Chapter 10
Planning Sustainable Agricultural Development Under Risks

G. Fischer, T. Ermolieva, and L. Sun

Abstract In this paper we show that explicit treatment of risks and uncertainties is an essential element in planning sustainable agricultural development. Introduction of risks and uncertainties in production models considerably alter strategies for achieving robust outcomes. We discuss stochastic models that may assist to derive optimal agricultural production allocation and expansion within environmental and health risk indicators. Approaches are illustrated with the example of spatially-explicit livestock production allocation in China to 2030.

10.1 Introduction

Global change, economic-demographic and urbanization growth, changing consumption preferences alter the structure of agricultural production systems. In particular, they promote industrial agriculture geared towards making use of economies of scale to produce the highest output at the lowest cost. Although intensification has shown many positive effects, there are significant disadvantages, risks, and costs involved. Undesirable impacts of intensification include environmental pollution, input-intensive mono-cropping, and the marginalization and decline of smallholder farms, causing abandonment of land and migration of rural population to cities. These are further exacerbated by various risks such as climate change and variability, natural catastrophes, market distortions and instabilities.

Alone environmental impacts and health hazards associated with intensive agricultural production have increased awareness and established the need to identify pathways towards sustainable agriculture.

This paper aims to show that adequate accounting and treatment of risks and uncertainties is a necessary condition for planning sustainable agricultural development. Naturally that considerations of risks may considerably alter production and consumption decisions. This fact is illustrated in Sect. 10.2 with a stylized model of

T. Ermolieva (✉), G. Fischer, and L. Sun
Institute for Applied Systems Analysis, Laxenburg, Austria
e-mail: ermol@iiasa.ac.at

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two agricultural producers characterized by different levels of efficiency and exposure to risks. The example captures, in a nutshell, the features of a geographically detailed and dynamic model for agricultural production planning under risks and uncertainties, as adopted for the analysis of livestock production development in China to 2030 [12, 14].

Now, a growing share of livestock products in China is coming from industrial and specialized enterprises associated with hazardous pollution of the atmosphere, water and soil resources, which becomes a critical environmental issue [17, 25]. Traditional livestock systems represented a natural farming cycle; livestock was kept on grass areas or in confined places close to farmland. Primary sources of feed were grass, feed from fodder crops and other crops, household wastes and crop residues. In these systems, livestock waste and manure were considered valuable sources of nutrients for crop production or for fuel. The manure was recycled efficiently, causing minimal environmental degradation and pollution. With the introduction of large-scale industrial livestock production, especially of pigs and poultry, this closed cycle is collapsing. Intensive livestock production enterprises are located close to meat markets, near urban areas, and in these locations there is much more livestock concentrated than land can support for proper manure recycling.

Geographical allocation of animals and the levels of intensification at which livestock is kept, differently affect the occurrences and spread of livestock diseases. In a sense, increasing specialization and intensification of livestock production is associated with newly emerging diseases (e.g., possibly SARS, avian flu) that can threaten human health.

Concentration of intensive livestock production is an important cause of environmental pollution and health hazards. When coinciding with intensive crop cultivation, the problem of pollution through excess nutrients from livestock operations is further exacerbated by imbalanced fertilizer application. Over-supply of nutrients may lead to toxic nitrate pollution in the water supply and may cause eutrophication of surface water. The trend is alarming and in some locations, without appropriate measures, it may turn irreversible. The analysis in [14] has shown that the development of China livestock production sector cannot just continue along past intensification trends. The goal of this paper is to discuss model-based approaches to guide decisions regarding the inevitable and significant future expansion of livestock production with respect to economic conditions at locations accounting for sustainability and risk indicators. Indicators of sustainability and risks are defined by various interdependent factors including the spatial distribution of people and incomes, the current levels of livestock production and intensification, and the conditions and current use of land resources. Combinations of these factors are used in proposed models to distinguish different locations by the degree of their risk exposure in order to achieve robust solutions.

In Sect. 10.3 we introduce a stochastic spatially explicit and dynamic simulation model used for planning livestock and crop production expansion coherently with projected demand increases to 2030. It allows for spatio-temporal and risk-adjusted analysis of production developments under alternative socio-economic, demographic, and technological scenarios. This allows to address not only environmental and social concerns, but also investigate innovative policies offering new viable opportunities to farmers, agricultural workers, consumers, and markets. The approach has also been discussed in [13] with alternative scenario settings.

The meaningful specification of risk indicators and constraints to define alternative allocation scenarios is often constrained by the paucity of data at required resolutions. In this case, specific downscaling (disaggregating) and upscaling (aggregating) procedures [11] provide a tool for estimation of dependencies between the geographical factors, constraints, and economic-environmental policy responses. In Sect. 10.3 we analyze the main features of these procedures for spatial production allocation with respect to risks and suitability constraints in locations. Section 10.4 introduces a new stochastic optimization approach for planning production allocation when some of the risks in the model of Sect. 10.3 are explicitly taken into account by stochastic scenarios. In fact, the Sect. 10.3 and Sect. 10.4 distinguish two types of uncertainties: endogenous uncertainties associated with behavioral principles regarding production expansion and exogenous uncertainties associated with parameters of models. Section 10.5 describes alternative allocation scenarios and presents selected numerical results. Section 10.6 concludes and indicates directions for future work.

10.2 Cooperation and Co-existence for Risk Sharing

Over the last 20 years, China's demand and production of livestock products has increased remarkably due to rapid development of the national economy, urbanization, rising living standards, and population growth [5]. Increasing incomes and changing consumption preferences have boosted production and have shifted the composition of producers towards specialized enterprises with a number of advantages: they are more feed efficient and profitable, flexible in terms of management, may better adjust and comply to legislation, and, in general benefit from economies of scale. In a sense, these trends follow the Ricardo's assertion [24] that trading nations gain from production specialization and intensification. Accordingly, we may expect that production should be undertaken by the most efficient agent, with intensified production on large farms. This is true only under idealized conditions when risks are not accounted for.

In reality, agricultural production facilities may be exposed to various risks, but also may cause different negative impacts. Depending on the location and intensity, values of the facilities are interdependent subject to contingencies, and are determined endogenously. For this reason, of particular interest are production chains with large and small units to stabilize the aggregate production. Contrary to Ricardo, the less efficient and intensive producer may provide the supply of production and enhance market stability, say, if the producer's risks are different and weakly or even negatively correlated with others. Such diversification of producers by scale and location hedges against economic and environmental risks, improves welfare and ensures continuous supply of agricultural products to markets. Explicit accounting of risks may considerably alter the composition of production units and their intensification levels in a chain.

Let us illustrate this with a stylized model of only two producers, $i = 1, 2$, which in Sect. 10.4 will be extended to a multi-producer case. Let x_i denote the production level of i-th producer and assume that only one good is produced, e.g., meat; c_i is the cost per unit of produce. The product can also be imported from an external source with price b per unit of produce. Assume $c_1 < c_2 < b$, i.e., the cheapest source is the first producer. The production has to satisfy the exogenous inelastic demand d of a given region.

In the *absence of risks*, the model is formulated as the minimization of the total cost function:

$$c_1 x_1 + c_2 x_2 \tag{10.1}$$

subject to

$$\begin{aligned} x_1 + x_2 &= d, \\ x_1 \geq 0, x_2 &\geq 0, \end{aligned} \tag{10.2}$$

where x_1, x_2 are production capacities. The optimal solution to the problem is $x_1^* = d, x_2^* = 0$, i.e., the production is undertaken by the more efficient producer, which accords with Ricardo's views.

In case of *risk exposure*, the endogenous supply (10.2) is expressed, for example, as a linear function

$$a_1 x_1 + a_2 x_2 = d, \tag{10.3}$$

where a_1, a_2 are contingencies or "supply" shocks to x_1, x_2, e.g., due to outbreaks of diseases, weather risks, or other hazardous events. We assume that a_1, a_2 are random variables $0 \leq a_i \leq 1$, which may reduce the supply from $i = 1, 2$. If endogenous supply $a_1 x_1 + a_2 x_2$ falls short of demand d, the residual amount $d - a_1 x_1 - a_2 x_2$ must be obtained from external sources at unit import cost b. The planning of production capacities x_1, x_2 can be evaluated from the minimization of total production costs and potential import cost, i.e., the minimization of the function

$$F(x) = c_1 x_1 + c_2 x_2 + bE \max\{0, d - a_1 x_1 - a_2 x_2\},$$

where $x_1 \geq 0$, $x_2 \geq 0$ and the expected import cost when the demand d exceeds the supply $a_1 x_1 + a_2 x_2$ is $bE \max\{0, d - a_1 x_1 - a_2 x_2\}$. In this case, the role of a less efficient producer for stabilizing supply is clearly visible.

Assume that only the efficient producer is at risk, that is $a_2 = 1$. Let function $F(x)$ have continuous derivatives, e.g., the cumulative distribution function of a_1 has a continuous density function. It is easy to see that the optimal positive decisions $x_1^* > 0, x_2^* > 0$ exist in the case when partial derivatives meet $F_{x_1}(0, 0) < 0$, $F_{x_2}(0, 0) < 0$. We have $F_{x_1}(0, 0) = c_1 - bEa_1$, $F_{x_2}(0, 0) = c_2 - b$ and, perhaps counter intuitively, the less efficient, but without risks producer 2 is active unconditionally (since $c_2 - b < 0$). The cost efficient producer 1 is inactive in the case $c_1 - bEa_1 \geq 0$, leaving production entirely to the higher-cost producer 2. Only in the case $c_1 - bEa_1 < 0$ both producers are active. Hence, in this example the less cost-efficient producer is able to stabilize the aggregate production in the presence of contingencies affecting the more cost-effective producer 1.

To derive the market share of the producer 2, take the derivative

$$F_{x_2}(x, x_2) = c_2 - bP[d > a_1 x + x_2]$$

according to optimality conditions of stochastic minimax problems [8]. This means that the optimal production level $x_2^* > 0$ of producer 2 is a quantile defined by the equation $P[d > a_1 x_1^* + x_2^*] = c_2/b$, assuming $x_1^* > 0$ (otherwise $x_2^* = d$). It also depends on x_1^* and all conditions ensuring a positive share x_1^* of producer 1. Although not at risk ($a_2 = 1$), the optimal production level of producer 2 is defined by (10.3) through interdependencies among producers participating in the same market with demand d. Let us now consider the case when both producers are at risks, i.e., $a_1 \neq 1$, $a_2 \neq 1$. The existence of optimal positive production of both producers follows from similar equations

$$F_{x_1}(0, 0) = c_1 - bEa_1 < 0,$$

$$F_{x_2}(0, 0) = c_2 - bEa_2 < 0.$$

The structure of optimal solution is similar to the case when only one producer is at risk. In particular, there may be a situation where $c_2 - bEa_2 \geq 0$, when producer 2 is inactive, but the cost effective producer 1 is active now with the insurance provided by the external source (import or borrowing).

Apart from exogenous risks, the production and the market are subject to endogenous risks dependent on the level of x_1, x_2. Negative impacts of production increase and intensification cause contamination of water, soil, air in the densely populated areas, which may incur uncertain, possibly highly non-linear costs, increasing with increasing x_1, x_2. In this case, the cooperation and market sharing may be unconditionally advantageous, as the following case illustrates.

Let us now consider a case when costs are increasing non-linear functions, for the sake of simplicity, *quadratic*, $c_1 x_1^2 + c_2 x_2^2$, $c_1 < c_2$, and there are no production distortions, i.e., $a_1 = a_2 = 1$. The problem is to minimize

$$c_1 x_1^2 + c_2 x_2^2$$

subject to the demand-supply constraints

$$x_1 + x_2 = d, x_1 \geq 0, x_2 \geq 0.$$

At least one producer must be active, say producer 1. It is easy to see from the standard optimality condition that the optimal level is $x_1^* = \frac{c_1}{c_1 + c_2} d$. Therefore, the optimal level for producer 2 is $x_2^* = \frac{c_2}{c_1 + c_2} d$. In other words, both $x_1^* > 0$, $x_2^* > 0$, i.e., unconditional on the cost effectiveness of the producer 1, the increasing non-linear production costs require co-existence and cooperation of both producers. These examples emphasize that market shares are to a larger extent determined by the production costs, the import price, and the contingencies of producers. In fact, the less efficient but with lower risk, producer will likely have a higher share than a more efficient, but with higher risk exposure, producer. For the sake of simplicity, in the above examples the contingencies are characterized by a probability distribution. In reality, the contingencies, e.g., livestock diseases, environmental pollution, demand fluctuations, economic instabilities, have complex geographical and temporal patterns of occurrences, are subject to spatial interactions. Their mutual probability distribution functions may not be analytically tractable and thus require stochastic simulation models as presented in Sect. 10.3 and downscaling procedures allowing for estimation of required values based on all available auxiliary statistics and model-derived results. Risk exposures are often characterized by certain standards commonly imposed as additional safety constraints on admissible values of some indicators, e.g., constraints on ambient standards in the pollution control.

10.3 Agricultural Planning Under Risks

10.3.1 A Simulation Model

The stochastic and dynamic livestock and crop production model developed by the Land Use Change and Agriculture (LUC) program at the International Institute for Applied Systems Analysis (IIASA) [10,12] integrates demographic, economic, agricultural and environmental modeling components. The IIASA model is essentially an accounting GIS-based model, which allows to incorporate inherent processes in an endogenized manner.

The model is developed with the aim to assist in planning sustainable agricultural developments combining various national, subnational and regional interacting agricultural activities, production, processing, consumers. Together with reasonable scales of biophysical modeling, this allows for production planning within limited resources and possibilities to improve or recover production potentials, against uncertainties of weather, climate change, market situation or other risks such as the contamination of land or pasture. Simplicity of model's structure enables to incorporate individual and collective risks combined with proper equity, fairness and safety constrains, which leads to welfare generating policies. Contrary to traditional linear programming [2] and general equilibrium approaches [19], the model allows to deal with economies of scales, time dynamics and increasing returns. This phenomenon is typical for practical problems of production and resource allocation, however the discussion of these topics is beyond the scope of the paper. In contrast to general equilibrium and standard growth theory, the proposed risk-adjusted approach permits to deal with issues involving externalities, inherent uncertainties, non-monetary values such as environmental degradation, non-marketable risks of high consequences, social heterogeneities regarding various representative agents.

Allocation of production facilities have to reasonably confirm to the distribution of current and future consumers including evaluation of the option make-vs.-buy typically addressed in spatial production planning models [15, 18, 20]. This implies the analysis of main production and demand driving forces such as population growth, urbanizations, energy provision, infrastructure, markets and market access. The discussed model can easily address regional "behavioral" aspects of production planning if these are determined by criteria other than pure cost-benefit or risks analysis. For example, rebalancing production allocation procedure in Sect. 10.3.3 allows to account for heterogeneous cultural traditions, complex interactions of behavioral, socio-economic, cultural and technological factors [7, 26], or specific fairness and equity considerations [23].

Within a project on "Policy Decision Support for Sustainable Adaptation of China's Agriculture to Globalization" (CHINAGRO [17]), the model included specifics of China agricultural developments and has been applied for the spatial analysis of future livestock sector expansions. Using alternative economic and demographic projections [4, 16, 17, 21, 22], the model estimates per capita demand increases and consumption of major agricultural products, e.g., cereals, meat, milk, etc. Demand patterns differ between urban and rural areas, between geographical regions, and vary with income. Thus, with increasing incomes higher quality low-fat meat, e.g., poultry is preferred. In fact, evolution of consumption is modeled as a function of group-specific per capita income increases by applying income elasticities and distinguishing urban and rural consumers.

Agricultural supply is represented at county level, i.e., for about 2,430 spatial units. Smallholders and specialized livestock farms adjust the livestock herd structure and production in response to the demand increase and the changes of consumption patterns. The model distinguishes the following livestock types: poultry, pigs, dairy, cattle, buffaloes, yaks, sheep and goats, and other large animals (combining horses, donkeys, and camels). To examine the current situation and the production intensification trends, modeling of livestock production considers three management systems: traditional, specialized/industrial, and grazing.

In the environmental module, the environmental loads caused by intensive crop and livestock production are evaluated against admissible environmental and health thresholds (which can be proposed by stakeholders and environmental experts). Indicators used for measuring environmental impacts and human health risk are: the density of livestock, nutrients from manure and chemical fertilizers in excess of a location's nutrient uptake by crop production, urbanization share, density of population, and others. Combinations of these and other factors (see Sect. 10.5) reflect different degrees of socio-economic and environmental risk exposures and can be used to guide sustainable production allocation. The model simulates different paths of demand increase, which induces respective location-specific production adjustments. In some locations, the environmental and health risk indicators may already exceed admissible thresholds, which signals that further production growth in these locations should not take place. This raises the question of how to adjust the composition and allocation of livestock production facilities in response to increasing demand but without exacerbating environmental and health problems. The detailed description of the model and the allocation procedure [12] is rather lengthy. Therefore, in the following we provide only rather aggregate representation of their main constraints.

10.3.2 A Simplified Production Model

When planning livestock development, the objective is to allocate the foreseeable increases of demand for livestock products among the locations and the main production systems in the best possible way while accounting for various risks. In the following model the risks are treated as constraints restricting production expansion. In Sect. 10.4 we introduce a stochastic model that allows to account for risks and uncertainties in a more explicit manner.

Denote the expected national demand increase (to be satisfied by supply increase) in livestock product i by d_i, $i = \overline{1,m}$. Let x_{ijl} be the unknown supply increase in product i at location j and by management system l. In its simplest form, the problem is to find x_{ijl} satisfying the following system of equations:

$$\sum_{l,j} x_{ijl} = d_i, \tag{10.4}$$

$$x_{ijl} \geq 0 \tag{10.5}$$

$$\sum_{i} x_{ijl} \leq b_{jl}, l = \overline{1,L}, j = \overline{1,n}, i = \overline{1,m}, \tag{10.6}$$

where b_{jl} are thresholds aggregating environmental and health risks and imposing limitations to expand production in system l and location j. Equation (10.6) restricts prevalence of specific production systems. For example, the dominance of industrial systems in a location inevitably leads to intensification of feeding operations, the need in recycling facilities, etc. For simplicity of presentation, the constraint (10.6) captures only production side. Apart from b_{jl}, there may be additional limits on x_{ijl}, $x_{ijl} \leq r_{ijl}$, which can be associated with legislation, for example, to restrict production within a production belt, or to exclude from urban or protected areas, etc. Thresholds b_{jl} and r_{ijl} may either indicate that livestock in excess of these values is strictly prohibited or it incurs penalties such as taxes or premiums, for mitigation of the risks, say, livestock disease outbreaks or environmental pollution. Equations (10.4)–(10.6) belong to the type of transportation problems. However, there may be more general constraints of type $\sum_{ij} a_{ijl} x_{ijl} \leq d_i$ as in Sect. 10.2, $0 \leq a_{ijl} \leq 1$, which require extensions of the proposed approach.

In general, there exist infinitely many solutions of (10.4)–(10.6). The aim is to derive a solution that ensures appropriate balance between the efficiency and the risks. We can distinguish two sources of uncertainties generating potential risks: behavioral or endogenous uncertainties associated with allocation of new production capacities and exogenous uncertainties related to parameters of the model. In this section we consider only the first type of uncertainties. Section 10.4 addresses the second type of constraints.

The information on the current production facilities, threshold values b_{jl}, r_{ijl}, and costs are used to derive a prior probability q_{ijl} reflecting our belief that a unit of demand d_i should be allocated to management system l in location j. The use of priors is consistent with spatial economic theory (see discussion, e.g., in [7, 20, 26]). The likelihood q_{ijl} can be inversely proportional to production costs and inherent risks r_{ijl} [6, 7]. In Sect. 10.3.3 we show how it is used in a rebalancing procedure to determine the solution of (10.4)–(10.6) relying on behavioral, in a sense, risk-averse and cost-minimizing principles defined by this prior as in (10.10).

10.3.3 A Rebalancing Production–Allocation Algorithm

For simplicity of exposition, let us renumerate all pairs (l, j), $l = \overline{1, L}$, $j = \overline{1, n}$ by $k = \overline{1, K}$. In this new notation, the problem is formulated as finding y_{ik} satisfying constraints:

$$\sum_k y_{ik} = d_i \tag{10.7}$$

$$y_{ik} \geq 0, \tag{10.8}$$

$$\sum_k y_{ik} = b_k, i = \overline{1, m}, k = \overline{1, K} \tag{10.9}$$

consistent with a prior q_{ik} belief that a unit of demand for product i should be supplied by activity k. For instance, it is reasonable to allocate more livestock to locations with a larger demand increase, higher productivity, or better feed access. Assume that this preference structure is expressed in prior q_{ik}, $\sum_k q_{ik} = 1$ for all i. In this case, the initial amount of production i allocated to k can be derived as $q_{ik} d_i$. But this may lead to violation of constraints (10.9). Sequential rebalancing [11] proceeds as follows. Relying on prior probability q_{ik}, the *expected* initial allocation of d_i to k is $y^0_{ik} = q_{ik} d_i$, $i = \overline{1, m}$. However, this allocation may not satisfy constraint $\sum_i y^0_{ik} \leq b_k$, $j = \overline{1, n}$. Derive the relative imbalances $\beta^0_k = b_k / \sum_i y^0_{ik}$ and update $z^0_{ik} = y^0_{ik} \beta^0_k$, $i = \overline{1, m}$. Now the constraint $\sum_i y_{ik} \leq b_k$ is satisfied, $k = 1, 2, \ldots$, but the estimate z^0_{ik} may cause imbalance for (10.7), i.e., $\sum_k z^0_{ik} \neq d_i$.

Continue with calculating $\alpha_i^0 = d_i / \sum_k z_{ik}^0$, $i = \overline{1,m}$, and updating $y_{ik}^1 = z_{ik}^0 \alpha_i^0$, an so on. The estimate y_{ik}^s can be represented as

$$q_{ik}^s = (q_{ik}\beta_k^{s-1})/(\sum_j q_{ik}\beta_k^{s-1}),$$

where $i = \overline{1,m}$, $k = 1,2,\ldots$.

Assume $y^s = y_{ik}^s$ has been calculated. Find $\beta_k^s = \bar{b}_k / \sum_i y_{ik}^s$ and $q_{ik}^{s+1} = (q_{ik}\beta_j^s / \sum_i q_{ik}\beta_j^s)$, $i = \overline{1,m}$, $k = 1,2,\ldots$, and so on.

In this form the procedure can be viewed as a redistribution of required supply d_i among producers $k = 1,2,\ldots$ by applying sequentially adjusted q_{ik}^{s+1}, e.g., by using a Bayesian type of rule for updating the prior distribution:

$$q_{ik}^{s+1} = q_{ik}\beta_k^s / \sum_i q_{ik}\beta_k^s,$$

were $q_{ik}^0 = q_{ik}$.

The update is done on an observation of imbalances of basic constraints rather than observations of random variables. A rebalancing procedure, similar to the one described above for Hitchcock–Koopmans transportation constraints (10.7)–(10.9), was proposed by G.V. Sheleikovskii (see a proof and references in [3]) for estimation of passenger flows between regions. A proof of its convergence to the optimal solution maximizing the cross-entropy function

$$\sum_{i,k} y_{ik} ln \frac{y_{ik}}{q_{ik}} \tag{10.10}$$

is given in [11] for rather general types of constraints. It should be noted that in our model we use equality constraints (10.9). The general inequality constraints are reduced to this model by introduction of a fictitious demand constraint.

10.4 Stochastic Production Allocation Model

The approach presented in Sect. 10.3 evaluates the increase of livestock production relying on individual behavioral principles set by priors. There, the risks are characterized in a simplified deterministic way by imposing certain standards as additional "safety" constraints. In general, these constraints may depend on some scenarios of potential future shocks. The behavioral uncertainty in Sect. 10.3 can also be treated in a stochastic manner as allocation of random demand $d_i(\omega)$ among points $k = \overline{1, K}$ with respect to the prior q_{ik}, which is a topic of a separate paper.

Let us consider now a more general multi-producer model in a stochastic environment analogous to the Example of Sect. 10.2. We may assume that there is a coordinating agency. The goal of this agency is to maximize the overall performance of the production chain with large and small units to stabilize the aggregate production and increase the facility values. Suppose that the agency has to determine levels of livestock product i in locations k in order to meet stochastic demand $d_i(\omega)$, where $\omega = (\omega_1, \omega_2, \ldots)$ is a vector of all contingencies affecting demand and production. Naturally to assume that the decision on production expansion has to be made before the information on contingencies arrives. In this case, the total ex-ante production may not exactly correspond to the real demand, i.e., we may face both oversupplies and shortfalls. In other words, the amount of production y_{ik}, $k = \overline{1, K}$, which is planned ex-ante to satisfy the demand $d_i(\omega)$, $y_i(\omega) = \sum a_{ik}(\omega) y_{ik}$ may underestimate $(y_i(\omega) < d_i(\omega))$ or overestimate $(y_i(\omega) > d_i(\omega))$ the real demand $d_i(\omega)$ under revealed contingencies and the safety constraints imposed by strict thresholds b_k in (10.9). The constraint (10.9) necessitates, in general, additional supply of ex-ante production $z_i \geq 0$ from external sources (say, through international trade). It may also require the ex-post redistribution of the production from internal producers, $k = \overline{1, K}$, to eliminate arising shortfalls and oversupplies in locations. For now, let us ignore these ex-post redistributional aspects assuming that the most significant impacts are associated with ex-ante decisions y_{ik} and z_i. In fact, the presented further model can be easily extended to represent the ex-post adjustments of decisions y_{ik}, z_i, as well as temporal aspects of production planning.

Let c_{ik} be the unit production cost. In more general model formulation, c_{ik} may also include the unit transportation cost for satisfying location-specific demand. Then the model of production planning among the facilities can be formulated as the minimization of the total cost function:

$$f(y, z) = \sum_{i,k} c_{ik} y_{ik} + \sum_{i=1}^{m} e_i z_i,$$

subject to constraints (10.8), (10.9), and the following additional safety constraints

$$P[\sum_{k=1}^{K} a_{ik}(\omega) y_{ik} + z_i \geq d_i(\omega)] \geq p_i, z_i \geq 0, i = \overline{1, m}, \tag{10.11}$$

where $e_i > 0, i = \overline{1, m}$, denotes the unit import cost. A safety level p_i, $0 < p_i < 1$, defines (ensures) the stability of the supply-demand relations for all possible scenarios (contingencies) ω. The introduction of constraints of type (10.11) is a standard approach for characterizing stability in case of the insurance business, operations of nuclear power plants and other risky activities especially when involving catastrophic risks [9]. Safety constraints of type (10.11) are usually used in cases where impacts of random interruptions can not be easily evaluated. In this case, the value p_i is selected such that an expected shortfall occurs only, say, once in 100 month, i.e., $p_i = 0.01$.

The main methodological challenge is concerned with the lack of convexity of constraints (10.11). Yet, the remarkable fact is that the model defined by

(10.8)–(10.11) can be effectively solved by linear programming methods due to the following equivalent convex form of this model. Let us consider the minimization of the expectation function

$$F(y, z) = f(y, z) + \sum_{i=1}^{m} \alpha_i E \max\{0, d_i(\omega) - \sum_{k=1}^{K} a_{ik}(\omega) y_{ik} - z_i\}, \qquad (10.12)$$

subject to constraints (10.8), (10.9), and $z_i \geq 0, i = \overline{1, m}$. The minimization of function $F(y, z)$ is a rather specific case of stochastic minimax models analyzed (both optimality conditions and solution procedures) in [8]. In particular, if $F(y, z)$ has continuous derivatives with respect to z_i, e.g., the probability distribution function of ω has continuous density function, then

$$\frac{\partial F}{\partial z_i} = e_i - \alpha_i E I(d_i(\omega) - \sum_{k=1}^{K} a_{ik}(\omega) y_{ik} - z_i \geq 0)$$

where $I(\xi \geq 0)$ is the indicator function: $I(\xi \geq 0) = 1$, if $\xi \geq 0$, and $I(\xi \geq 0) = 0$ otherwise. Therefore, we can rewrite $\frac{\partial F}{\partial z_i}$ as

$$\frac{\partial F}{\partial z_i} = e_i - \alpha_i P[d_i(\omega) - \sum_{k=1}^{K} a_{ik}(\omega) y_{ik} - z_i \geq 0], \qquad (10.13)$$

which allows to establish connections between the original model defined by (10.8)–(10.11) and the minimization of convex function $F(y, z)$ defined by (10.12).

Assume (y^*, z^*) minimizes $F(y, z)$ subject to constraints (10.8), (10.9), and $z_i \geq 0, i = \overline{1, m}$. Assume also that $e_i < \alpha_i, i = \overline{1, m}$. Then from (10.13) it follows that for all i with positive components $z_i^* > 0$, i.e., when $\frac{\partial F}{\partial z_i} = 0$, the optimal solution (y^*, z^*) satisfies the following safety constraints

$$P[d_i(\omega) - \sum_{k=1}^{K} a_{ik}(\omega) y_{ik} - z_i \geq 0] = e_i / \alpha_i. \qquad (10.14)$$

Moreover, for all i with $z_i^* = 0$, i.e., when $\frac{\partial F}{\partial z_i} \geq 0$, the optimal (y^*, z^*) satisfies the following safety constraint

$$P[d_i(\omega) - \sum_{k=1}^{K} a_{ik}(\omega) y_{ik} \geq 0] \leq e_i / \alpha_i. \qquad (10.15)$$

If we choose α_i as $e_i / \alpha_i = 1 - p_i$, i.e., $\alpha_i = e_i / (1 - p_i)$, then (10.14)–(10.15) become equivalent to the safety constraint (10.11) of the original model (10.8)–(10.11). In other words, the minimization of convex function $F(y, z)$ defined by

(10.12) subject to (10.8), (10.9), and $z_i \geq 0$, $i = \overline{1,m}$, yields the optimal solution of the original model (10.8)–(10.11). Efficient computational procedures for solving stochastic minimax problems with objective functions defined as in (10.12) can be found in [8, 25]. In particular, the paper [25] discussed the applicability of linear programming methods in cases where the original model defined by a general probability distributions of ω can be sufficiently approximated by models with discrete probability distributions. This paper establishes also important connections between the minimization of (10.12)-type functions and Conditional-Value-at-Risk risk measure.

The minimization of function (10.12) can also be solved by a stochastic quasi-gradient method [8]. In applying this method to minimization of (10.12), the differentiability of $F(y)$ and any assumption on probability distribution of ω is not required. Also, the probability distribution of ω may only be given implicitly. For instance, only observations of random $d_i(\omega)$ and $a_{ik}(\omega)$ may be available or only a Monte Carlo procedure (pseudo-sampling simulation model such as described in Sect. 10.3.1) is used to simulate supply and demand. In the following section we illustrate some applications by using only the rebalancing algorithm described in Sect. 10.3.3; elaboration of the outlined stochastic allocation algorithm is a topic for future implementation.

10.5 Numerical Experiments

The model in Sect. 10.3 is used in the analysis of current and plausible future livestock production allocation and intensification in China. Namely, in each time period the simulation model generates levels and geographic distribution of demand for livestock products coherent with urbanization processes [22], demographic change [4] and expected growth of incomes [16, 17]. Production allocation and intensification levels are projected from the base year data for the main livestock types (pigs, poultry, sheep, goat, cattle) and management systems (grazing, industrial/specialized, traditional) at the level of counties (about 2,500 administrative units). For production allocation, we used the sequential rebalancing procedure described in Sect. 10.3.3. Two scenarios of future production allocation corresponding to different priors q_{ik}, $i = \overline{1,m}$, $k = \overline{1,K}$, are compared: (1) an intensification scenario, when production is allocated proportionally to the geographical patterns of demand increases, and (2) a risk-adjusted scenario that combines the preference structure as defined by the geographical distribution of demand with indicators of environmental pressure.

Intensification scenario. Currently, common practice is to allocate intensive livestock production in areas with good access to consumers, close to high demand and high population density [1]. In many practical problems of large dimensionality, to describe the "profitability" of a location it has been standard practice to use an ad hoc but reasonable measure referred to as market access function. The typical market access function measures the potential of location k as a weighted sum of purchasing power of all other locations in some vicinity of the given k. The weights are defined either as a function of distance or as a function of other factors, say, costs or losses. In these studies, each county is characterized by its market access calculated as a weighted sum of demand for product i in nearby counties within some vicinity. Values $\tilde{\triangle}_{ik}$, determine a profit-based prior q_{ik}, $k = \overline{1, K}$ for allocation of demand increase among production units in locations as it is described in Sect. 10.3.3.

Risk-adjusted scenario. The objective of this scenario is to care for the balance between profitability of the agricultural production, rural welfare, and the respect of nature and the environment. Challenges of spatially-explicit planning for sustainability are related to the choice of adequate location-specific indicators to guide rural development within defined socio-economic and environmental objectives. While information on economic and livelihood conditions at location may be available from statistics and census data, estimation of agricultural pollution and health risks (for example, related to livestock diseases) is a more challenging task.

The agricultural pollution falls into the category of non-point source pollution, which is geographically disperse, and the likelihood of disease occurrences is determined by a combination of factors. Measurements of the pollution level, health risks, and related impacts or losses are hardly possible as they depend on multiple highly uncertain socio-economic and environmental factors: weather patterns, population density, level of development, agricultural inputs and intensification levels, etc. In many practical situations when the target variable is impossible or impractical to measure, it is possible to use context-specific proxies or even a set of proxies that can considerably well represent the state of the non-measurable variable (see, e.g., [13]).

For planning sustainable agricultural developments, the profit-driven prior of the "intensification scenario" is adjusted with such variables as nutrients in excess of crop uptakes, density of livestock biomass, etc., are used to characterize environmental risks. Health norms and associated health risks are introduced by a combination of urbanization share (share of urban population in total population) and availability of non-residential area suitable for further production expansion in each location. In general, allocation prior is defined by a compound probability distribution function of relevant variables.

The intensification scenario implicitly minimizes the transportation costs as the production concentrates in the proximity of large markets in urban areas with high demand. In the alternative scenario, which is a compromise between the demand driven production allocation and the considerations of health and environmental risks, the production is shifted to more distant locations characterized by availability of cultivated land, lower livestock and population density, which increases transportation. However, the measure of goodness for the scenarios accounts not only for the transportation cost but also includes environmental and health risk proxies. Thus, the two scenarios are compared with respect to number of people in China's regions exposed to different categories of environmental risks.

Environmental risks are measured in terms of environmental pressure in relation to the coincidence of three factors: density of confined livestock, human population density, and availability of cultivated land. For this purpose some 2,434 counties

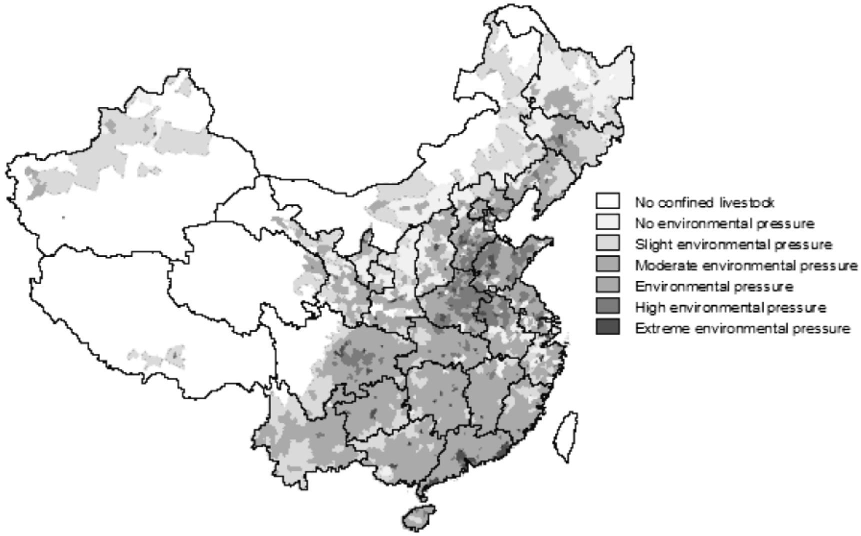

Fig. 10.1 Environmental pressure from confined livestock production, 2000

were classified as follows into seven categories, namely: (a) *No confined livestock*, i.e., counties in scarcely populated areas (desert or mountain/plateau) and with very little confined livestock; (b) *No environmental pressure*, i.e., counties with substantial crop production but with little confined livestock; (c) *Slight environmental pressure* counties with low environmental pressure from confined livestock production; (d) *Moderate environmental pressure*, i.e., counties with moderate environmental pressure from confined livestock production; (e) *Environmental pressure*, i.e., counties with substantial urbanization and environmental pressure from confined livestock production; (f) *High Environmental pressure*, i.e., counties with substantial urbanization and high environmental pressure from livestock production, and (g) *Extreme environmental pressure* i.e., counties with high degree of urbanization coinciding with high environmental pressure from confined livestock production. Figure 10.1 presents the above classification of environmental pressure for the year 2000. Figure 10.1 indicates that currently (i.e., year 2000) hot-spots of environmental pressure are located mainly in provinces covering the North China Plain, the Sichuan basin, and several locations along the coast of South China. Locations of livestock production concentrate around or in the vicinity of areas where the livestock demand grows fast, e.g., highly populated and urban areas.

Figure 10.2 presents diagrams of the distribution of current population against the mapped classes of severity of environmental pressures from livestock. The left diagram shows absolute numbers, i.e., million people per class and region. The diagram on the right gives shares of population within each region falling into respective classes. For year 2000, the estimates suggest that about 20% of China's population lives in counties characterized as having high or extreme severity of environmental pressure from intensive livestock production. In the "intensification" scenario, by

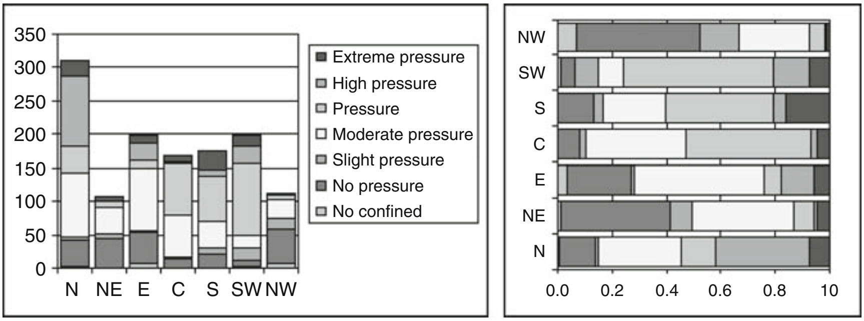

Fig. 10.2 Absolute (million people) and relative (share of total population) distribution of population according to classes of severity of environmental pressure from livestock, 2000. The *label on the horizontal axis* indicate China regions: *N*, *NE*, *E*, *C*, *S*, *SW*, *NW* stand for North, North-East, East, Center, South, South-West, North-West, respectively

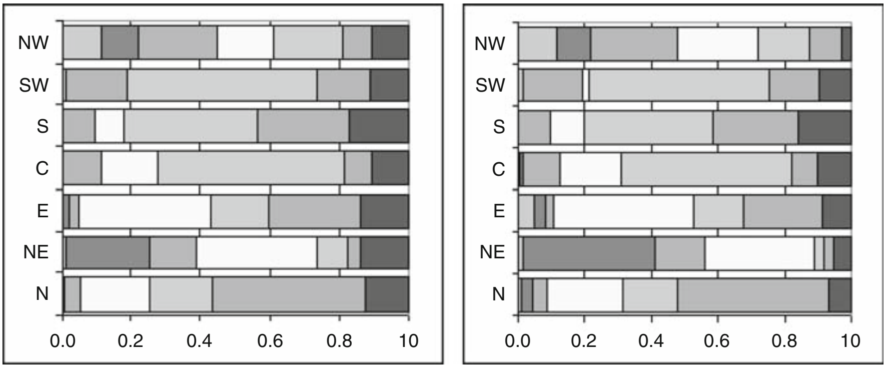

Fig. 10.3 Relative (share of total population) distribution of population according to classes of severity of environmental pressure from livestock, 2030: **a** "intensification" scenario, **b** risk-adjusted scenario

2030 this population share increases to 36% (Fig. 10.3a), i.e., from one-fifth in 2000 to about one-third in 2030. Looking only at the highest pressure class, the South region appears to have the largest number of people and the highest population share in such unfavorable environmental pressure, about 38 million or 22% of population in 2000 increasing to nearly 45 million or 17% in 2030. The region with the highest occurrence of people (both absolute and relative) in the two highest pressure classes is the North region, with more than 40% of the population. In 2030, the estimated share becomes 57%, followed by the South region with 27% population in two highest pressure classes in 2000 and with 44% in 2030. Looking at the second allocation scenario, the positive changes are quite visible (see Fig. 10.3b). The estimate of people living in highest pressure class for South region changes from 45 to 42 million. Percentage of population in the two highest pressure classes for the same region varies between scenarios as 43 for the bad and 41 for the good. For

North region, 56.5% of total population will live in two highest pressure classes in 2030 in bad scenario and only 52.3 – in good, In North East, the highest pressure classes change percentage from about 18 to less than 10. The intensification scenario (1) implicitly minimizes the transportation costs as production concentrates in the vicinity of urban areas with high demand. In the alternative scenario (2), the production is shifted to more distant locations characterized by availability of cultivated land, lower livestock and population density, but at the expense of additional transportation. Environmental sustainability aspects of the two scenarios were compared with respect to the share of people in China's regions exposed to different severity classes of environmental risks. Environmental risks are measured in terms of environmental pressure in relation to the coincidence of three factors: density of confined livestock, human population density, and availability of cultivated land. For year 2000, the estimates suggest that about 20% of China's population lives in counties characterized as having high or extreme severity of environmental pressure from intensive livestock production. In the "intensification" scenario, by 2030 this population share increases to 37%, while in the second, environmentally friendly scenario, it stays below 30%. To finally compare the two scenarios, it is necessary to "normalize" gains due to improved life conditions with expenses of additional transportation.

10.6 Conclusions

This paper addresses some important aspects of agricultural production planning under risks, uncertainties and incomplete information. When planning agricultural developments, the objective is to allocate the foreseeable increases of demand in the best possible way while accounting for various risks associated with production and suitability criteria for profitability, transport, health and environmental impacts. Models for production allocation under risks and uncertainties may have considerable implications. In particular, the allocation of livestock production away from urban peripheries where pressure is highest to regions where feed grains are in abundance could decrease the income gaps between the regions. Similarly, establishment of agricultural pollution regulations, e.g., taxation, at locations with high environmental loads may change the balance of agricultural market attracting imports from abroad.

In Sect. 10.3, the production allocation procedure is proposed for situations when the available information is given in the form of aggregate values without providing necessary local perspectives. Therefore, the main issue is to downscale these values to the local levels consistently with location specific behavioral principles based on some priors. Yet, many practical situations may require more rigorous probabilistic treatment of priors and safety constraints. Section 10.4 proposes an allocation mechanism with more general treatment of uncertainties and risks based on principles of stochastic optimization. This is a promising approach for a coordinating agency aiming to improve the overall performance of the production chain.

By diversifying large and small units the agency may stabilize the aggregate production and increase "utility" of individual facilities. The application of this allocation procedure is a topic for future research.

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