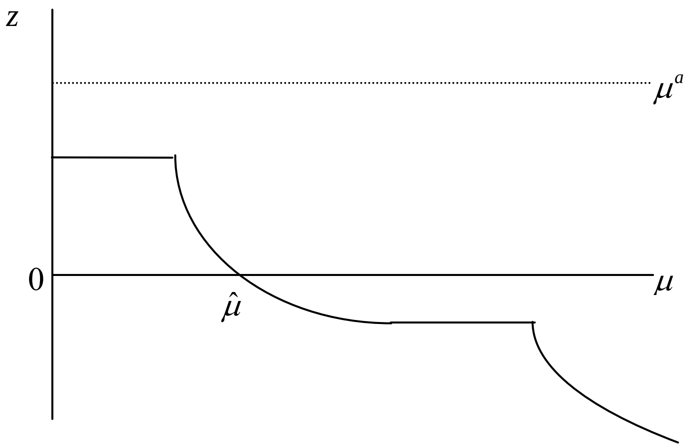

Figure 3. Excess labor demand as function of the wage rate

In the figure two possible solutions are indicated. If the horizontal axis is the solid line the equilibrium wage is $\hat{\mu}$, with excess demand equal to zero. Alternatively, if the horizontal axis is the dotted line μ^a, the excess demand function does not intersect the horizontal axis. In this case, the solution has excess supply and, hence, zero wage. Below we will prove convergence of the algorithm.

Proposition 3 (bisection): If Assumption Y holds then Procedure (i)-(vii) converges globally and in a finite number of iterations to the optimum of program (5.10).

Proof. Because of the monotonicity of $z(\mu)$, the gap $(\overline{\zeta}_t - \underline{\zeta}_t)$ is strictly reduced from one iteration to the next. Hence, the bisection converges globally, either to $\mu = 0$, in which case there is a labor surplus, or to $\mu > 0$, in which case the labor constraint clears. Moreover, at every iteration, step (iii) of the procedure defines an exact solution under an assumed configuration of market regimes. Since the number of regimes is finite, market imbalance will eventually be small enough to ensure that step (iii) yields an exact solution and convergence is achieved in a finite number of iterations. ■

5.7 Local deliveries of animal feeds and plant nutrients

So far, all deliveries of animal feeds and plant nutrients are taken to take place at prevailing market prices in the county. Hence, crop residuals used as feed are in the output matrix with elements B^{j}_{kh} expressed as animal feeds through conversion to usable calories, and manure from livestock to fertilizer equivalent, while accounting for various loss factors. Consequently, these are byproducts whose valuation follows the prices of the goods they compete with. Similarly, nightsoil may be valued as a fertilizer. All land use types supply such goods, generally for use by other land use types.

Yet, we must also account for the fact that these byproducts are only to a limited extent tradable among farmers, and hence remain available freely to the farmers as natural resources without alternative use. For crops, the natural fertility of the soil is usually treated in this way. Rather than being rewarded directly, it is a factor that raises the productivity of the land, and is rewarded via the land rent. Similarly, manure and feeds from household waste that are available locally can be represented through positive shifters σ^{f}_{j} on the intercepts γ^{i}_{j} of the feed and fertilizer demand curve. Starting from $i = 2$, the same shifters apply to all branches, implying that the piecewise linear curve is shifted but keeps its shape. For simplicity, we assume that these shifters depend on the areas cultivated and livestock numbers only. Hence the intercepts specified so far become variable, for $i = 2,...,M$:

$$\gamma^{i}_{j} = \breve{\gamma}^{i}_{j} + \sigma^{f}_{j}\ , \tag{5.20}$$

where $\breve{\gamma}^{i}_{j}$ are the estimated coefficients that are differentiated by region or agro-ecological zone, while the shifters are by county, treated as data in the estimation process and as variables in model simulation, and defined as:

$$\sigma^{f}_{j} = (\textstyle\sum_{j'} \bar{\sigma}^{f}_{j'j} \bar{A}_{j'}) / \bar{A}_{j}\ , \tag{5.21}$$

where $\bar{\sigma}^{f}_{j'j}$ is the supply coefficient of local manure or feed from land use j' to land use *j* per unit of the supplying land use j'. Combined, relationships (5.20) and (5.21) also suggest that the σ-coefficients should to the extent possible reflect marginal (as opposed to average) effects of changes in activity levels $\bar{A}_{j}$ on the supply of labor and feed and fertilizer substitutes, since for these non-priced goods average values do not play any role.

Similarly for animal and mechanical power that to some extent substitute for labor we introduce the shifter:

$$\alpha_{j} = \breve{\alpha}_{j} + \sigma^{\alpha}_{j} \tag{5.22a}$$

with

$$\sigma^{\alpha}_{j} = (\textstyle\sum_{j'} \bar{\sigma}^{\alpha}_{j'j} \bar{A}_{j'}) / \bar{A}_{j} \tag{5.22b}$$

where $\bar{\sigma}^{\alpha}_{j'j}$ is the supply coefficient of local power from land use j' to land use j, expressed per unit of j'.

Local supplies enter the production relationships in different ways. For local power, we assume that it increases the capacity of individual workers, since it consists of animal and mechanical traction. Hence, we adopt a multiplicative formulation to incorporate it within the Mitscherlich-Baule function that modifies to:

$$y_j = \bar{y}_j(1 - exp(\alpha_j - \beta_j \ell_j(\kappa_\alpha^1 + \sigma_j^\alpha)^{\kappa_\alpha^2}), \qquad (5.23)$$

where a positive intercept κ_α^1 is needed to ensure that labor without any implements remains productive, while the exponent κ_α^2 reflects the decreasing returns to traction with $0 < \kappa_\alpha^2 < 1$.

For feed-fertilizer the local inputs act as perfect substitutes as losses and alternative uses such as fuel are already accounted for in the calculation of the σ-coefficients, for $i = 2,..,M$:

$$f_j \geq max(-(\breve{\gamma}_j^i + \sigma_j^f) + \eta_j^i y_j, 0) \qquad (5.24)$$

Here the important point to note is that a high availability of local inputs will eliminate all purchases and tend to take the input demand in the first segment, with possibly unused surpluses of these inputs.

The coefficients $\bar{\sigma}_{j'j}^f$ and $\bar{\sigma}_{j'j}^\alpha$ cover four types of local feeds (straw and other crop residuals, grass, green fodder and household waste), two types of local fertilizer (animal manure and nightsoil) and two types of power (animal and mechanized traction). In the relations above, the land use types j refer to sets J_p and J_g. Inputs of local feed in land use types $j \in J_o$ are defined via coefficients similar to $\bar{\sigma}_{j'j}^f$, but this time expressed per capacity unit of the receiving land use type *j*.

The above relationships and their insertion in the farm model imply that the user values these inputs but does not reward the supplier. Yet, the calibration procedure to be formulated in the next section will allow for an additional payment justifying the level at which the activity is conducted, and reflecting an implicit reward for local byproducts.

5.8 Estimation and calibration

Data availability

For 1997, the model's base year, a comprehensive county level database has been compiled with the same coverage, the same classifications and the same commodity balances as the model. This cross-sectional data set is used to estimate and calibrate the supply module. No use is made of any time-series. The data set contains resources and output data at county level. Input use (labor, tradable commodities and local commodities) is also specified at county level, partly based on observed county data, partly constructed by combining provincial input-output coefficients with county balance requirements. Price observations are available at provincial level, and applied to all counties in the same province, albeit with adjustments that reflect the distinction between buying and selling counties. This data set and its derivation are described in Van Veen et al (2005).

Consequently, estimation and calibration can start from a complete database of resources, output volumes, input volumes and prices at county level. Below, we first describe the estimation of parameters of the output CES, the piecewise linear feed input curve and the Mitscherlich-Baule function. Next, the calibration procedure is discussed, for each of these three functions separately and for the profit maximizing farm module as a whole. In this process, all input and output coefficients specified per unit of $\bar{A}_j$ are calculated directly from the data set. Also the composition of the purchased aggregate feed input f_j is derived straightforwardly from the baseyear volumes, assuming fixed coefficients. These coefficients define at the same time the aggregate price p_j^f as a linear combination of input prices $\hat{p}$.

Estimation

The decomposition and availability of closed form solutions, much as in algorithm design, facilitate the estimation and calibration of this model, which also proceeds in the same order, starting from observed prices $(\breve{p},\hat{p})$. First, to estimate the parameter values (a,B,ρ) for the CES revenue function, identification requires taking the joint output matrix *B* as given (calculated from base year data), and then for assumed ρ the coefficients *a* can be calibrated in the way to be described shortly.

Second, for the piecewise linear input demand function, the coefficients (γ,η) can be estimated in various ways: (a) as linear approximation of a (parametrically or non-parametrically) estimated convex, differentiable cost function; (b) by non-parametric enveloping techniques; (c) by linear regression if we assume that the input demand function is linear; (d) jointly with the coefficients (α,β) of the Mitscherlisch-Baule yield function, in primal form; or (e) by estimating all first-order conditions jointly. However, for the data under consideration these approaches prove to yield wrong signs and implausible numerical values (not all options were tested but inspection of the data and preliminary regressions are sufficient to establish this). Furthermore, since the estimated values of the intercepts α and γ are to be overwritten by calibrated values anyway so as to account for fixed effects at county level, and goodness of fit is therefore not a concern, all emphasis can be placed on obtaining acceptable slope coefficients β and η.

For the input function, we apply a simple version of the method of moments, at $i=2$

$$\eta_j^i = \frac{\Sigma_c(f_{jc} + \sigma_{jc}^f)(1+\kappa_\eta)}{\Sigma_c y_{jc}}$$

for some given positive fraction κ_η, that, for n denoting the number of counties in the "regression", enforces a positive intercept on the yield axis, by letting the function pass through the data mean:

$$\begin{aligned}\gamma_j^i &= -\Sigma_c(f_{jc} + \sigma_{jc}^f)/n + \eta_j^i \Sigma_c y_{jc}/n \\ &= \kappa_\eta \Sigma_c(f_{jc} + \sigma_{jc}^f)/n\end{aligned}$$

These regressions are conducted at province level. Similarly, for the Mitscherlich-Baule function, we estimate:

$$\beta_j = -\frac{\sum_c ln(1 - y_{jc} / \bar{y}_{jc})(1 + \kappa_\alpha^0)}{\sum_c \ell_{jc}(\kappa_\alpha^1 + \sigma_{jc}^\alpha)^{\kappa_\alpha^2}}$$

for some given positive coefficients κ_α^0, κ_α^1 and κ_α^2 in the "regression", where κ_α^0 enforces a negative value for α_j by letting the function pass through the data mean:

$$\begin{aligned}\alpha_j &= \sum_c ln(1 - y_{jc} / \bar{y}_{jc}) / n + \beta_j \sum_c \ell_{jc}(\kappa_\alpha^1 + \sigma_{jc}^\alpha)^{\kappa_\alpha^2} / n \\ &= -\kappa_\alpha^0 \sum_c ln(1 - y_{jc} / \bar{y}_{jc}) / n\end{aligned}$$

keeping the intercept $\bar{y}_j(1 - e^{\alpha_j})$ on the yield axis positive.

Calibration of output CES-coefficients: solving for a_{hj} under assumed elasticities ρ_j

Dropping the county subscript, we recall from (5.5) that

$$r_j(\breve{p}) = (\sum_h a_{hj}(\breve{r}_{hj}(\breve{p}))^{\rho_j})^{\frac{1}{\rho_j}},$$

where $\breve{r}_{hj}(\breve{p}) = \sum_k max(B_{kh}^j \breve{p}_k, 0)$, and output prices at county level are obtained from the regional prices according to (4.6). Conversely, observed output by commodity *k*, denoted q_{kj}^o, relates to observed supply s_{hj}^o of commodity aggregates *h* according to:

$$q_{kj}^o = \sum_h B_{kh}^j s_{hj}^o,$$

which also defines the total revenue $R_j^o = \sum_h r_{hj}^o s_{hj}^o$, where r_{hj}^o is the observed $\breve{r}_{hj}(\breve{p})$. We treat the elasticity coefficients ρ_j as given. Calibration starts from the production side, with Shephard's lemma:

$$s_{hj}^o = a_{hj}(r_{hj}^o)^{\rho_j - 1} P_j^{1 - \rho_j} Q_j,$$

for $Q_j = y_j^o A_j^o$, where y_j^o is the observed yield (in the same units as $\bar{y}_j$) and A_j^o the observed activity level in the base year, while $P_j = R_j^o / Q_j$. The a_{hj}-coefficients follow directly from this equation. This also yields the aggregate unit value $r_j(\breve{p})$ for use in the calibration of the labor allocation module.

Calibration of allocation modules by land use type

The calibration of the allocation module of the agricultural supply model can be looked at as an inclusion of fixed (county-specific) effects in the earlier cross county regression that by its very nature is better suited for estimating the slopes β_j and η_j^i than the intercepts α_j and γ_j^i. We proceed as follows.

(1) *Labor balance*. We assume that for observed labor intensity ℓ_j^o and "area" $\bar{A}_j = A_j^o$, labor balance $\sum_j \ell_j^o \bar{A}_j = \bar{L}$ holds at county level (here labor supply $\bar{L}$ is net of fixed residual labor requirements by land use types J_g and J_o). All subsequent calibration is at county level on a per "hectare" basis for labor intensity ℓ_j^o, yields y_j^o and feed/fertilizer f_j^o and is independent of $\bar{A}_j$.

(2) *Mitscherlich-Baule*. The Mitscherlich-Baule (MB) slope-coefficients β_j estimated in the way described earlier are treated as fixed during calibration. For ease of notation, we write $\hat{\beta}_j = \beta_j(\kappa_\alpha^1 + \sigma_j^\alpha)^{\kappa_\alpha^2}$. For given asymptote $\bar{y}_j^o$, we calibrate the coefficient α_j of the MB-function to fit the observed yield $y_j^o < \bar{y}_j^o$ at the observed labor intensity ℓ_j^o. We test for satisfaction of the assumption $\alpha_j < 0$, and if necessary, for small positive ε, adjust the asymptote (upward):

$$\hat{\alpha}_j = \hat{\beta}_j \ell_j^o + ln(1 - y_j^o / \bar{y}_j)$$

$$\begin{aligned}
&if\ \hat{\alpha}_j < 0\ then \\
&\quad \alpha_j = \hat{\alpha}_j \\
&\quad \bar{y}_j = \bar{y}_j^o \\
&else \\
&\quad \alpha_j = -\varepsilon \\
&\quad \bar{y}_j = y_j^o / (1 - e^{(-\varepsilon - \hat{\beta}_j \ell_j^o)}) \\
&endif
\end{aligned}$$

This also gives the first yield-threshold:

$$\hat{y}_j^i = \bar{y}_j(1 - e^{\alpha_j}) \text{ for } i = 1.$$

(3) *Input functions*. Regarding feed/fertilizer input, we initialize on the segment $i_j^o = 2$ and suppose that the observed values f_j^o are positive for all *j* and that the (increasing) slopes of η_j^i from regression are known as well. For the observed feed/fertilizer input f_j^o at yield y_j^o, and recalling that $\eta_j^i = \gamma_j^i = 0$ for $i = 1$, we calculate the intercept of the non-horizontal segment of the feed demand curve, given the estimated slope η_j^2:

$$\gamma_j^2 = \eta_j^2 y_j^o - f_j^o.$$

This coefficient should be such that the yield γ_j^2 / η_j^2 corresponding to zero fertilizer demand is larger than that for zero labor. If this is not the case, we adjust this yield accordingly and draw the feed demand segment between the observed level and this new yield:

$$\tilde{y}_j^2 = \hat{y}_j^1 / (1-\varepsilon)$$
$$\eta_j^2 = f_j^o / (y_j^o - \tilde{y}_j^2)$$
$$\gamma_j^2 = \eta_j^2 \tilde{y}_j^2$$

It may be added that a final, upward correction is made in case γ_j^2 becomes too small relative to the local input σ_j^f . Finally, for the switch to the third regime we assume:

$\eta_j^3 = \eta_j^2(1+\kappa)$ with κ a positive value
$\hat{y}_j^3 = \bar{y}_j(1-\varepsilon)$
$\gamma_j^3 = (\eta_j^3 - \eta_j^2)\hat{y}_j^3 + \gamma_j^2$ (calculation in the switchpoint of the two branches)

(4) *First-order conditions.* After calibrating the physical relationships, we turn to first-order conditions. We specifically seek to ensure that, at the observed values of $r_j(\breve{p})$ and p_j^f , the farm allocation module reproduces for every $j \in J_p$ the observed labor input ℓ_j^o. From there will follow that aggregate yields y_j^o and feed-fertilizer inputs f_j^o with associated commodity demand e_{kj}^o are replicated, while the calibrated CES output functions will transform output aggregates $y_j^o \bar{A}_j$ into the observed activity volumes s_{hj}^o such that application of the B_{kh}^j-coefficients replicates the observed output volumes q_{kj}^o. Finally, since step (1) guarantees that total labor $\bar{L}$ is consistent with the observations, the key requirement is to ensure that, at the observed labor volumes, the marginal revenues of labor are equal across all land use types $j \in J_p$.

Therefore, we now focus on the first-order conditions with respect to labor. We denote by $\tilde{\eta}_j^o$ the slope of the observed branch of the feed-fertilizer relation (by construction either η_j^1 or η_j^2). To meet the first-order conditions, we adjust marginal revenues π_j^o for every j so as to equalize the marginal productivities of labor

$$\mu_j^o = \hat{\beta}_j \pi_j^o \bar{y}_j e^{\alpha_j - \hat{\beta}_j \ell_j^o} ,$$

across j, where $\pi_j^o = r_j(\breve{p}) - p_j^f \tilde{\eta}_j^o$. We might consider ensuring equality by reducing marginal costs. However, since some land use types may have low feed input this is not a practicable approach. Hence, we impute additional revenues to the land use types so as to ensure that all can earn sufficient marginal revenue to pay for the marginal costs of labour. To keep feed demand

f_j^o and yield y_j^o optimal at the observed level, we introduce an additional output of non-agricultural product, as follows.

We evaluate the highest marginal productivity of labor as:

$$\bar{\mu} = max_j(\mu_j^o, \underline{\mu})$$

where $\underline{\mu}$ is a given minimal wage. This defines the increment χ_j, interpreted as additional output of non-agriculture (per unit of aggregate yield y_j):

$$\chi_j = \frac{(\bar{\mu} - \mu_j^o)}{\breve{p}_n y_j^{'}(\ell_j^o)}$$

for marginal productivity $y_j^{'}(\ell_j^o) = \hat{\beta}_j \bar{y}_j e^{\alpha_j - \hat{\beta}_j \ell_j^o}$. Non-negative χ_j is needed to prevent the land use from becoming unprofitable at zero inputs in simulation. To keep net output of non-agriculture unchanged, a compensating input is defined via coefficients $\chi_j y_j^o$, expressed per unit of $\bar{A}_j$. Hence, since this input is kept independent from labor effort the increment χ_j can be used to equalize the marginal productivities of labor. Both χ_j and $\chi_j y_j^o$ are included as coefficients in the simulation model, the former per unit of y_j, the latter per unit of $\bar{A}_j$; hence, only for the base year they perfectly neutralize each other.

Dependencies in calibration

To illustrate the operation of this calibration procedure (1)-(4), we make the dependencies explicit, writing the parameter value after calibration as a function of the parameters and observations it depends on. This is helpful to indicate how regression estimates and observations affect the eventual parametrization.

In step (2) β_j is estimated from regression and not affected by calibration; $\bar{y}_j$ is a function of $(\beta_j, \ell_j^o, \bar{y}_j^o)$; α_j of $(\beta_j, \bar{y}_j, y_j^o)$; $\hat{y}_j^1$ of $(\alpha_j, \bar{y}_j)$; in step (3) η_j^2 and γ_j^2 are functions of $(\hat{\eta}_j^o, y_j^o, f_j^o, \hat{y}_j^1)$, among which $\hat{\eta}_j^0$ is estimated from regression; η_j^3 and γ_j^3 depend on η_j^2, γ_j^2 and $\bar{y}_j$.

Hence, it appears that parameters α_j and γ_j^2 are fully determined by calibration and therefore, do not have to be estimated by regression. This is also practical because these parameters are in fact resulting from a fixed part and a variable (endogenous) part that refers to local, non-marketed supply. Once α_j and γ_j^2 are obtained from calibration, accounting for the variable part gives the truly fixed part that acts as a coefficient in the model.

5.9 Application

The formulation of the agricultural supply program offers several advantages. While allowing for an exact solution, it incorporates information on agronomic potential, on labor availability, on production capacity, on local non-tradable resources. This design is especially tailored to the data availability for China. Yet, a disadvantage that deserves to be noted is that it does not incorporate information on crop-specific yields, and consequently, cannot accommodate land balances that would sum over several crops and crop-specific fertilizer responses.

The exact termination property improves the speed of the algorithm. More importantly, it makes it possible to embed the optimization within a larger model, as if it was a function in closed form. The function can be called very frequently, at low computational cost. In the Chinagro-model, this enables us to apply it in the national welfare program, solving a farm model for the 2433 counties, at given prices for $\breve{p}$, $\hat{p}$ for inputs and outputs, which are updated in a feedback on the basis of the Lagrange multipliers of a welfare program with transportation between eight regions that treats the production as given.

The formulation highlights the importance of the classification decisions, for example on whether agricultural production sectors should be considered as separate land use types, say with only one activity with an exogenous resource $\bar{A}_j$ and an input structure of its own, or as different activities within one land use type sharing a common resource and a common input structure. Substitution among land use types is effectuated via shifts in labor allocation induced by relative profitability.

Among activities of one land use type, the relative output values are the driving force of substitution, which depend on the prices of the tradable commodities in the model. As these commodities are treated as homogeneous, with prices differing across regions only due to trade and transportation costs and taxes, their classification is critical as well. For crops, Chinagro distinguishes eight commodities of which one (*maize*) is also used as feed.[6] In addition, the model distinguishes *carbohydrate feed*, with commodities rich in energy content and *protein feed*, with the protein-rich commodities. For livestock products, it distinguishes three types of meat as well as *milk*, and *eggs*. Hides and wool are considered as part of non-agriculture. Consequently, the output value of an activity generally depends on the price of a basket of commodities, such as *other* (i.e. non-cereals) *staple food*, *vegetable oil* and *protein feed* for *soybean growing*, and *ruminant meat*, *milk* and *non-agriculture* for *cattle raising*.

A final remark concerns the interpretation of the wage rates resulting from the model. In supply module (5.1), labor use covers all types of labor. A substantial part of these activities is performed by own labor of which the rate of remuneration is not directly observed and must be assessed via imputation, a difficult process due to the close ties between own labor and other resources such as land and herds. In general, one expects the wage rate in (5.1) to be higher than the wage rates reported in the agricultural cost-revenue surveys, for two reasons. One is that the farm's entrepreneurial activities may be more complex than the work commonly done by hired labor whose wages are reported in these surveys. The other, more important reason is that the calibrated wage reflects the labor immobility of the various land use types, and operates like a rent on the lower bounds resulting from this immobility. In fact, the actual return to labor is the marginal value of labor minus the value per unit of labor of the compensating input: $w = \mu - \sum_j \chi_j y_j^o \bar{A}_j / \bar{L}$. Indeed, the calibration procedure described in section 5.8 finds that the wage rates of different land use types agree well with wage statistics.

[6] The full list of tradable commodities is given in Appendix B.

6. Scenario design

Scenario simulation with the Chinagro-model proceeds by specifying exogenous variables of two types: trends and policy variables. Trends (or drivers) express predictions of variables not studied within the model about developments in China and abroad. Policy variables refer to assumptions on choices made by government. These exogenous variables enter the model in every year of simulation within the period 1997-2030 and generate endogenous supply, demand and prices in the various geographic units considered. When applicable, trends are specified by region or by province, not by individual county.

Actual implementation of the scenarios is based on several background studies conducted in the course of the Chinagro project. We mention Chen et al. (2002) and Hu et al. (2002) for technological and institutional aspects of the agricultural sector, Fischer et al. (2002), Li and Zhang (2002) and Lu et al. (2002) for agricultural land and its potential, Liu et al. (2003) and Toth et al. (2003) for demography and migration, and Huang et al. (2003) for regional development. Here we discuss the various elements of a scenario.

Price normalization. A first item to be discussed is price normalization. As was seen in welfare program (4.9), price normalization in the model depends on the shadow price ρ of the balance of payments, which is equal to the exogenous dollar-to-Yuan conversion rate, since we ensure that the adjusting non-agricultural consumption c_n remains positive. More precisely, domestic prices follow from the import and export prices, trade margins and tariffs via the first-order conditions of welfare program (4.9) with respect to m_{rk}^- and m_{rk}^+:

$$p_{rk} \le \rho \overline{p}_{rk}^+ + p_{rn}\zeta_{rk}^+ + \xi_{rk}^+ \qquad \text{with equality if } m_{rk}^+ > 0$$

$$p_{rk} \ge \rho \overline{p}_{rk}^- - p_{rn}\zeta_{rk}^- - \xi_{rk}^- \qquad \text{with equality if } m_{rk}^- > 0$$

where, in fact, the tariff wedges ξ_{rk}^+ and ξ_{rk}^- are obtained by multiplying the foreign prices with a tariff factor and by the dollar-to Yuan conversion rate. The scenarios conducted so far keep the non-agricultural foreign price (identical for import and export) equal to the base year level, and express the scenario trends of the agricultural foreign prices relative to this constant price. Thus, all domestic prices in the simulation outcomes are directly comparable to base year prices, provided that the dollar-to-Yuan conversion rate is kept constant in the scenario.

Demography and migration. Population scenarios are specified as growth factors by province, for urban and rural separately, that are applied uniformly to all counties within the same province. Together, they determine the regional population numbers n_{ir}^u and n_{ir}^v. During the period of simulation, population growth will tend to be larger in urban than in rural areas and widely different across regions, due to differences in fertility, mortality and especially migration flows. The migration component in the population trends is kept consistent with the assumptions about regional development that underlie the non-agricultural output trends below. All income classes i within one urban or rural region are taken to follow the same rate of population growth.

Income distribution. Income distribution follows endogenously from the assumed welfare weights α_{ir}^u and α_{ir}^v. Changes in these weights can be used to represent changes in policy emphasis, in particular redistribution of tax revenue in favor of particular groups.

Consumer preferences. The changes in consumptions patterns are captured by exogenously adjusting the marginal expenditure coefficients b^{u}_{irk} and b^{v}_{irk} of the linear expenditure systems over time.

Farm resources. Farm resources adjust according to the classification given in appendix B. For cropland and herds (other than grazing), this classification corresponds directly to the land use types, hence the resource trends are also the trends in land use capacities $\bar{A}_{cj}$. The same applies to green feed availability and installed machine power. For the other land use types, the resources follow a different classification and conversion factors are applied to obtain $\bar{A}_{cj}$. All resource trends are specified at provincial level and applied uniformly to all counties within the same province. Urbanization, industrialization, environmental policies and infrastructural works are the driving forces behind the assumptions on provincial availability of crop land, specified separately for irrigated land, rainfed land and orchards. Similar considerations lead to assumptions of provincial trends for the stable units of the six land use types that the model distinguishes with respect to livestock. Stable units are cast in terms of (standard) animal places of the relevant land use type. Grassland resources distinguish natural grassland and improved sown grassland. From these resources the capacities $\bar{A}_{cj}$ of land use types 'grazing' and 'harvested grass' are obtained. For household manure and household waste, the trends in capacities $\bar{A}_{cj}$ are obtained from the population projections. For farm labor $\bar{L}_{c}$, separate provincial assumptions are made, obviously related to the trend in rural population.

Technical coefficients in farming. The specification of the supply module offers several possibilities to implement assumptions on technical change in agriculture. For land use types $j \in J_p$, increases in labor productivity are represented as labor saving, i.e. as a factor of improvement on labor input ℓ_{cj} in the Mitscherlich-Baule function. For the other land use types labor productivity changes are implemented by reducing the fixed labor coefficients per hectare or stable unit. (Solow) neutral technical progress in land use types $j \in J_p$ and $j \in J_g$ is dealt with on the output side, as output increasing, by raising the coefficients a_{chj} of the CES-revenue index $r_{cj}(\breve{p}_c)$ in the same proportion for all activities h. Though not present in the current scenario specification increases in fertilizer or feed efficiency can be accounted for through shifts in coefficients and effects of climate change, land improvement or land degradation by changes in yield potential $\bar{y}_{cj}$. Other technical coefficients in the supply module are coefficients $\bar{\sigma}^{\alpha}_{cjj'}$ and $\bar{\sigma}^{f}_{cjj'}$ describing respectively the supply of machine and animal power and the supply of local feed and fertilizer per unit of capacity $\bar{A}_{cj}$, as well as coefficients B^{j}_{kh} containing commodity outputs k per unit of activity h in land use type j. Although largely of a technical nature, these coefficients incorporate also certain distributional assumptions, e.g. in $\bar{\sigma}^{\alpha}_{cjj'}$ about the allocation of power to rainfed and irrigated land, in $\bar{\sigma}^{f}_{cjj'}$ about the share of crop residuals that is used for feed, as opposed to fuel and other non-agricultural purposes, and in B^{j}_{kh} about the proportion of oilseeds that is directly available for consumption instead of being processed. All these coefficients could be shifted but restraint is advised on this, because these were determined either on the basis of extensive calculations outside the model or from base-year calibration only, in both cases making it difficult to isolate various components of technical progress.

Forestry and fisheries. Supply of forestry and fishery products is exogenous with fixed coefficients for commodity outputs and required intermediate inputs, at regional level, hence, not as part of the supply modules at county level. A scenario comprises assumptions on the regional trends in both supply volumes and input coefficients, together determining (part of) net endowments ω_{rk}^{u}.

Ouput non-agricultural sector. As in forestry and fisheries, manufacturing and services output enter exogenously, with fixed input coefficients, at regional level, leading to (the major part of) net regional endowments ω_{rk}^{u}. Here the scenario assumptions should also translate future changes of output composition and output quality into volume changes, possibly based on trends in expected price indices of sub-sectors. Another consequence of the heterogeneity of non-agriculture is that the scenario will have to express differences in expected price developments between chemical fertilizer and the aggregate non-agricultural commodity as an adjustment of the coefficients of the aggregate fertilizer price functions p_{cj}^{f}.

Investment and public consumption. With respect to final demand, scenario trends are specified for regional public consumption, regional investment and regional inventory changes, together summing to $\overline{g}_{rn}$. Since the Chinese economy is dominated by non-agricultural output, the exogenous supply and demand scenario assumptions must be checked a priori on their consistency with the assumptions about the country's trade deficit (discussed below), to avoid the situation that the compensating non-agricultural consumption volume c_n in the model drops to zero or becomes too large.

World prices. The scenario specifies the trends in agricultural import and export prices $\overline{p}_{rk}^{+}$ and $\overline{p}_{rk}^{-}$, reflecting future developments on the international markets. In fact, the same trend is applied to each region. As mentioned in connection with price normalization, the non-agricultural import and export price are kept constant at their base year level. This implies that available predictions on international agricultural price trends should be converted before use in Chinagro, since these trends are usually expressed relative to the unit value of international trade in manufacturing.

Trade deficit. The trend in the country's trade deficit $\overline{B}$ (in fact a surplus) consists of a general part and a specific part that captures increasing non-agricultural import costs to which China will be committed in order to realize the growth pace assumed in the scenario. This cost component must be taken into account since the model can, with its single non-agricultural commodity, not make a distinction between the composition of non-agricultural imports and non-agricultural exports. Regarding the exchange rate, we reiterate that the conversion rate from US dollar to Yuan transforms dollar prices into Yuan prices as a unit of account. Money merely serves as unit of account. The role of money as medium of exchange and as store of value is not accounted for in the model.

Tariffs and commodity taxes. Import tariff wedges ξ_{rk}^{+} cover applied tariffs, imputed non-tariff barriers and differences in value added tax compared to domestic supply. The scenarios specify trends for each of these three categories, without differences across regions. Similarly, scenarios for the export tariff wedges ξ_{rk}^{-} are built up from trends in imputed tariffs, rebates and subsidies. All scenarios run so far have in common that the wedges are gradually reduced or phased out. Furthermore, for a few commodities the model has exogenous (committed) subsidized exports $\underline{m}_{rk}^{-}$ in the base year, which are reduced or abolished in the course of the scenario-period. Farm tax policies are represented in the scenarios via national commodity-specific trends in tax rates that are applied in all counties to the agricultural producer taxes wedges ξ_{ck}^{q}. These trends may reflect phasing out of taxes (including the recent abolition of the agricultural tax) as well as the introduction of subsidies. Consumer tax rates are generally taken to rise as a reflection of the broadening of the value added tax-base.

Non-tariff barriers and transportation costs. The model does not distinguish separate taxes or non-tariff barriers on domestic trade flows. Existing wedges are subsumed in the regional trade and transport coefficients $\theta_{rr'k}, \tau_{rk}^{+}$ and τ_{rk}^{-} and in the county-specific coefficients $\breve{\kappa}_{ck}$ and $\widehat{\kappa}_{ck}$. Hence, scenario trend assumptions on these coefficients are required to represent improvements in the transportation system, increased competition among traders or reduction of tariff and non-tariff barriers.

This completes the description of the various exogenous model variables and coefficients that may figure as part of the specification of a scenario. We end by emphasizing once more that a good scenario is a coherent package of assumptions on trends and policies, against the background of prevailing international and technological trends. A mere combination of isolated assumptions on the variables listed above leads to a meaningless simulation exercise.

Appendix A: Global convergence of price adjustment process

This appendix describes the price adjustment process used as algorithm to solve the general equilibrium welfare model by decomposition into a supply and an exchange component and establish the convergence of the associated outer iterative price adjustment process. Starting point is welfare program (4.9), of which we initially only consider the exchange component, i.e. treat net county supply as given.

We rewrite this program in more compact form, for notational convenience. To ensure feasibility of the program and uniform boundedness of Lagrange multipliers (Slater' qualification), we allow for relaxation of the balance of payments constraint, i.e. for additional foreign loans B^+ at a cost κ assumed to be sufficiently high to keep the program bounded. This enables us to define the value or welfare function *U*, i.e. the maximal welfare obtainable from the given net availability of goods for final use $(d_1,...,d_C)$, as:

$$U(d) = \max_{v_{rr'}\geq 0; B^+, e_r^\circ, e_r^\bullet, m_r^-, m_r^+, q_r^\circ, q_r^\bullet, x_{ir}^u, x_{ir}^v \geq 0; z_r^-, z_r^+ \geq 0, c_n \geq 0, g_r} \sum_r \sum_i \alpha_{ir}^u n_{ir}^u u_{ir}^u(x_{ir}^u) + \sum_r \sum_i \alpha_{ir}^v n_{ir}^v u_{ir}^v(x_{ir}^v)$$
$$- \sum_r (\xi_r^{+\prime} m_r^+ + \xi_r^{-\prime} m_r^-) + \bar{p}_n c_n - \kappa B^+$$

subject to (A.1)

$$\sum_i x_{ir}^u n_{ir}^u + \sum_i x_{ir}^v n_{ir}^v + \sum_{r'} v_{rr'} + g_r \delta^n + m_r^- + e_r^\bullet + e_r^\circ$$
$$= \sum_{r'} \frac{1}{1+\rho_{r'}} v_{r'r} + m_r^+ + \omega_r^u + q_r^\bullet + \omega_r^\bullet + q_r^\circ + \omega_r^\circ \qquad (p_r)$$

$$g_r = \sum_{r'} \theta_{rr'}' v_{rr'} + \tau_r^{+\prime} z_r^+ + \tau_r^{-\prime} z_r^- + \zeta_r^{+\prime} m_r^+ + \zeta_r^{-\prime} m_r^- + \bar{g}_r + \eta_r c_n$$

$$\sum_r (\bar{p}_r^{+\prime} m_r^+ - \bar{p}_r^{-\prime} m_r^-) \leq \bar{B} + B^+$$

$$m_r^+ \leq \bar{m}_r^+$$

$$\underline{m}_r^- \leq m_r^- \leq \bar{m}_r^-$$

$$\Gamma_r \sum_i x_{ir}^v n_{ir}^v + e_r^\circ = q_r^\circ + \omega_r^\circ + z_r^+$$

$$(I - \Gamma_r) \sum_i x_{ir}^v n_{ir}^v + e_r^\bullet + z_r^- = q_r^\bullet + \omega_r^\bullet$$

$$q_r^\circ - e_r^\circ = \sum_{c \in C_r^\circ} d_c$$

$$q_r^\bullet - e_r^\bullet = \sum_{c \in C_r^\bullet} d_c$$

where the given net availability can be negative because of imports. The only simplification relative to (4.9) is that we have disregarded producer taxes ξ_c^q and county-specific processing margins $\breve{\kappa}_c$ and $\hat{\kappa}_c$. Considering these would require a separate treatment of inputs and outputs and unnecessarily burden the notation. Note that the physical possibility to import all commodities and the opportunity to borrow B^+ guarantee uniform boundedness of prices at all demand levels. Now the function *U* can be shown to be strictly concave increasing (Perturbation Theorem, see e.g. Ginsburgh and Keyzer, 2002). We define the index set $\bar{H}$ with elements *h* to specify the stacked vectors over all commodities, by region for urban supply, demand and prices, and by county for rural supply, demand and prices, Hence, q_h, ω_h and e_h denote the production, endowment and input demand of a commodity in some region or county and p_h the associated price. Then using $U(d)$ we can rewrite (4.9) in compact form as:

$$
\begin{aligned}
&\quad max_{e,q \geq 0,d}\, U(d) \\
&subject\ to \\
&\quad d + e \leq q + \omega \qquad\qquad (p) \\
&\quad F(q,e) \leq 0
\end{aligned}
\tag{A.2}
$$

where F is the transformation function of the whole economy, $F(q,e) = max_c F_c(q_c, e_c)$. In (4.5), (4.6), we have specified a decomposition, whereby the welfare program is solved at given levels of farm output and input, while production and input demand are obtained through the procedures of section 5, as exact functions of prices. Hence, the welfare model is solved for given levels of q and e, i.e. it is only concerned with the evaluation of the value function U, which is not available in closed form and possibly non-differentiable, and the Lagrange multipliers $\hat{p}$.

$$
\begin{aligned}
&\quad max_d\, U(d) \\
&subject\ to \\
&\quad d + e \leq q + \omega \qquad\qquad (\hat{p})
\end{aligned}
\tag{A.3}
$$

where as before the opportunity in (A.1) to borrow keeps the program feasible and the multipliers bounded. The output and input demand levels q_k, e_k are optimal in

$$
\begin{aligned}
&\Pi(\tilde{p}) = max_{e,q \geq 0}\, \tilde{p}'(q - e) \\
&\quad subject\ to \\
&\qquad F(q,e) \leq 0
\end{aligned}
\tag{A.4}
$$

and the welfare optimum is found when the e, q levels entering (A.3) agree with the values generated by (A.4), and equivalently, when the prices $\tilde{p}$ agree with $\hat{p}$ as generated by (A.3).

Before discussing the algorithm proper, we recall that in our single agent economy, any Walrasian tatonnement, i.e. proportionate adjustment in the direction of excess demand (total consumer demand by region using consumer's surplus maximization, minus total supply), would for a step-size small enough converge globally (see e.g. Arrow and Hahn, 1971). However, in practice this procedure has the drawback that it adjusts prices (in money per quantity unit) to quantity deficits (in quantity units). Hence, it necessarily imposes a conversion in dimension that creates scaling problems in the sense that the step size may have to be so small that the algorithm becomes too slow. The decomposition (A.3)-(A.4) avoids this conversion, because it derives the price adjustment from the Lagrange multipliers of the welfare program of the exchange component. This adjustment is expressed in money per quantity units, and proves to be effective indeed. The welfare program (A.3) is a standard convex program of tractable dimensions, that can in GAMS be solved by a regular call of (Minos) SOLVE routine. The supply component is also solved in GAMS but by tailor made coding of the supply algorithm in section 5.6, through parameter operations. To co-ordinate both parts we nest them within an outer loop, which is of concern here.

It remains to formulate the algorithm to adjust prices $\tilde{p}$ iteratively. Note that if we start from arbitrary non-negative prices $\tilde{p}$, solve (A.4) and feed the outcome into (A.3), then the resulting price gap between $\tilde{p}$ and $\hat{p}$ can be interpreted as a tax wedge ξ on net supply, and given this tax wedge, we can also obtain this initial solution by solving the tax-ridden welfare program, in which the tax on net supply appears as additional terms in the objective. The resulting modification of (A.2) reads:

$$
\begin{aligned}
&\tilde{W}(\xi) = \max_{e,q\geq 0,d} U(d) + \xi'(q-e) \\
&\quad \textit{subject to} \\
&\qquad d + e \leq q + \omega \qquad\qquad (\hat{p}) \\
&\qquad F(q,e) \leq 0
\end{aligned}
\qquad (A.5)
$$

while $\xi = \tilde{p} - \hat{p}$, and solves (A.3)-(A.4). We propose to reduce all elements of the tax wedge proportionately. Before turning to the proof we provide the basic intuition as to why this would work. Suppose that we apply proportionate reduction in (A.5), multiplying the vector of tax-coefficients by a common scalar factor λ. As shown in Ginsburgh and Keyzer (2002, propositions 1.11, 5.3, 5.5), this would never lead to a drop in U in (A.5) and actually generates an increase whenever $\xi'(q-e)$ changes under this perturbation. In fact, this property holds globally and irrespective of the sign of the functions. Since the tax might also be interpreted as referring to monopoly rents, this "flat reduction" generally suggests to implement across the board but possibly piecemeal, a reform agenda of improved competition and economic liberalization. However, in our scheme of calculations that operates on (A.3)-(A.4), rather than perturbing ξ we can only shift $\tilde{p}$. We must prove that, locally, a change in $\tilde{p}$ made so as to reduce all taxes proportionately for given $\hat{p}$, will never cause welfare to fall. This price adjustment rule amounts to adjusting $\tilde{p}^t$ according to the simple averaging process:

$$\tilde{p}^{t+1} = (1-\sigma)\,\tilde{p}^t + \sigma\,\hat{p}^{t+1}, t = 1,2,... \qquad (A.6)$$

where $\hat{p}^{t+1} = \hat{p}(\tilde{p}^t)$ is obtained from (A3) and (A.4) and for given $\tilde{p}^1$ and positive step size constant σ.

Proposition 4 (tax-reducing algorithm) *For positive σ small enough and less than unity process (A.6) converges globally to the optimum of welfare program (A.2).*

Proof. The proof consists of two parts. Part 1 establishes that the sequence of solutions to problems (A.3) and (A.4), jointly with the price adjustment rule (A.6) is well defined. Part 2 proves convergence.

Part 1. The implementability of the procedures for solving the sequence of national welfare and county specific farm programs was already established in (A.3) and (A.4). The important point to note is that the supply component can extract all the prices $\hat{p}$ it needs from the exchange component, since by the assumptions underlying (A.1) all goods are consumed in every region.

Specifically, the procedure generates for every given $\tilde{p}^t$, a price $\hat{p}^{t+1}$ that is single-valued, because the strict quasiconcavity of utility leads to a unique consumption for every group, collectively consuming all goods in positive quantities, and hence, by differentiability of the utility function, to a bounded and unique price equal to the welfare weighted marginal utility of consumption. Furthermore, for non-negative $\tilde{p}^t$ and $\hat{p}^{t+1}$, (A.6) produces a non-negative $\tilde{p}^{t+1}$.

Part 2. We note that substitution of (A.6) in (A.4) gives

$$max_{e,q\geq 0}\ \hat{p}'(q-e)+\lambda\xi'(q-e)$$
subject to
$$F(q,e)\leq 0$$

for $\lambda=1$ and $\hat{p}=\hat{p}(\tilde{p}^t)$ and $\xi=\tilde{p}^t-\hat{p}(\tilde{p}^t)$. Now for σ small enough, we can reduce λ to $\lambda=1-\sigma$. Then, by the same "flat reduction" argument mentioned earlier a small reduction in λ never leads to a reduction in $\hat{p}'(q-e)$. Hence, $\hat{p}'(q-e)$ is (globally) non-increasing in λ. Furthermore, by construction, locally, *U* is increasing in $\hat{p}'(q-e)$. Consequently, as welfare is bounded, U^t, $t=0,1,...$ is a non-decreasing Cauchy sequence and, therefore, converges to a point *U**, the global optimum of (A.2). By strict convexity of (A.2) this corresponds to a unique value d^*, and by differentiability of the utility functions to a unique price $\hat{p}^*$. Then, for σ small enough, in (A.6) $\tilde{p}^*$ converges to $\hat{p}^*$ as well. ■

We remark that the convergence to the global optimum of *U** is irrespective of the strictness of the convexity of (A.2), and the differentiability of the utility functions. Hence, under such less restrictive conditions the convergence of *U* rather than of $\tilde{p}^*$ should be used as testing criterion for terminating the iterations. A main point confirmed by the proof is that, unlike in say, gradient algorithms, it is very important in (A.6) to keep a common step size σ across commodities *k.*

Finally, we mention that some modification of the present decomposition algorithm would be required in case that some goods were only used as input in production, unless their exchange price is fixed, say, because it is determined by the foreign import or by the foreign export price.

Appendix B: Model classifications

This appendix summarizes the model classifications as presented in Van Veen et al. (2005)

```
  R Regions

    R1          North
    R2          Northeast
    R3          East
    R4          Central*
    R5          South
    R6          Southwest*
    R7          Plateau*
    R8          Northwest*

* regions without foreign trade


  PV            Provinces in regional order (first digit points to region)

    PV11         Beijing
    PV12         Tianjin
    PV13         Hebei
    PV14         Shanxi
    PV37         Shandong
    PV41         Henan
    PV21         Liaoning
    PV22         Jilin
    PV23         Heilongjiang
    PV31         Shanghai
    PV32         Jiangsu
    PV33         Zhejiang
    PV34         Anhui
    PV36         Jiangxi
    PV42         Hubei
    PV43         Hunan
    PV35         Fujian
    PV44         Guangdong
    PV45         Guangxi
    PV46         Hainan
    PV50         Chongqing
    PV51         Sichuan
    PV52         Guizhou
    PV53         Yunnan
    PV54         Tibet
    PV63         Qinghai
    PV15         Inner Mongolia
    PV61         Shaanxi
    PV62         Gansu
    PV64         Ningxia
    PV65         Xingjiang
```

I	Household classes and aggregates
RURLOW	Rural low income
RURMID	Rural middle income
RURHIGH	Rural high income
RURAL	Rural population
URBLOW	Urban low income
URBMID	Urban middle income
URBHIGH	Urban high income
URBAN	Urban population

C	County codes
CN110105*	"Chaoyang Qu "
CN110106	"Fengtai Qu "
...	
CN654326	"Jimunai Xian "
CN659001	"Shihezi Shi "

* first two digits Province code, last four digits county postal code (the full list of 2433 counties is available upon request)

J	Land use types cropping and livestock
IRRICROP	Irrigated cropping
RFEDCROP	Rainfed cropping
TREECROP	Tree cropping
DRAUGHTSYS	Draught animal system
GRAZINGSYS	Grazing system
TRADRUMIN	Trad.mixed ruminant farm
SPECDAIRY	Specialized dairy farm
TRADNORUM	Trad.mixed nonruminant farm
INTNORUM	Intensified nonruminant farm
MPOWERJ	Machine power
HHWASTEJ	Household waste
HHMANJ	Household manure
GREENFEEDJ	Green feed
GRASSJ	Utilizable grass
OTHERAGRJ	Fish and forestry

H	Supply activities
PADDY	Paddy
WHEATGRAIN	Wheat
MAIZEGRAIN	Maize
OTHERGRAIN	Minor grain crops
ROOTCROPS	Roots and tubers
SOYBEAN	Soybean
GROUNDNUT	Groundnuts
OILSEEDS	Oilseeds
SUGARCANE	Sugarcane
SUGARBEET	Sugarbeets
FRUITPROD	Fruits

VEGETPROD	Vegetables
COTTON	Cotton
OTHNONFOOD	Other nonfood crops
BUFFALOES	Buffaloes
DRCATTLE	Draught cattle
DRAUGHTNES	Other draught animals
MILKCATTLE	Milk cattle
MEATCATTLE	Meat cattle
OVINE	Sheep and goat
YAKS	Yaks
HOGS	Hogs
POULTRY	Poultry
MPOWERH	Machine power
HHWASTEH	Household waste
HHMANH	Household manure
GREENFEEDH	Greenfeed
GRASSH	Utilizable grass
FISHPROD	Fish
FORESTRY	Forest products
MANUFCONST	Industry and construction
SERVICES	Services

K Commodities with interregional trade

RICE	Milled rice (1000 Mt)
WHEAT	Wheat flour (1000 Mt)
MAIZE	Maize (1000 Mt)
OTHSTAPLE	Other staple food (1000 Mt)
VEGETOIL	Vegetable oil (1000 Mt)
SUGAR	Sugar (1000 Mt)
FRUIT	Fruits (1000 Mt)
VEGET	Vegetables (1000 Mt)
RUMINMEAT	Ruminant meat (1000 Mt)
PORK	Pork (1000 Mt)
POULTRYMT	Poultry meat (1000 Mt)
MILK	Milk (1000 Mt)
EGGS	Eggs (1000 Mt)
FISH	Fish (1000 Mt)
NONFOOD	Non-food excl feed (10 million Yuan-1997)
CHFEED	Carbohydratefeed (1000 Gcal)
PROTFEED	Protein feed (1000 Gcal)

ZLT Resources

IRRILAND	Irrigated crop land
RFEDLAND	Rainfed crop land
TREELAND	Tree crop land
GRASSNAT	Natural grass land
GRASSSOWN	Sown grass land
FOREST	Forests and bushes
BUILT	Built-up land incl. roads
WATERBODY	Inland water bodies
UNUSEDLAND	Unused land
ZDRAUGHT	Draught animals

ZGRAZING	Grazing ruminants
ZTRADRUM	Trad-mixed ruminants
ZSPECDAIRY	Specialized milk cattle
ZTRADNORUM	Trad-mixed nonruminants
ZINTNORUM	Intensive nonruminants
FARMLABOR	Farm labor force
AGMACH	Agricultural machine power
GRFDCAP	Greenfeed supply capacity
RURPOP	Rural population
URBPOP	Urban population

Appendix C: List of main symbols

Here, we list the main symbols of partial equilibrium program (2.1), welfare program (4.9) and supply program (5.1) with its components.

c	county index
h	index for farm activity
i	consumer group index
i	superscript line-segment fertilizer/feed demand
j	land use type index
k	commodity index
s	site index
u	superscript urban
v	superscript rural/village

a_{ir}^u, a_{ir}^v	constant of Cobb Douglas utility function of group i in region r (urban/rural)
a_{chj}	constant of activity *h* in CES output revenue index of land use type *j* in county *c*
b_{irk}^u, b_{irk}^v	exponent of Cobb Douglas utility function of group i in region r (urban/rural)
c_{cj}	unit cost function of land use type *j* in county *c*
c_n	additional non-agricultural consumption
e_{ck}	input demand of commodity *k* in farm supply in county c
e_{ckj}	input demand of commodity *k* in land use type j in county c
$e_{rk}^\bullet, e_{rk}^\circ$	input demand of commodity *k* in net selling/buying counties of region *r*
f_{cj}	fertilizer/feed input per hectare/stable unit of land use type *j* in county *c*
g_r	subset of demand for non-agriculture in region r
$\overline{g}_r$	exogenous demand for non-agriculture in region r
ℓ_{cj}	labor per hectare/stable unit of land use type *j* in county *c*
m_{rk}^-, m_{rk}^+	export, import of commodity *k* in region *r* to/from foreign market
$\overline{m}_{rk}^-, \overline{m}_{rk}^+$	quota on export, import of commodity *k* in region *r*
$\underline{m}_{rk}^-$	export commitments of commodity *k* in region *r*
n_{ir}^u, n_{ir}^v	population of group i in region r (urban/rural)
p_s	price at site s
p_{rk}	market price of commodity k in region r
$\overline{p}_n$	foreign price of non-agriculture
$\breve{p}_{ck}$	producer price of commodity *k* in county c
$\widehat{p}_{ck}$	input price of commodity *k* in county c
p_{cj}^f	feed/fertilizer price of land use type j in county c
$\overline{p}_{rk}^-, \overline{p}_{rk}^+$	export, import price of commodity *k* in region *r* to/from foreign market

q_{ck}	output of commodity *k* from farm supply in county c
q_{ckj}	output of commodity *k* from land use type j in county c
$q^{\bullet}_{rk}, q^{\circ}_{rk}$	output of commodity *k* from net selling/buying counties of region *r*
r_{cj}	gross revenue of land use type *j* in county *c*
$\breve{r}_{chj}$	gross revenue of activity *h* of land use type *j* in county *c*
u_s	money-metric utility function at site s
u^u_{ir}, u^v_{ir}	utility function of group *i* in region *r* (urban/rural)
$v_{ss'}$	flow from site *s* to s'
$v_{rr'k}$	flow of commodity *k* from region *r* to r'
x_s	consumption demand at site s
x^u_{irk}, x^v_{irk}	per caput consumer demand of commodity *k* by group *i* in region *r* (urban/rural)
$\bar{x}^u_{irk}, \bar{x}^v_{irk}$	committed per caput consumer demand in Cobb Douglas utility function
y_{cj}	yield land use type *j* in county *c*
$\bar{y}_{cj}$	yield potential of land use type *j* in county *c*
z^-_{rk}, z^+_{rk}	intra-regional transport flows of commodity *k* (from/to counties)

A_{cj}	land/stable use of land use type *j* in county *c*
$\bar{A}_{cj}$	available land/stable capacity of land use type *j* in county *c*
B^j_{kh}	output coefficient of commodity *k* in activity *h* of type *j* (specified by province)
$\bar{B}$	upper bound on trade deficit
C_r	index set of counties in region *r*
$C^{\bullet}_{rk}$	index set of counties in region *r* that are net sellers of commodity *k*
C°_{rk}	index set of counties in region *r* that are net buyers of commodity *k*
F_c	overall transformation function of agriculture in county *c*
F_{cj}	transformation function of land use type *j* in county *c*
G_{cj}	input function of land use type *j* in county *c*
H_{cj}	output function of land use type *j* in county *c*
J	index set of land use types
J_p, J_g, J_o	index set of price-responsive, grazing and other land use types, respectively
L_{cj}	labor use of land use type *j* in county *c*
$\bar{L}_c$	availability of farm labor in county *c*
T_s	transport cost function from *s* to its neighbors
Y_{cj}	output of land use type *j* in county *c*

$\alpha^{u}_{ir}, \alpha^{v}_{ir}$	welfare weight of group i in region r (urban/rural)
α_{cj}	intercept in Mitscherlich-Baule yield function of land use type *j* in county *c*
β_{j}	slope Mitscherlich-Baule yield function of land use type *j* (specified by province)
γ^{i}_{cj}	intercept of branch *i* of piecewise linear fertilizer/feed demand (type *j*, county *c*)
Γ_{rk}	share of net buying counties in rural consumption of commodity k in region r
$\zeta^{-}_{rk}, \zeta^{+}_{rk}$	input coefficient of transport of commodity *k* in region *r* to/from the foreign border
η^{i}_{cj}	slope of branch *i* of piecewise linear fertilizer/feed demand (type *j*, county *c*)
η_{r}	share of region r in additional consumption c_n
θ^{i}_{cj}	shadow price of branch *i* of piecewise linear fertilizer/feed demand (type *j*, county *c*)
$\theta_{rr'k}$	input coefficient of transport of commodity *k* from region r to r'
$\kappa^{1}_{\alpha}, \kappa^{2}_{\alpha}$	coefficients for the impact of labor equipment in the Mitscherlich-Baule
$\breve{\kappa}_{ck}$	composition coefficient for output of commodity *k* in county *c*
$\hat{\kappa}_{ck}$	composition coefficient for input of commodity *k* in county *c*
μ_{c}	Lagrange multiplier on labor in county *c*
$\xi^{-}_{rk}, \xi^{+}_{rk}$	tariff wedge on export, import of commodity *k* in region *r*
ξ^{q}_{ck}	producer tax on commodity *k* in county *c*
$\tilde{\pi}_{cj}$	unit profit function of land use type *j* in county *c*
ρ	shadow price balance of payments
ρ_{s}	physical loss factor at site *s*
ρ_{rk}	physical loss factor in transport of commodity *k* from region *r*
ρ_{j}	CES-output coefficient in revenue index of land use type *j* (specified by province)
σ^{f}_{cj}	local feed/fertilizer input per hectare/stable unit of land use type *j* in county *c*
σ^{α}_{cj}	local power input per hectare/stable unit of land use type *j* in county *c*
$\bar{\sigma}^{f}_{cjj'}$	supply coefficient of local feed/fertilizer from land use type *j* to j' in county *c*
$\bar{\sigma}^{\alpha}_{cjj'}$	supply coefficient of local power from land use type *j* to j' in county *c*
$\tau^{-}_{rk}, \tau^{+}_{rk}$	input requirements of intra-regional transport flows of commodity *k*
χ_{cj}	additional non-agricultural output per unit of y_{cj}, from calibration
ω_{s}	endowment at site *s*
ω_{ck}	endowment in county *c*
$\omega^{\bullet}_{rk}, \omega^{\circ}_{rk}$	endowment of commodity *k* in net selling/buying counties of region *r*
ω^{u}_{rk}	urban endowment of commodity *k* in region *r*

Appendix D: Job flow and directory structure

DOS-Jobs

The software distinguishes three tasks, each implemented by means of a DOS “.bat“ dialog file:

(1) **RUNSIM**	:	calibration and simulation steps (1)-(3) below
(2) **TABULATE**	:	tabulation of scenario and scenario comparison
(3) **MAPOUT**	:	produce geographic maps of simulation results

GAMS file groups (all files have extension .gms)

(1) **SUPCALIB:** *estimate and calibrate the agricultural supply component*

Declarations:	CNTSET	list of counties
	SETS	main sets
	PARAM97	base-year parameters
	PARAM	model input parameters
	PARAMLOC	local parameters used in calibration and simulation
Data:	EXCINP97	input exchange data ′97
	SUPINP97	input supply data ′97
Output:	SUPDAT	

(2) **EXCALIB:** *calibrate the exchange component*

Declarations:	CNTSET	list of counties
	SETS	main sets
	PARAM97	base-year parameters
	PARAM	model input parameters
	PARAMLOC	local parameters used in calibration and simulation
Data:	EXCINP97	input exchange data ′97
	SUPDAT	supply data as generated by SUPCALIB
Output:	EXCDAT	

(3) **CHINASIM**: *Chinagro-simulation over selected time period, and report writing*

Declarations:	CNTSET	list of counties
	SETS	main sets
	PARAM	model input parameters
	PARAMLOC	local parameters used in calibration and simulation
	PARAMSC	parameters of scenario specification
	TABFILEA4	parameters for report writing
	TABSPEC	specification of tables for printing

Data:	EXCDAT	exchange data as generated by EXCALIB
	SUPDAT	supply data as generated by SUPCALIB
	BASERUN	basic scenario input (directory WKINP)
Output:		
	BASERUN	basic scenario output (directory WKOUT)

The **TABULATE**-job can be used after completion of a simulation, to produce user defined subsets from tables as well as comparisons across scenarios.

Directory structure

Chinagro	: main directory
- **Dat**	: data files for 1997 and supply and exchange files from SUPCALIB and EXCALIB
- **Declarations**	: declarations of sets and variables
- **Library**	: GAMS-utilities
- **Makemap**	: make maps of China
- *Pict*	: gif-files with maps (output from **MAPOUT**-job)
- *SasDat*	: SAS-file with mask of regions/provinces/counties (input)
- *Sasjobs*	: SAS-jobs
- Macros	: SAS-utilities
- **Scenarios**	: Scenario input files
- **Src**	: GAMS source codes
- **Utscript**	: DOS executables (.bat)
- *Utdos*	: Fortran and DOS executables (.bat and .exe)
- **Wkinp**	: Binary GAMS-files from scenario simulation
- **Wkout**	: ASCII files with tabulations (**RUNSIM**-job: scenario by name, **TABULATE-**job: scenario by name or user-defined name of file, with extension .txt)
- **Wkrun**	: working directory with intermediate files

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The Centre for World Food Studies (Dutch acronym SOW-VU) is a research institute related to the Department of Economics and Econometrics of the Vrije Universiteit Amsterdam. It was established in 1977 and engages in quantitative analyses to support national and international policy formulation in the areas of food, agriculture and development cooperation.

SOW-VU's research is directed towards the theoretical and empirical assessment of the mechanisms which determine food production, food consumption and nutritional status. Its main activities concern the design and application of regional and national models which put special emphasis on the food and agricultural sector. An analysis of the behaviour and options of socio-economic groups, including their response to price and investment policies and to externally induced changes, can contribute to the evaluation of alternative development strategies.

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