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The microeconomics of food security

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This article develops a dynamic microeconomic model of food security under uncertainty, with special focus on the relationships between food demand, nutrition and human survival. It investigates the influence of entitlements on malnutrition, hunger and starvation under uncertainty. It develops useful insights on the links between food security and a number of policy instruments commonly used in dealing with malnutrition and starvation.

1. Introduction

Despite a rising real income per capita in the world, millions of people die every year from malnutrition and starvation and many more face hunger and insecurity in satisfying their basic wants. While the starvation rate in the world population is relatively low, starvation remains a feature found in many developing countries. Also, short of starving to death, individuals may be subject to malnutrition because of low food consumption, both in developing and developed countries. Much research has focused on food demand and its implications for nutrition (e.g. Barrett 1999; Behrman and Deolikar 1987; Bouis 1994; Bouis and Haddad 1992; Duncan 1999; Phillips and Taylor 1990; Pinstrup-Andersen and Caicedo 1978; Pitt 1983; Pitt, Rosenzweig and Hassan 1990; Ravallion 1987, 1997; Singh, Squire and Strauss 1986; Schiff and Valdés 1990; Staatz *et al.* 1990). While the relationship between food and human survival is often not explicit in the literature (e.g. Deaton and Muellbauer 1980; Singh *et al.* 1986), there is interest in exploring the links between food security and economic behaviour. This includes links with saving behaviour (Gersovitz 1983), consumption

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behaviour (Glomm and Palumbo 1993), or labour allocation and destitution (Dasgupta 1993). As argued by Ravallion (1997) and Barrett (1999), there is a need to refine our current understanding of food security and the economics of human survival.

This article develops a dynamic microeconomic model of food security, stressing the relationships between food demand, nutrition and human survival. It builds on the work of Gersovitz, Dasgupta, Glomm and Palumbo, Sen and Drèze, and Sen. It emphasises the influence of entitlements on malnutrition, hunger and starvation and extends Sen's entitlement approach by integrating it in a dynamic framework under uncertainty. It explores links between economic rationality, entitlements and food security. The article also integrates food security with Stigler and Becker's (1977) household production model that treats consumption goods as 'intermediate goods' that are combined with time and human capital to produce non-market goods generating utility to the consuming units. This is relevant here since nutrition is a clear example of a non-market utility-yielding good that individuals 'produce' from food consumption.

Two important characteristics of our approach are worth emphasising. First, our microeconomic analysis is at the individual level (and not the household level). The reason is that nutritional status is fundamentally an individual characteristic. Since significant differences can exist in the nutritional status of individuals within the same household, a household level analysis is too aggregated for our purpose. One implication is that our analysis is conditional on the (implicit) contracts that govern intra-household resource allocation. The more traditional household-level analysis (commonly found in the literature) is typically conditional on the contractual relationship between the household and the rest of the world (e.g. land rights, labour contract, inter-household transfers). Here, our analysis adds the intra-household institutional arrangements (e.g. intra-household transfers) and investigates their influence on individual food security. This is a desirable feature to the extent that intra-household resource allocation affects individual food security (e.g. Drèze and Sen 1993; Pitt *et al.* 1990).

Second, uncertainty and dynamics fundamentally characterise food security. The uncertainty relates to the amount of food available (as influenced by the weather, pest damages, etc.), as well as the ability to pay for it (as influenced by income and price uncertainty). Dynamics relate to both predictable and unpredictable fluctuations in food allocation over time (e.g. seasonality, food production uncertainty). In this context, we develop a dynamic representation of resource allocation for an individual facing possible food insecurity. We explicitly represent fundamental features of human life: health, nutrition and death. Since an individual's life is clearly non-stationary, no attempt is made to provide a stationary representation of dynamic resource allocation throughout the individual's life. We explore the relationships between human behaviour, entitlement and food security. We also investigate the links between food security and a number of policy instruments commonly used in dealing with malnutrition and starvation. The analysis provides useful insights on the influence of market transaction costs, credit rationing, storage, cash transfers, as well as in-kind transfers on food security.

2. The model

Consider an individual making resource allocation decisions over time under uncertainty. Uncertainty is represented by the random vector e_t. At time t, the decisions include the control variables x_t, and the state variables y_t which evolve over time according to the state equation:

$$y_{t+1} = f_{t+1}(y_t, x_t, e_t), \tag{1}$$

$t = 0, 1, 2, \ldots$ The random vector e_t has a subjective probability measure $P_{e,t}(\cdot \mid y_t, x_t)$, $t = 0, 1, 2, \ldots$ The initial state is also random and has a probability measure $P_{y,0}$. The allocation decisions x_t made at time t are subject to the feasibility condition:

$$x_t \in X_t, \tag{2}$$

where X_t is the feasible set for x_t, $t = 0, 1, 2, \ldots$ The individual is assumed to learn over time. The learning process is represented by the observation of signals z_t at time t, generated as follows:

$$z_t = g_t(y_t, x_{t-1}, v_t), \tag{3}$$

where v_t is a random vector, $t = 1, 2, \ldots$ The random vector v_t has a subjective probability measure $P_{v,t}(\cdot \mid y_t, x_{t-1})$, $t = 1, 2, \ldots$ Under imperfect state information, observing the signal z_t at time t provides information about the true state y_t. Intuitively, the more correlated the random variables z_t and y_t are, the more informative the signal z_t is. Equation 3 can reflect 'active learning' when the individual's decisions x affect directly the functional relation between z_t and y_t: $z_t = g_t(y_t, x_{t-1}, v_t)$. Finally, the case of 'perfect state information' is a special case when equation 3 becomes $z_t = y_t$, i.e. when the actual state y_t is observed and thus becomes known at time t.[1]

Under equation 3, the information available to the individual at time t is given by the information vector $I_t \equiv (z_0, \ldots, z_t, x_0, \ldots, x_{t-1})$. With $I_0 = z_0$ as initial conditions at time $t = 0$, the dynamics of the information vector I_t is:

[1] Note that 'perfect state information' does not imply the absence of uncertainty. It simply means that the uncertainty related to the state variables y_t is resolved at time t by the observation of the random variables $z_t = y_t$.

$$I_{t+1} = (I_t, z_{t+1}, x_t), \tag{4}$$

$t = 0, 1, 2, \ldots$ Given the subjective probability measures $P_{y,0}$, $P_{e,t}(\cdot \mid y_t, x_t)$ and $P_{v,t}(\cdot \mid y_t, x_{t-1}), t = 1, 2, \ldots,$ learning is represented in a Bayesian framework. From equations 1 and 3, learning takes place from period t to period $(t+1)$ through the Bayesian updating of the probability distribution of the state vector y_{t+1}.

Assume that the preferences of the individual at time $t = 0$ are given by the ex-ante utility function $E_0\{\sum_{t=0}^{\infty} \beta^t U(y_t, x_t)\}$, where E_0 is the expectation operator based on the subjective information available at time $t = 0$, β is the discount factor $(0 < \beta < 1)$ reflecting time preferences, and $U(y_t, x_t)$ is a von Neumann-Morgenstern utility function at time t. The individual makes allocation decisions over time by maximising his/her preference function subject to the constraints of expressions 1, 2, 3 and 4 reflecting the individual's socio-economic environment. This is represented by the dynamic programming problem (Bertsekas 1976, p. 118):

$$V_t(I_t) = \text{Max}_{x_t \in X_t}\{E_t U(y_t, x_t) + \beta E_t V_{t+1}[I_t, g_{t+1}[f_{t+1}(y_t, x_t, e_t), x_t, v_{t+1}], x_t]\} \tag{5}$$

for any time period t, where E_t is the expectation operator based on I_t, the information available at time t. Equation 5 is Bellman's equation, which defines recursively the optimal value function at time t, $V_t(I_t)$.

The general problem in equation 5 can be specialised to handle the economics of food, nutrition and health. Let x_t denote the vector of commodities under the control of the individual at time t. Since we focus our attention on food allocation, we will distinguish explicitly between food and non-food items. On that basis, we consider $x_t = (x_{fc,t}, x_{fm,t}, x_{nc,t}, x_{np,t}, x_{nm,t})$, where:

$x_{fc,t}$ = quantity of food commodities consumed at time t,[2]
$x_{fm,t}$ = quantity of food commodities marketed at time t, assumed to be positive (negative) when sold (purchased),
$x_{nc,t}$ = quantity of non-food commodities consumed as final products at time t,
$x_{np,t}$ = quantity of non-food commodities controlled by the individual, assumed to be positive (negative) for outputs produced (inputs used),
$x_{nm,t}$ = quantity of non-food commodities marketed at time t, assumed to be positive (negative) when sold (purchased).

[2] Throughout the article, the term 'food' is used generically to mean all commodities providing a source of nutrients to the individual.

The food commodities in $(x_{fc,t}, x_{fm,t})$ typically include storable foods (e.g. grains) as well as non-storable foods (e.g. fresh fruits). Similarly, the non-food commodities in $(x_{nc,t}, x_{np,t}, x_{nm,t})$ include non-durable goods (e.g. services), durable goods (e.g. housing, clothing), as well as the individual's time. Thus, the individual's leisure time is part of the vector $x_{nc,t}$, the time spent on 'household production' is an element of the vector $(-x_{np,t})$, and the individual's time spent on wage labour is part of the vector $x_{nm,t}$.

Next, let $y_t = (y_{h,t}, y_{p,t}, y_{w,t}, y_{f,t}, y_{n,t}, y_{o,t})$, where:

$y_{h,t}$ = the individual's health status,
$y_{p,t}$ = quantity of food commodities produced under the control of the individual at time t,
$y_{w,t}$ = the individual's monetary wealth,
$y_{f,t}$ = inventory level of food commodities at time t,
$y_{n,t}$ = inventory level of non-food commodities under the control of the individual at time t (including his/her physical capital), and
$y_{o,t}$ = other relevant state variables (including the individual's human capital).

The variables $(y_{p,t}, y_{w,t}, y_{f,t}, y_{n,t})$ measure the amount of resources under the control of the individual, conditional on a set of property rights. This will require modelling explicitly income transfers as well as in-kind transfers (both inter- and intra-household) affecting the individual (see below). We assume that the state variables $(y_{p,t}, y_{w,t}, y_{f,t}, y_{n,t})$ are imperfectly known before time t, but become observed by the individual at time t. However, the other state variables $(y_{h,t}, y_{o,t})$ may not be observable at time t, thus contributing to imperfect state information.

The state equation 1 includes the dynamic individual's health function:

$$y_{h,t+1} = f_{h,t+1}(y_{h,t}, x_{fc,t}, x_{nc,t}, e_t), \tag{6}$$

Equation 6 relates the individual's health at time $(t + 1)$ to previous health status $y_{h,t}$, food consumption $x_{fc,t}$, non-food consumption $x_{nc,t}$ (e.g. health care), as well as uncertain factors e_t (e.g. accident, illness). The relationship between food consumption and health in equation 6 can be characterised in terms of nutrition. For example, equation 6 can be alternatively written as:

$$y_{h,t+1} = f'_{h,t+1}(y_{h,t}, N_t(x_{fc,t}), x_{nc,t}, e_t), \tag{6$'$}$$

where N_t is the vector of nutrients intake by the individual at time t, and $N_t(x_{fc,t})$ is the 'nutrient production function', which translates food consumption $x_{fc,t}$ into nutrients intake. In equation $6'$, the effects of food consumption on the individual's health are through their impact on the nutritional status N_t.

The following assumptions will be made about equation 6:

Assumption A1: The function $f_{h,t+1}(x_{fc,t}, \cdot)$ is continuous in $x_{fc,t}$, and non-decreasing (non-increasing) in $x_{fc,t}$ for small (large) values of $x_{fc,t}$.

Assumption A2: The function $f_{h,t+1}(y_{h,t}, \cdot)$ exhibits an absorbing state y_h^a (representing death) at its lower bound such that $f_{h,t+1}(y_h^a, x_{fc,t}, x_{nc,t}, e_{t+1}) = y_h^a$ for all feasible values of $(x_{fc,t}, x_{nc,t}, e_t)$, and $f_{h,t+1}(y_{h,t}, x_{fc,t}, x_{nc,t}, e_t) \geq y_h^a$ for all feasible values of $(y_{h,t}, x_{fc,t}, x_{nc,t}, e_t)$.

Assumption A3: There exists a non-empty food consumption set $S_t \subset \{x_{fc,t} : x_{fc,t} \geq 0\}$ satisfying:

1. $f_{h,t+1}(y_{h,t}, x_{fc,t}, x_{nc,t}, e_t) = y_h^a$ for any $x_{fc,t} \in S_t$, for all feasible values of $(y_{h,t}, x_{nc,t}, e_t)$, and
2. if $x_{fc,t} \in S_{t,}$, then $x'_{fc,t} \in S_t$ for any $x'_{fc,t}$ satisfying $0 \geq x'_{fc,t} \geq x_{fc,t}$.

Assumption A4: There exists a time $t^a \geq 0$ such that:
$\text{Prob}(y_{h,t} = y_h^a) = 1$ for all $t > t^a$, for all feasible (x_t, y_t), $t = 0, \ldots, t^a$.

Assumptions A1 and A3 reflect the nutritional effects of food intake on health. Too little food leads to malnutrition and health deterioration and too much food has adverse health effects (e.g. indigestion). The peak of the function $f_{h,t+1}(x_{fc,t}, \cdot)$ is the same as the peak of the function $f'_{h,t+1}(N_t, \cdot)$ in equation 6′. This latter peak is the nutrients intake typically recommended by nutritionists and dietitians.

Assumption A2 characterises death by the absorbing state y_h^a. In A2, the individual's death is represented as the lower bound of the health index $f_{h,t+1}(.)$, i.e. as the most extreme form of health deterioration. The absorbing state y_h^a reflects the irreversibility of death. Assumption A3 states that food consumption is necessary to sustain life.[3] It defines a set S_t of low food consumption such that choosing any $x_{fc,t} \in S_t$ necessarily implies the individual's death (as reflected by y_h^a). Thus, the set S_t can be interpreted as the 'starvation set'. Finally, assumption A4 indicates that the individual's life is surely finite, no matter what decisions he/she makes. Assumptions A1–A4 reflect the biological realities of human life.

The state equation 1 also includes the food production equation:

$$y_{p,t+1} = f_{p,t+1}(y_{h,t}, y_{n,t}, y_{o,t}, x_{np,t}, e_t). \tag{7}$$

[3] Note that this assumption would not hold if the observation period is very short: an individual could possibly survive without food for a few days. Thus, throughout the article, we assume that the observation period is 'long enough' to guarantee that the absence of food intake would necessarily induce the individual's death.

Equation 7 indicates that the food produced under the control of the individual, $y_{p,t+1}$, depends on the individual's health status $y_{h,t}$, on his/her physical capital $y_{n,t}$, on his/her human capital $y_{o,t}$, on the vector $x_{np,t}$ of non-food inputs (including the individual's time), on non-food outputs involved in the production process, and on the random variables e_t. The delayed effects of inputs at time t ($y_{h,t}, y_{n,t}, y_{o,t}, x_{np,t}$) on food outputs at time $t+1$ ($y_{p,t+1}$) reflect the existence of biological lags typically found in food production processes. The individual's health status $y_{h,t}$ can influence food production through its effects on labour productivity (e.g. Strauss 1986). The random variables e_t in equation 7 indicate the presence of production uncertainty (e.g. the unpredictable effects of weather on crop yield). The food production equation in equation 7 is assumed to represent both the household production technology as well as the institutional setting reflecting various contracts between the individual and its socio-economic environment. These contracts can be either implicit or explicit. They could be intra-household contracts between the individual and other household members or they could be contracts between the individual and other members of society (e.g. property rights). To the extent that these contracts affect the individual's control and access to resources, they can have a direct influence on the food produced under the control of the individual.

The state equation 1 includes the dynamic individual's monetary wealth function:

$$\begin{aligned} y_{w,t+1} &= f_{w,t+1}(y_{w,t}, x_{fm,t} x_{nm,t}, e_t) \\ &\equiv (1+\alpha_t)[y_{w,t} + p_{f,t} x_{fm,t} + p_{n,t} x_{nm,t} - s_{f,t} y_{f,t} - s_{n,t} y_{n,t} + T_{w,t}], \end{aligned} \tag{8a}$$

subject to:

$$y_{w,t} + p_{f,t} x_{fm,t} + p_{n,t} x_{nm,t} - s_{f,t} y_{f,t} - s_{n,t} y_{n,t} + T_{w,t} \geq R_t, \tag{8b}$$

where α_t is the rate of return on monetary wealth held at time t, $p_{f,t} \geq 0$ is the price vector for the food commodities $x_{fm,t}$, $p_{n,t} \geq 0$ is the price vector for the non-food commodities $x_{nm,t}$, $s_{f,t} \geq 0$ is the unit storage cost of food, $s_{n,t} \geq 0$ is the unit storage cost of non-food at time t, $T_{w,t}$ denotes exogenous income transfer, and $R_t \geq 0$ is a parameter measuring the individual's largest borrowing capacity reflecting possible credit rationing. The random variables e_t in equation 8a can represent uncertainty about the rate of return (α_t) and prices ($p_{f,t}, p_{n,t}, s_{f,t}, s_{n,t}$). We assume that the prices ($p_{f,t}, p_{n,t}, s_{f,t}, s_{n,t}$) are observed at time t, but may not be precisely known before time t. The income transfer $T_{w,t}$ can be positive or negative: it is positive when paid *to* the individual, and negative when paid *by* the individual at time t. The variables $x_{fm,t}$ and $x_{nm,t}$ being positive for sales and negative for purchases, it follows that ($p_{f,t} x_{fm,t} + p_{n,t} x_{nm,t}$) in equations 8a or 8b denotes the net income received by the individual at time t as the result of market trading activities. The individual time being included among non-food commodities, $(p_{n,t}x_{nm,t})$ includes wage income from the labour market. Finally, $(s_{f,t}y_{f,t} + s_{n,t}y_{n,t})$ in equations 8a or 8b denotes the storage cost of both food and non-food items.

In general, the determination of market prices $(p_{f,t}, p_{n,t})$ in equations 8a or 8b reflects the nature of the corresponding markets. Denote by $p^o_{f,t}$ and $p^o_{n,t}$ the market prices for food and non-food items, respectively, in some central markets.[4] The individual's access to these markets may be costly. Let the effective prices facing the individual be:

$$\begin{aligned} p_{f,t} &= p^-_{f,t} \equiv p^o_{f,t} + c^-_{f,t} \qquad \text{if } x_{fm,t} < 0 \\ &= p^+_{f,t} \equiv p^o_{f,t} - c^+_{f,t} \qquad \text{if } x_{fm,t} > 0, \end{aligned} \tag{8c}$$

and

$$\begin{aligned} p_{n,t} &= p^-_{n,t} \equiv p^o_{n,t} + c^-_{n,t} \qquad \text{if } x_{nm,t} < 0 \\ &= p^+_{n,t} \equiv p^o_{n,t} - c^+_{n,t} \qquad \text{if } x_{nm,t} > 0, \end{aligned} \tag{8d}$$

where p^- denotes effective purchase prices, p^+ denotes effective selling prices, $(c^-_{f,t}, c^-_{n,t}) \geq 0$ are the individual's unit transaction costs of purchasing the market goods $(x_{fm,t}, x_{nm,t})$, and $(c^+_{f,t}, c^+_{n,t}) \geq 0$ are the individual's unit transaction costs of selling the market goods in the central markets. The transaction costs $(c^-_{f,t}, c^-_{n,t}, c^+_{f,t}, c^+_{n,t})$ can reflect information costs, transportation costs, etc.[5] They create a wedge between buying prices p^- and selling prices p^+: $p^-_{f,t} - p^+_{f,t} = c^-_{f,t} + c^+_{f,t} \geq 0$, and $p^-_{n,t} - p^+_{n,t} = c^-_{n,t} + c^+_{n,t} \geq 0$. When positive, this price wedge corresponds to a sunk cost for the individual since any purchase decision cannot be reversed at zero cost. In the presence of sunk costs, $p^-_{f,t} > p^+_{f,t}$ and $p^-_{n,t} > p^+_{n,t}$, and the incentive for the individual to trade declines. And if sunk costs become large, there is no incentive to trade, and the individual would choose not to participate in markets (by choosing $x_{fm,t} = 0$ and/or $x_{nm,t} = 0$).

In general, the individual's borrowing capacity parameter $R_t \geq 0$ in equation 8b represents credit rationing and reflects the functioning of the capital market. In the absence of credit rationing, $R_t = \infty$, there is

[4] For simplicity, we consider only the case of competitive markets. The extension to situations with market power would be fairly straightforward. It would involve specifying $p_{f,t} = p_f(x_{fm,t})$ and $p_{n,t} = p_n(x_{nm,t})$, where the market prices depend on the corresponding volumes transacted.

[5] These costs need not be symmetric for buying versus selling. For example, because of different back-hauling possibilities, transportation costs *to* the central markets can differ from transportation costs *from* the central markets.

unrestricted borrowing and lending that can smooth monetary flows over time. Equation 8a then is the individual's intertemporal budget constraint on the evolution of his/her monetary wealth over time. It states that wealth at time t equals: previous wealth $y_{w,t}$; plus net income from trading food commodities $(p_{f,t}x_{fm,t})$ as well as non-food commodities $(p_{n,t}x_{nm,t})$; minus storage cost $(s_{f,t}y_{f,t} + s_{n,t}y_{n,t})$; plus income transfer $T_{w,t}$.

In contrast, in the presence of credit rationing, $R_t < \infty$. For example, if $R_t = 0$, credit rationing becomes effective whenever the individual's equity falls below zero. This reflects a situation where the individual cannot borrow against future wealth in order to finance current expenditures. In this case, the inequality in equation 8b becomes binding. Under credit rationing, equation 8b becomes a single period budget constraint, and the individual's ability to smooth intertemporal expenditures deteriorates.

The state equation 1 also includes the dynamics of the state variables $(y_{f,t}, y_{n,t})$ measuring the individual's inventory holding of durable goods. The dynamics of $(y_{f,t}, y_{n,t})$ take the form:

$$y_{f,t+1} = f_{f,t+1}(y_{f,t}, y_{p,t}, x_{fc,t}, x_{fm,t}) \equiv (1-\delta_f)[y_{f,t} + y_{p,t} - x_{fc,t} - x_{fm,t} + T_{f,t}], \quad (9a)$$

subject to

$$0 \leq y_{f,t} + y_{p,t} - x_{fc,t} - x_{fm,t} + T_{f,t} \leq K_{f,t}, \quad (9b)$$

and

$$y_{n,t+1} = f_{n,t+1}(y_{n,t}, x_{np,t}, x_{nc,t}, x_{nm,t}) \equiv (1-\delta_n)[y_{n,t} + x_{np,t} - x_{nc,t} - x_{nm,t} + T_{n,t}], \quad (9c)$$

subject to

$$0 \leq y_{n,t} + x_{np,t} - x_{nc,t} - x_{nm,t} + T_{n,t} \leq K_{n,t}, \quad (9d)$$

where δ_f and δ_n are depreciation rates for food and non-food commodities, $T_{f,t}$ and $T_{n,t}$ are exogenous in-kind transfers at time t, and $(K_{f,t}, K_{n,t}) \geq 0$ are parameters measuring the individual's maximum 'storage capacity' for food and non-food commodities, respectively. The in-kind transfers $T_{f,t}$ and $T_{n,t}$ in equations 9a–9d can be positive or negative: they are positive when they are transfers *to* the individual, and negative when they are transfers *from* the individual. The parameter values $K_{f,t}$ and $K_{n,t}$ in equations 9b and 9d reflect the durability or storability of the corresponding commodities: positive values are associated with durable commodities, while zero values imply non-storable goods. For non-storable foods, $K_{f,t} = 0$ and equations 9a and 9b imply $y_{f,t+1} = 0$ for all t. In the absence of transfers $(T_{f,t} = 0)$, this generates the traditional definition of 'marketed surplus' $x_{fm,t}$ as the difference between food production $(y_{p,t})$ and food consumption $(x_{fc,t})$: $x_{fm,t} = y_{p,t} - x_{fc,t}$. For storable foods $(K_{f,t} > 0)$ and in the absence of transfers

$(T_{f,t} = 0)$, equations 9a and 9b state that the part of food production $(y_{p,t})$ that is neither consumed $(x_{fc,t})$ nor sold $(x_{fm,t})$ is added to previous food stocks $(y_{n,t})$, as long as the maximum storage capacity $(K_{f,t})$ is not reached. Similar interpretations apply to non-food items in equations 9c and 9d, whether they are durable $(K_{n,t} > 0)$ or not $(K_{n,t} = 0)$. Examples of durable non-food items include various forms of physical capital under the individual's control (e.g. consumer durable, land, buildings, machinery). An example of a non-storable non-food item is the individual's time. In this context, with $K_{n,t} = y_{n,t} = y_{n,t+1} = 0$, interpret $T_{n,t}$ as the total amount of time available to the individual each period (e.g. 24 hours per day). Then, equation 9d generates the standard time constraint: total time available $(T_{n,t})$ equals leisure time $(x_{nc,t})$, plus wage labour $(x_{nm,t})$, plus the amount of time spent in the 'household production process' $(-x_{np,t})$.

Finally, the dynamics of the state variables $y_{o,t}$ in equation 1 is written as:

$$y_{o,t+1} = f_{o,t+1}(y_t, x_{fc,t}, x_{nc,t}, e_t). \quad (10)$$

We interpret $y_{o,t}$ as a vector of non-market goods other than the individual's health status $y_{h,t}$. These non-market goods include the individual's human capital, the enjoyment of eating, etc. In equation 10, the non-market goods $y_{o,t+1}$ are obtained from a household production process that combines previous states y_t with consumption of food items $(x_{fc,t})$ and non-food items $(x_{nc,t})$, along with uncertain factors (e_t). Since non-food $x_{nc,t}$ includes the individual's leisure, equation 10 is consistent with Stigler and Becker's (1977) household production model, where time and market goods are combined to produce non-market goods.

In the characterisation of individual behaviour, equations 6–10 thus represent the dynamic state equation 1. We focus on the case where the individual utility function $U(y_t, x_t)$ in equation 5 takes the form:

$$U(\cdot) = U(y_{h,t}, y_{o,t}). \quad (11)$$

In equation 11, only the non-market goods $(y_{h,t}, y_{o,t})$ are assumed to enter the utility function. This is consistent with Stigler and Becker's household model, which assumes that market goods are combined with time and human capital to generate non-market goods, which in turn generate utility. The inclusion of $(y_{h,t}, y_{o,t})$ as utility-yielding goods means that equations 6 and 10 can be interpreted as production functions for the corresponding non-market goods. The specification in equation 11 implies that wealth $(y_{w,t})$, food or non-food inventories $(y_{f,t}, y_{n,t})$, production decisions $(y_{p,t}, x_{np,t})$, consumption decisions $(x_{fc,t}, x_{nc,t})$, or marketing decisions $(x_{fm,t}, x_{nm,t})$ do not have a direct effect on individual welfare. Rather, these variables have an impact on welfare only by affecting the production of the non-market utility-yielding goods $(y_{h,t+1}, y_{o,t+1})$ through the individual's market and resource allocation decisions (Deaton and Muellbauer 1980, p. 245).

The utility function in equation 11 is assumed to satisfy the following assumption:

Assumption A5: $U(y_{h,t}, y_{o,t}) > U(y_h^a, y_{o,t}) = U^a$ for all feasible $(y_{h,t}, y_{o,t})$ satisfying $y_{h,t} > y_h^a$.

Assumption A5 states that death (corresponding to y_h^a) provides a lower bound U^a on the utility index $U(\cdot)$. It simply means that the individual would always choose life over death.

Finally, the feasible set X_t in equation 2 is defined as $X_t = \{x_t$: $x_{fc,t} \geq 0, x_{nc,t} \geq 0$, equations 8b, 9b and 9d$\}$. It reflects appropriate non-negativity constraints on x_t $(x_{fc,t} \geq 0, x_{nc,t} \geq 0)$, along with the financial constraint in equation 8b and the physical constraints in equations 9b and 9d restricting individual choice.

Given these assumptions, the optimisation problem in equation 5 becomes:

$$V_t(I_t) = \text{Max}_{x_t \in X_t}\{E_t U(y_{h,t}, y_{o,t}) + \beta E_t V_{t+1}[I_t, g_{t+1}[f_{t+1}(y_t, x_t, e_t), x_t, v_{t+1}], x_t]\} \tag{12}$$

where $f_{t+1}(\cdot)$ is given in equations 6–10. Denote the solution of the optimisation problem in equation 12 by $x_t^*(I_t)$. The optimal dynamics is then given by: $y_{t+1} = f_{t+1}(y_t, x_t^*(I_t), e_t)$ and $I_{t+1} = (I_t, g_{t+1}(y_t, x_{t-1}, v_t), x_t^*(I_t))$. The formulation in equation 12 is general enough to allow for imperfect state information (where the actual value of some of the state variables in y_t is unobservable at time t) and active learning (where the individual's decisions influence how much information becomes available over time). This is important since the individual's nutritional status and health status are often imperfectly known. Also, individuals can learn about the state variable y_h through nutrition education, health education, health monitoring, etc.

Perfect state information is a special case of equation 12. It corresponds to the situation where equation 3 becomes $z_t = y_t$, i.e. where learning takes place through the observation of the actual state y_t at time t. Then, equation 12 simplifies to (e.g. Bertsekas 1976, p. 50):

$$V_t(y_t) = \text{Max}_{x_t \in X_t}\{E_t U(y_{h,t}, y_{o,t}) + \beta E_t V_{t+1}[f_{t+1}(y_t, x_t, e_t)]\}, \tag{12$'$}$$

where $f_{t+1}(\cdot)$ is given in equations 6–10. The optimal control associated with equation 12$'$ can be written as $x_t^*(y_t)$, and the optimal state dynamics is: $y_{t+1} = f_{t+1}(y_t, x_t^*(y_t), e_t)$.

3. Behavioural implications

The general model just presented can provide a basis for analysing the individual's behaviour. First, it is an extension of Stigler and Becker's (1977) model, incorporating risk and learning in the individual's production, consumption and investment decisions. Second, the model explicitly handles the evolution of the individual's health y_h over time. This includes the endogeneity of death, as represented by the absorbing state y_h^a under assumptions A2, A3 and A4. While assumption A4 makes the individual's death certain in the long run, the probability of living (or dying) is still subject to management in the short run. In this section, we investigate the behavioural implications of our model, focusing on the role of food and nutrition in the management of the individual's health.

Under differentiability, the first-order condition for an interior solution to the problem in equation 12 is:

$$E_t\{(\partial V_{t+1}/\partial z_{t+1})[(\partial g_{t+1}/\partial y_{t+1})(\partial f_{t+1}/\partial x_t) + (\partial g_{t+1}/\partial x_t)] + (\partial V_{t+1}/\partial x_t)\} = 0. \quad (13)$$

Equation 13 decomposes the marginal utility of x_t into three additive parts. The first term in equation 13, $E_t[(\partial V_{t+1}/\partial z_{t+1})(\partial g_{t+1}/\partial y_{t+1})(\partial f_{t+1}/\partial x_t)]$, reflects the marginal effect of x_t on the state variable y_{t+1}. This effect remains present even in the absence of uncertainty. More generally, it reflects the influence of the decisions x_t under perfect state information. To see that, consider the special case of equation 12′ where equation 3 takes the form $z_t = y_t$ corresponding to perfect state information. Under differentiability, the first-order condition for an interior solution to equation 12′ is:

$$E_t[(\partial V_{t+1}/\partial y_{t+1})(\partial f_{t+1}/\partial x_t)] = 0. \quad (13')$$

By comparing equations 13 and 13′, it is clear that the term in equation 13′ corresponds to the first term in equation 13. Thus, the first term in equation 13 reflects the marginal valuation of x_t under perfect state information. This implies that the second and third terms in equation 13 are necessarily associated with imperfect state information.

Equation 13 characterises the individual's optimal behaviour. We explore its implications for food allocation. First, consider the food consumption decision $x_{fc,t}$. From equation 13, the first-order condition for an interior solution to $x_{fc,t}$ is:

$$\begin{aligned} E_t\{(\partial V_{t+1}/\partial z_{t+1})[&(\partial g_{t+1}/\partial y_{h,t+1})(\partial f_{h,t+1}/\partial x_{fc,t}) - (\partial g_{t+1}/\partial y_{f,t+1})(1-\delta_f) \\ &+ (\partial g_{t+1}/\partial y_{o,t+1})(\partial f_{o,t+1}/\partial x_{fc,t}) + (\partial g_{t+1}/\partial x_{fc,t})] \\ &+ (\partial V_{t+1}/\partial x_{fc,t})\} = 0. \end{aligned} \quad (14a)$$

Equation 14a includes five additive terms. The first term measures the effect of food consumption on health, $\partial f_{h,t+1}/\partial x_{fc,t}$. The second term concerns the effect of food consumption on food inventory $y_{f,t+1}$. The third term represents the non-nutritional benefits of food consumption as it influences $y_{o,t+1}$. The fourth term (involving $\partial g_{t+1}/\partial x_{fc,t}$) and the fifth term ($E_t[\partial V_{t+1}/\partial x_{fc,t}]$) correspond to imperfect state information. This shows that the motivations for food consumption decisions can be complex.

Second, consider the food marketing decision $x_{fm,t}$. The first-order necessary condition for an interior solution to $x_{fm,t}$ is:

$$\begin{aligned} E_t\{(\partial V_{t+1}/\partial z_{t+1})[(\partial g_{t+1}/\partial y_{w,t+1})(1+\alpha_t)p_t - \partial g_{t+1}/\partial y_{f,t+1}(1-\delta_f) \\ + (\partial g_{t+1}/\partial x_{fm,t})] + (\partial V_{t+1}/\partial x_{fm,t})\} = 0. \end{aligned} \quad (14b)$$

Equation 14b includes four additive terms. The first term measures the effect of food marketing on the individual's budget constraint as reflected by $y_{w,t+1}$. The second term concerns the effect of food marketing on food inventory $y_{f,t+1}$. The third term (involving $\partial g_{t+1}/\partial x_{fm,t}$) and the fourth term ($E_t[\partial V_{t+1}/\partial x_{fm,t}]$) reflect imperfect state information. Again, this indicates that the motivations for making food marketing decisions can be complex.

Equations 14a and 14b can be combined to yield:

$$\begin{aligned} & E_t\{(\partial V_{t+1}/\partial z_{t+1})[(\partial g_{t+1}/\partial y_{h,t+1})(\partial f_{h,t+1}/\partial x_{fc,t}) + (\partial g_{t+1}/\partial y_{o,t+1})(\partial f_{o,t+1}/\partial x_{fc,t}) \\ & \quad + (\partial g_{t+1}/\partial x_{fc,t})] + (\partial V_{t+1}/\partial x_{fc,t})\} \\ & = E_t\{(\partial V_{t+1}/\partial z_{t+1})[(\partial g_{t+1}/\partial y_{w,t+1})(1+\alpha_t)p_t - (\partial g_{t+1}/\partial x_{fm,t}) + (\partial V_{t+1}/\partial x_{fm,t})\}. \end{aligned} \quad (15)$$

How does this analysis relate to more traditional microeconomic analysis of behaviour? In the context of food demand and nutrition, the investigation of an 'optimal diet' has been the subject of much research (e.g. Stigler 1945; Silberberg 1985). The optimal diet problem can be formulated as follows:

$$\mathrm{Min}_{x_{fc,t}\geq 0}\{p_t x_{fc,t}\colon N = N_t(x_{fc,t})\}, \quad (16)$$

where $N_t(x_{fc,t})$ is the nutrient production function in equation $6'$ and N is exogenously given. For example, N can be set equal to the nutrients actually consumed by the individual (e.g. Silberberg 1985). Alternatively, N can be chosen as the nutrients intake associated with a balanced diet recommended by nutritionists or dietitians. Denote the solution of equation 16 by $x^d_{fc,t}(N)$. It can provide a basis for investigating the links between food demand and nutrition. But, under what conditions does equation 16 provide an appropriate characterisation of consumption behaviour as given by equation 12? To answer this question, decompose the optimisation problem in equation 12 into two stages: a first stage where $x_{fc,t}$ is chosen subject to the additional constraint $N = N_t(x_{fc,t})$, conditional on given values of N and the other control variables in x_t; and a second stage where N and the remaining control variables are chosen. The first stage is:

$$\text{Max}_{x_{fc,t} \geq 0}\{E_t V_{t+1}[I_t, g_{t+1}(y_{t+1}, x_t, v_{t+1}), x_t]: N = N_t(x_{fc,t}); \text{equ. 6–10}\}. \qquad (17)$$

Denote by $x^c_{fc,t}(N)$ the optimal solution in equation 17, and by N^*_t the optimal solution for N in the second stage. The first stage problem in equation 17 being just a decomposition of the original problem in equation 12, the first stage decision is necessarily consistent with the optimal decision associated with equation 12 and always satisfies $x^*_{fc,t} = x^c_{fc,t}(N^*_t)$. We want to know under what conditions is the solution of equation 12 (and thus equation 17) also the solution of the diet problem equation 16.

Definition 1: The minimal cost diet problem in equation 16 is consistent with the individual's behaviour given by equation 12 whenever $x^d_{fc,t}(N) = x^c_{fc,t}(N)$ for all feasible N.

Conditions satisfying this consistency are presented next. (See the proof in the Appendix.)

Proposition 1: Assuming a positive marginal utility of income, the minimal cost diet problem in equation 16 is consistent with the individual's behaviour given by equation 12 if:

1. all the state variables y_t become observed at time t, and
2. the state variables $y_{o,t+1}$ are not affected by food consumption $x_{fc,t}$.

Proposition 1 presents conditions that makes the diet problem in equation 16 consistent with the more general allocation problem in equation 12. When consistency is satisfied, then $x^d_{fc,t}(N^*_t) = x^c_{fc,t}(N^*_t) = x^*_{fc,t}$, where N^*_t is the optimal nutrients intake from equation 12. This indicates that the diet problem in equation 16 can provide a useful basis for investigating food and nutrition decisions. Proposition 1 states that equation 16 is consistent with equation 12 if there is perfect state information, and if nutrition is the only motivation for consuming food. However, these two conditions are rather restrictive. First, the individual's health status is typically not perfectly known and is often the subject of active learning as the individual spends resources to monitor and evaluate his/her health over time. Second, food consumption seems prompted at least in part by non-nutritional motives. This includes factors such as the enjoyment of eating, food taste, food appearance, etc. Under such conditions, the minimal cost diet in equation 16 will not be consistent with individual behaviour given in equation 12.

To illustrate these arguments, consider the differentiable case. Under condition 1 in proposition 1, there is perfect state information. And under condition 2, $\partial f_{o,t+1}/\partial x_{fc,t} = 0$. Under these conditions, assuming that the marginal utility of income is positive, the first-order condition in equation 15 becomes:

$$\frac{E_t[(\partial V_{t+1}/\partial z_{t+1})(\partial g_{t+1}/\partial y_{h,t+1})(\partial y_{h,t+1}/\partial N_t)]}{E_t[(\partial V_{t+1}/\partial z_{t+1})(\partial g_{t+1}/\partial y_{w,t+1})(1+\alpha_t)]}(\partial N_t/\partial x_{fc,t}) = p_t. \qquad (18)$$

Interpreting

$$E_t[(\partial V_{t+1}/\partial z_{t+1})(\partial g_{t+1}/\partial y_{h,t+1})(\partial y_{h,t+1}/\partial N_t)]/E_t[\partial V_{t+1}/\partial z_{t+1})(\partial \partial_{t+1}/\partial y_{w,t+1})(1+\alpha_t)]$$

as the shadow price of nutrients, equation 18 states that the marginal value product of $x_{fc,t}$ equals the vector of food prices p_t. This familiar condition implies cost minimising behaviour as stated in equation 16. In this case, equation 16 can be interpreted as a first stage decomposition of the more general allocation problem in equation 12. However, comparing equations 15 and 18, it is clear that equation 18 is a rather restrictive case. As noted above, under imperfect state information or non-nutritional motives for food consumption, equation 18 does not hold in general, and cost minimising behaviour in equation 16 is not consistent with the individual's behaviour given in equation 12. The empirical results presented by Silberberg (1985) give strong evidence of the inconsistency of the two problems. Silberberg showed that, compared to $x^*_{fc,t}$, the cost minimal diet $x^d_{fc,t}(N^*)$ involves much fewer food commodities as it specialises in the food items that provide a cheaper source of nutrients. Also, Silberberg found that the discrepancy between $x^*_{fc,t}$ and $x^d_{fc,t}(N^*)$ tends to grow with income, as non-nutritional motives for food consumption become more important with higher income. On this basis, in many situations, one would expect observed behaviour to be inconsistent with the diet problem in equation 16.

So, is there any situation where the diet problem in equation 16 may be consistent with the more general allocation problem in equation 12? We argue here that this may happen under malnutrition. To see this, define a range $[y^a_h, y^a_h + v]$ identifying low levels of the individual's health status, for some small $v > 0$. We assume that the parameter $v > 0$ is chosen according to medical criteria such that $(y^a_h + v)$ represents some critical level of deteriorated health.

Definition 2: Given the information I_t available at time t, define the 'malnutrition set' M_t as follows:[6]

[6] Definition 2 defines malnutrition in terms of the expected health, $E_t f_{h,t+1}(\cdot)$. Note that alternative measures could be used as well. For example, in definition 2, expected health $E_t f_{h,t+1}(\cdot)$ could be replaced by median health or by some decile of the probability distribution of health, $y_{h,t+1}$.

$$M_t = \{x_t\colon x_t \in X_t;\ E_t f_{h,t+1}(y_{h,t}, x_{fc,t}, x_{nc,t}, e_t) \leq y_h^a + v;$$
$$E_t f_{h,t+1}(y_{h,t}, x_{fc,t} + d, x_{nc,t}, e_t) > y_h^a + v,\ \text{for some } d > 0\},$$

where E_t denotes the expectation operator given I_t.

By definition 2, any allocation $x_t \in M_t \subset X_t$ generates (on average) a low health status: $y_h^a < E_t(y_{h,t+1}) \leq y_h^a + v$. This low health level can be attributed to malnutrition since an increase in food intake is sufficient to improve the expected individual's health: $E_t f_{h,t+1}(y_{h,t}, x_{fc,t} + d, x_{nc,t}, e_t) > y_h^a + v$. It is on this basis that the set M_t is called the 'malnutrition set'. Finally, note that, food being necessary to sustain life (from assumption A3), the malnutrition set is always non-empty ($M_t \neq \emptyset$) for a healthy individual (where a healthy individual is any one with a 'high' expected health level, $E_t y_{h,t+1}$). For example, from assumption A3, any feasible x_t satisfying $x_{fc,t} \in S_t$ (e.g. $x_{fc,t} = 0$) is necessarily an element of M_t for a healthy individual. This suggests that all healthy individuals will be concerned with possible malnutrition. This is the issue of 'food security' further discussed in the next section.

Assuming that $M_t \neq \emptyset$, any allocation $x_t \in M_t$ represents a situation where the individual's health status $y_{h,t+1}$ is low because of lack of food consumption. Under what conditions is it likely that $x_t^* \in M_t$, where x_t^* is the solution of equation 12? This could happen under two possible scenarios. In the first scenario, the feasible set X_t is larger than M_t, but the individual is poorly informed on his/her health status $y_{h,t+1}$. In this case, the individual could choose $x_t \notin M_t$, but may elect to be malnourished because of poor nutritional information. Individuals who are poorly informed about nutrition and its health effects include infants and children. They can also include adults who are unaware of the strong links between individual nutrition and health. In addressing malnutrition issues, this stresses the role and importance of nutrition education.

The second scenario is the one where the malnutrition set M_t and the feasible set X_t are the same: $M_t = X_t$. In this case, no matter what decision is made about x_t, the individual has no choice but to be severely malnourished: $x_t \in M_t = X_t$. This may happen because not enough food is available, and/or because the individual is not entitled to the food that is available (Sen 1981).

We make the following additional assumption.

Assumption A6: For an individual facing $M_t = X_t$, the effect of food consumption of $x_{fc,t}$ on the state variables $y_{o,t+1}$ (as given by equation 10) is negligible.

Assumption A6 states that the feasible set X_t is a region where the marginal impact of $x_{fc,t}$ on $y_{o,t+1}$ is negligible: $\partial f_{o,t+1}/\partial x_{fc,t} = 0$. This means that food consumption does not provide non-nutritional benefits to an individual who is constrained to be severely malnourished. It is consistent with a common symptom of near-starvation: the insensitivity of the sufferer to every other feeling except that of satisfying his/her own wants for food intake.

What are the implications of our analysis for individual behaviour? To answer this question, note that the optimisation problem in equation 12 is conditional on the following parameters: $B_t = (s_{f,t}, s_{n,t}, T_{w,t}, R_t, c_{f,t}^-, c_{f,t}^+, c_{n,t}^-, c_{n,t}^+, T_{f,t}, T_{n,t}, K_{f,t}, K_{n,t})$, where $(s_{f,t}, s_{n,t}, T_{w,t}, R_t, c_{f,t}^-, c_{f,t}^+, c_{n,t}^-, c_{n,t}^+)$ are parameters of the wealth equation 8, and $(T_{f,t}, T_{n,t}, K_{f,t}, K_{n,t})$ are parameters of the inventory equation 9. What are the effects of changing the parameters B_t on behaviour $x_t^*(B_t)$ associated with equation 12? Consider two values for the vector B_t: B_t' and B_t''. The vector B_t' is defined such that it satisfies $M_t = X_t$. The vector B_t' thus corresponds to a situation where the individual is constrained to be malnourished. Define the vector B_t'' as follows:

$$B_t'' = \{B_t\colon s_{f,t}'' \leq s_{f,t}', s_{n,t}'' \leq s_{n,t}', T_{w,t}'' \geq T_{w,t}', R_t'' \geq R_t', c_{f,t}^{-\,\prime\prime} \leq c_{f,t}^{-\,\prime}, c_{f,t}^{+\,\prime\prime} \leq c_{f,t}^{+\,\prime},$$
$$c_{n,t}^{-\,\prime\prime} \leq c_{n,t}^{-\,\prime}, c_{n,t}^{+\,\prime\prime} \leq c_{n,t}^{+\,\prime}, T_{f,t}'' \geq T_{f,t}', T_{n,t}'' \geq T_{n,t}', K_{f,t}'' \geq K_{f,t}', K_{n,t}'' \geq K_{n,t}'\}.$$

Compared to B_t', B_t'' identifies an improved situation as the individual faces lower costs $(s_{f,t}'' \leq s_{f,t}', s_{n,t}'' \leq s_{n,t}', c_{f,t}^{-\,\prime\prime} \leq c_{f,t}^{-\,\prime}, c_{f,t}^{+\,\prime\prime} \leq c_{f,t}^{+\,\prime}, c_{n,t}^{-\,\prime\prime} \leq c_{n,t}^{-\,\prime}, c_{n,t}^{+\,\prime\prime} \leq c_{n,t}^{+\,\prime})$, higher income $(T_{w,t}'' \geq T_{w,t}')$, higher in-kind transfers $(T_{f,t}'' \geq T_{f,t}', T_{n,t}'' \geq T_{n,t}')$, higher storage capacities $(K_{f,t}'' \geq K_{f,t}', K_{n,t}'' \geq K_{n,t}')$, and higher borrowing capacity $(R_t'' \geq R_t')$. The following results hold. (See the proof in the Appendix.)

Proposition 2: Under assumption A6 and perfect state information, we have:

1. $x_{fc,t}^*(B_t') = x_{fc,t}^d(N_t^*(B_t'))$,
   where $N_t^*(B_t')$ is the optimal nutrients intake from equation 12 under situation B_t'.
2. Let m denote the total number of nutrients in equation 16. If the nutrient production function $N_t(x_{fc,t})$ in equation 16 is linear, then the number of food commodities exhibiting positive consumption in $x_{fc,t}^*(B_t')$ is at most equal to m.
3. $p_{f,t}'' x_{fc,t}^*(B_t'') \geq p_{f,t}'' x_{fc,t}^d(N_t^*(B_t''))$.

Proposition 2 compares the individual's behaviour in two situations: a situation B_t' where the individual is constrained to be malnourished; and an improved situation given by B_t''. It indicates how constrained malnutrition affects behaviour and how improved nutrition relates to the individual's behaviour.

To interpret results 1 and 2 in proposition 2, consider a well-informed individual being constrained to be malnourished (i.e. facing $M_t = X_t$) under assumption A6. Here, 'being well informed' is interpreted to correspond to 'perfect state information'. It rules out the case of 'poor nutritional information' discussed in scenario 1 above. And under B_t' and assumption A6, the effect of food consumption of $x_{fc,t}$ on the state variables $y_{o,t+1}$ is negligible: $\partial f_{o,t+1}/\partial x_{fc,t} = 0$. Under these conditions, the individual's behaviour (as represented by equation 12) is consistent with the minimal cost diet problem (equation 16) (see proposition 1). This is result 1, stating that a well-informed individual who is constrained to be malnourished $(M_t = X_t)$ would behave as if he/she minimises diet cost as given in equation 16. Result 2 shows that such an individual would also tend to consume only a limited number of food commodities. Under the stated conditions, minimising the cost of the diet implies consuming a number of food items no larger than the number of nutrients. Typically, the number of food items available to most individuals is much larger than the number of nutrients. Result 2 has significant implications: the consumption pattern of individuals who are constrained to be malnourished tends toward specialisation. This specialisation is characterised by positive consumption of few food items providing low-cost nutrients, and zero consumption of the other food items (Silberberg 1985).

Result 3 states that a well-informed individual facing the improved situation B_t'' may not consume food $x_{fc,t}^*$ so as to minimise diet cost. This means that the actual cost of obtaining the nutrients $N_t^*(B_t'')$, $(p_{f,t}'' x_{fc,t}^*(B_t''))$, can be larger (and possibly much larger) than the minimal cost $(p_{f,t}'' x_{fc,t}^d(N_t^*(B_t''))$. The reason is that, if situation B_t'' correspond to $X_t \neq M_t$, the individual may consume food for motives other than nutrition (e.g. taste, appearance, . . .). This would tend to raise the average cost of nutrients. Compared to situation B_t', it would also tend to increase the number of food items consumed. Food commodities that would not be consumed under B_t' (because of their high cost of providing nutrients) may be consumed under B_t'' because of their non-nutritional characteristics.

These results are consistent with the empirical evidence presented by Silberberg (1985), Behrman and Deolikar (1987), Bouis and Haddad (1992), and others. Silberberg showed that the fraction of food expenditures devoted to pure nutrition tends to decrease with income. Also, Behrman and Deolikar (1987), and Bouis and Haddad found that higher income tends to increase total food expenditure relatively more than nutrients intake. These empirical findings agree with our analysis since the move from B_t' to B_t'' can simulate an increase in income $(T_{w,t}'' \geq T_{w,t}')$. However, proposition 2 applies in a broader context. It shows that similar results hold when the change from B_t' to B_t'' simulates a decrease in cost $(s_{f,t}'' \leq s_{f,t}', s_{n,t}'' \leq s_{n,t}', c_{f,t}^{-\,''} \leq c_{f,t}^{-\,'}, c_{f,t}^{+\,''} \leq$

$c_{f,t}^{+\prime}$, $c_{n,t}^{-\prime\prime} \leq c_{n,t}^{-\prime}$, $c_{n,t}^{+\prime\prime} \leq c_{n,t}^{+}$), higher in-kind transfers ($T_{f,t}'' \geq T_{f,t}'$, $T_{n,t}'' \geq T_{n,t}'$), higher storage capacities ($K_{f,t}'' \geq K_{f,t}'$, $K_{n,t}'' \geq K_{n,t}'$), and/or higher borrowing capacity ($R_t'' \geq R_t'$). This indicates how the implicit cost of nutrition can vary with changes in the socio-economic environment surrounding any individual.

Our analysis can help shed some light on food consumption behaviour and nutrition. An example is the existence of inferior and Giffen goods. Proposition 2 predicts that, under constrained malnutrition ($M_t = X_t$), food consumption patterns will tend to specialise toward few food items that provide a cheap source of nutrients. In the case where malnutrition is associated with low income, this implies that low income will generate a relatively high consumption of few food items. As income goes up, this specialisation in food consumption can be expected to disappear. This can generate negative income effects for the few food items consumed under constrained malnutrition. As the income of a malnourished individual goes up, the non-nutritional motives for food consumption become more important, and the individual diversifies his/her consumption patterns: he/she consumes less of the food items found in the least-cost diet, and more of other food commodities. As a result, individuals belonging to the lowest income classes may exhibit negative income elasticities for the foods found in the least-cost diet. When strong enough (i.e., in the presence of extreme forms of specialisation in the least-cost diet), these negative income elasticities can contribute to generating 'Giffen effects'. An example is potato consumption during the 1845–48 famine in Ireland (Davies 1994).

Having negative income elasticities for foods in the low-cost diet contributes to finding small income elasticities for nutrient intake demand (Behrman and Deolikar 1987; Glomm and Palumbo 1993). This would be especially true if the least-cost diet is very specialised and/or if nutrition education is poor. In such situations, increasing income would have only modest effects on nutrient intake. In addressing malnutrition issues, this points to the limitations of relying exclusively on income policy, and to the need for complementary policy instruments (such as restricted in-kind transfers, or nutrition education). Alternatively, in situations where the least-cost diet is reasonably well diversified and nutrition education is good, the links between individual income and nutritional status are expected to be stronger and positive. Then, raising income (through either cash transfers or economic development policy) can be an effective way of dealing with malnutrition problems.

4. Implications for food security

In this section, we further explore the relationships between food consumption, nutrition and survival. In particular, we analyse food security in terms of the individual's ability to avoid starvation. Recall that y_h^a is an absorbing state for the individual's health status representing death (see assumption A2). Given x_t, the probability of the individual dying at time $(t+1)$ is the mortality probability:

$$\Pr_t(x_t) = \text{Prob}[y_{h,t+1} = y_h^a\colon x_t \in X_t;\ y_{t+1} = f_{t+1}(y_t, x_t, e_t) \text{ as in equations 6–10}], \tag{19}$$

where the probability Prob[·] is evaluated based on the information available at time t.

We want to study the general effects of the economic decisions x_t on the individual's ability to survive over time.[7] Define the set $F_t^d = \{x_t\colon \Pr_t(x_t) = 1\}$, corresponding to the decisions x_t that imply the individual's death with probability one at time $(t+1)$. This set is always non-empty $F_t^d \neq \emptyset$. For example, any feasible allocation x_t generating starvation (i.e., satisfying $x_{fc,t} \in S_t$) is necessarily an element of the set F_t^d. Also, we define the set $F_t^s = \{x_t\colon \Pr_t(x_t) < 1\}$ as the complement of F_t^d in X_t, i.e. as the set of all feasible decisions x_t that provide a positive probability of survival for the individual at time $(t+1)$. The following result is obtained. (See the proof in the Appendix.)

Proposition 3: Under assumptions A2 and A5, x_t^* (the optimal solution of (12)) satisfies $x_t^* \in F_t^s$ if the set F_t^s is non-empty. Alternatively, $x_t^* \in F_t^d$ only if $F_t^d = X_t$ (or equivalently, $F_t^s \neq \emptyset$).

Proposition 3 states the intuitive result that, under assumption A5, the individual always prefers positive probabilities of survival ($\Pr_t < 1$) to the certainty of death ($\Pr_t = 1$). He/she always tries to avoid choosing x_t in the set F_t^d, except when there is no other feasible choice, i.e. when the set F_t^s is empty. But when is the set F_t^s empty? For a living individual, the set F_t^s would be empty in situations of extreme deprivation involving a lack of access to basic necessities such as food or health care.

Consider the case where the individual has limited access to food consumption at time t. As argued above, the individual will choose $x_{fc,t}^* \in S_t$ only if there is no other feasible choice. It implies that starvation is always the outcome of severely constrained choices. This has motivated the 'entitlement approach' to food security, as proposed by Sen.

Our analysis allows alternative characterisations of food security. For example, a situation of trade-independent food security corresponds to: $\{x_t\colon x_t \in X_t;\ x_{fm,t} = 0\} \cap \{x_t\colon x_t \in X_t;\ x_{fc,t} \notin S_t\} \neq \emptyset$. This means that, in the

[7] Ravallion (1987) has examined the properties of the mortality probability $\Pr_t(x_t)$ with respect to food consumption $x_{fc,t}$, and its implications for the management of famine relief policy.

absence of food trade ($x_{fm,t} = 0$), it remains possible to choose x_t without falling within the starvation set S_t (Sen 1981, p. 172). In general, adult members of well-endowed farm households facing favourable agro-climatic conditions are expected to exhibit trade-independent food security. However, as noted by Sen (1981, p. 173), trade-independent security does not characterise a large part of the world population. The development of trade, the specialisation of labour, and the associated growth in urban populations have contributed to a decline in trade-independent food security around the world. For example, in the absence of transfers, any member of a working class with nothing to sell but labour power (e.g. urban worker, or landless agricultural labourer) typically lacks trade-independent food security.

Similarly, a situation of production-independent food security corresponds to: $\{x_t: x_t \in X_t; y_{p,t} = 0\} \cap \{x_t: x_t \in X_t; x_{fc,t} \notin S_t\} \neq \emptyset$. This means that, in the absence of food production ($y_{p,t} = 0$), it remains possible to choose x_t without facing certain starvation. In the presence of active food markets, adult members of rich urban households are expected to exhibit production-independent food security. However, production-independent food security is typically *not* satisfied for members of most farm households around the world. For example, in the absence of transfers, any member of a farm household that does not generate significant off-farm income typically lacks production-independent food security. In general, food security is threatened for farm households facing agricultural production shortfall due to drought, pest damage, flooding, soil erosion and/or environmental degradation.

In addition, a situation of transfer-independent food security corresponds to: $\{x_t: x_t \in X_t; T_{w,t} = 0, T_{f,t} = 0, T_{n,t} = 0\} \cap \{x_t: x_t \in X_t; x_{fc,t} \notin S_t\} \neq \emptyset$. This means that, in the absence of transfers to the individual ($T_{w,t} = 0$, $T_{f,t} = 0$, $T_{n,t} = 0$), it remains possible to choose x_t without starving.[8] In general, in the presence of active food markets, able-bodied adults in rich households are expected to exhibit transfer-independent food security. However, transfer-independent food security is typically not satisfied for significant parts of the world population. This includes infants, children, and the elderly, as well as members of poor households. Infants, children and the elderly commonly rely on income and in-kind transfers from other members of their household. Poor households are often the targets of income and in-kind transfers from local institutions, charitable organisations,

[8] Note that more specific definitions could be given. This includes income-transfer-independent food security corresponding to: $\{x_t: x_t \in X_t; T_{w,t} = 0\} \cap \{x_t: x_t \in X_t; x_{fc,t} \notin S_t\} \neq \emptyset$. It implies that it is possible to avoid starvation without income transfer to the individual ($T_{w,t} = 0$). This also includes food-transfer-independent food security corresponding to: $\{x_t: x_t \in X_t; T_{f,t} = 0\} \cap \{x_t: x_t \in X_t; x_{fc,t} \notin S_t\} \neq \emptyset$. It means that, in the absence of food transfer to the individual ($T_{f,t} = 0$), it remains possible to choose x_t without starving.

government welfare programs, as well as international donor agencies. And most households benefit from insurance schemes that generate 'state-dependent' transfers contributing significantly to long-term food security in an uncertain world. Such transfers are part of a system of 'safety nets' implemented in various ways both within the household and across households. It includes the activities of philanthropic organisations as well as government agencies involved in disaster assistance, unemployment compensations, etc. It also includes limited liability rules (e.g. bankruptcy laws) that reduce individuals' exposure to downside risk.

Finally, a situation of stock-independent food security corresponds to: $\{x_t: x_t \in X_t; y_{f,t} = 0\} \cap \{x_t: x_t \in X_t; x_{fc,t} \notin S_t\} \neq \emptyset$. It implies that, in the absence of food stocks ($y_{f,t} = 0$), it remains possible to choose x_t without facing starvation. Significant temporal fluctuations in supply and market conditions can contribute to the absence of stock-independent food security. This corresponds to situations where seasonality, cyclical production (as typically found in agriculture) and/or uncertainty about the economic environment (e.g. production risk or price uncertainty) are important features of the individual's surroundings. In general, in the presence of active food markets, adult members of well-endowed households would exhibit stock-independent food security. Alternatively, in the absence of transfers and under poorly functioning food markets, considerable fluctuations and uncertainty in temporal food production can yield a lack of stock-independent food security. This characterises many farm households in developing countries. It stresses the role of food stocks in food security.

The above discussion suggests a need to focus on the factors restricting the feasible set for food consumption $x_{fc,t}$. Under what situations would food consumption $x_{fc,t}$ be constrained within the starvation set S_t? Recall the definition of the feasible set $X_t = \{x_t: x_{fc,t} \geq 0, x_{nc,t} \geq 0$, equations 8b, 9b and 9d$\}$. Equations 8b and 9b give the following inequalities:

$$-p_{f,t}x_{fm,t} \leq y_{w,t} + R_t + p_{n,t}x_{nm,t} - s_{f,t}y_{f,t} - s_{n,t}y_{n,t} + T_{w,t}, \tag{20a}$$

and

$$x_{fc,t} \leq y_{f,t} + y_{p,t} - x_{fm,t} + T_{f,t}. \tag{20b}$$

Equation 20a is a budget constraint setting an upper-bound on food purchases ($-x_{fm,t}$). It shows that food expenditures ($-p_{f,t}x_{fm,t}$) can be no greater than current equity ($y_{w,t}$), plus maximal borrowing capacity (R_t), plus income from non-food commodities ($p_{n,t}x_{nm,t}$),[9] minus storage cost ($s_{f,t}y_{f,t} + s_{n,t}y_{n,t}$), plus income transfer to the individual ($T_{w,t}$). Equation 20b

[9] Recall that time allocation is included as a non-food commodity. As a result, ($p_{n,t}x_{nm,t}$) includes wage income earned by the individual on the labour market.

reflects the material balance for food. It states that food consumption at time t ($x_{fc,t}$) can be no greater than the sum of food stocks ($y_{f,t}$), food production ($y_{p,t}$), food purchases ($-x_{fm,t}$), and food transfers ($T_{f,t}$).

In the case where food is treated as a single aggregate commodity, equations 20a and 20b yield:

$$x_{fc,t} \leq y_{f,t} + y_{p,t} + [y_{w,t} + R_t + p_{n,t}x_{nm,t} - s_{f,t}y_{f,t} - s_{n,t}y_{n,t} + T_{w,t}]/p_{f,t} + T_{f,t}. \quad (21)$$

Equation 21 illustrates that the largest feasible food consumption $x_{fc,t}$ is positively related to food stock ($y_{f,t}$), food production ($y_{p,t}$), monetary wealth ($y_{w,t}$), maximal borrowing capacity (R_t), non-food income ($p_{n,t}x_{nm,t}$), income transfer ($T_{w,t}$), and food transfer ($T_{f,t}$); and negatively related to storage cost ($s_{f,t}y_{f,t} + s_{n,t}y_{n,t}$) and food price ($p_{f,t}$). Given $x_t \in X_t$, this shows that the upper-bound for $x_{fc,t}$ depends on the parameter vector $B_t = (s_{f,t}, s_{n,t}, T_{w,t}, R_t, c^-_{f,t}, c^+_{f,t}, c^-_{n,t}, c^+_{n,t}, T_{f,t}, T_{n,t}, K_{f,t}, K_{n,t})$. Also, from assumption A3, the level of this upper-bound influences whether or not the $x_{fc,t}$ is restricted to be within the starvation set S_t. On the one hand, a sufficiently low upper-bound implies starvation: $x_{fc,t} \in S_t$ for all feasible $x_t \in X_t$. On the other hand, a sufficiently high upper-bound guarantees that the individual can avoid starvation: $\{x_{fc,t}\colon x_t \in X_t; x_{fc,t} \notin S_t\} \neq \emptyset$. This establishes the link between the economic environment (as represented by the parameter vector B_t) and whether or not the constraint $x_{fc,t} \in S_t$ is binding. To illustrate this, consider two parameter vectors B^d_t and B^s_t. Define B^d_t as corresponding to a situation of extreme deprivation where the individual starves to death: $x_{fc,t} \in S_t$ for all $x_t \in X_t$. And define B^s_t as follows:

$$\begin{aligned} B^s_t = \{B_t\colon\ & s^s_{f,t} \leq s^d_{f,t}, s^s_{n,t} \leq s^d_{n,t}, T^s_{w,t} \geq T^d_{w,t}, R^s_t \geq R^d_t, (c^-_{f,t})^s \leq (c^-_{f,t})^d, (c^+_{f,t})^s \leq (c^+_{f,t})^d, \\ & (c^-_{n,t})^s \leq (c^-_{n,t})^d, (c^+_{n,t})^s \leq (c^+_{n,t})^d, T^s_{f,t} \geq T^d_{f,t}, T^s_{n,t} \geq T^d_{n,t}, K^s_{f,t} \geq K^d_{f,t}, K^s_{n,t} \geq K^d_{n,t}\}. \end{aligned}$$

Compared to B^d_t, B^s_t identifies an improved situation as the individual faces lower costs ($s^s_{f,t} \leq s^d_{f,t}, s^s_{n,t} \leq s^d_{n,t}, (c^-_{f,t})^s \leq (c^-_{f,t})^d, (c^+_{f,t})^s \leq (c^+_{f,t})^d, (c^-_{n,t})^s \leq (c^-_{n,t})^d, (c^+_{n,t})^s \leq (c^+_{n,t})^d$), higher income transfers ($T^s_{w,t} \geq T^{d\,\prime}_{w,t}$), higher in-kind transfers ($T^s_{f,t} \geq T^d_{f,t}, T^s_{n,t} \geq T^d_{n,t}$), higher storage capacities ($K^s_{f,t} \geq K^d_{f,t}, K^s_{n,t} \geq K^d_{n,t}$), and higher borrowing capacity ($R^s_t \geq R^d_t$). The following result follows directly from assumption A3 and the definition of the feasible set $X_t = \{x_t\colon x_{fc,t} \geq 0, x_{nc,t} \geq 0$, equations 8b, 9b and 9d$\}$.

Proposition 4: Under the two situations B^d_t and B^s_t just defined,

$$\emptyset = \{x_t\colon x_t \in X_t; x_{fc,t} \notin S_t;\ \text{given } B^d_t\} \subset \{x_t\colon x_t \in X_t; x_{fc,t} \notin S_t;\ \text{given } B^s_t\},$$

or equivalently,

$$1 = \Pr_t(x_t;\ \text{given } B^d_t) \leq \Pr_t(x_t;\ \text{given } B^s_t),$$

where $Pr_t(\cdot)$ is defined in equation 19.

Proposition 4 states that moving from B_t^d to B_t^s tends to enlarge the non-starvation set $\{x_t: x_t \in X_t; x_{fc,t} \notin S_t;$ given $B_t\}$ and increase the individual's odds of survival. It also indicates which changes in the individual's economic environment contribute to improving food security. This is of interest to the extent that these changes are linked to specific policy instruments. First, proposition 4 shows that a reduction in storage cost ($s_{f,t}^s \leq s_{f,t}^d$, $s_{n,t}^s \leq s_{n,t}^d$) and an increase in storage capacity ($K_{f,t}^s \geq K_{f,t}^d$, $K_{n,t}^s \geq K_{n,t}^d$) contribute to improving food security. This reflects the role of inventories in managing food security. Second, income transfer ($T_{w,t}^s \geq T_{w,t}^d$) and in-kind transfers ($T_{f,t}^s \geq T_{f,t}^d$, $T_{n,t}^s \geq T_{n,t}^d$) to the individual can help avoid starvation. These are the most common policy instruments used in dealing with famines, poverty and malnutrition. Income transfers can involve intra-household transfers, remittances, income tax, and cash-welfare government programs. In-kind transfers can involve food as well as non-food. Food transfers include intra-household transfers (e.g. to infants and children) as well as food aid implemented by charitable organisations (e.g. soup kitchens), government agencies (e.g. food stamp program), or international agencies. Non-food transfers include public works, inheritance as well as changes in property rights (e.g. land tenure reform). For example, Sen has argued that India's public employment schemes are a principal reason why India has eliminated famine over the last few decades. Third, a reduction in capital market imperfections and increases in borrowing capacity ($R_t^s \geq R_t^d$) can help ameliorate food security. This stresses the importance of a properly functioning capital market in dealing with famines, starvation and malnutrition. Finally, reduction in market transaction costs ($(c_{f,t}^-)^s \leq (c_{f,t}^-)^d$, $(c_{f,t}^+)^s \leq (c_{f,t}^+)^d$, $(c_{n,t}^-)^s \leq (c_{n,t}^-)^d$, $(c_{n,t}^+)^s \leq (c_{n,t}^+)^d$) can strengthen food security. This shows that market inefficiencies can contribute to food insecurity. And investments in infrastructure that reduce transportation cost (railroads, bridges, all-season roads, etc.) and information cost (e.g. published price surveys, market analysis) can help individuals avoid famines and starvation. This stresses the role of markets in managing food security.

As illustrated in equation 21, any decrease (increase) in non-food to food price ratios $p_{n,t}/p_{f,t}$ contributes to food insecurity (food security). For example, over the last decades, rising food prices have contributed significantly to several famines in South Asia and Africa, by reducing the food purchasing power of poor and food-deficit households (Sen 1981; Ravallion 1997). 'Cheap food' policies found in many developing countries in the 1960s and 1970s have helped enhance food security for the urban poor. 'Structural adjustment programs' put in place in the 1980s and 1990s have mostly ended such policies. With labour being included among non-food commodities, any decrease (increase) in the wage rate can threaten (improve) food security for the employed. For example, by reducing food purchasing power, a fall in the agricultural wage rate contributed to the 1974–75 famine in Bangladesh (Sen 1981; Ravallion 1997).

In a period of increased reliance on markets, the current challenge around the world is to design market and non-market institutions that effectively address the issues of food security, malnutrition and starvation, especially for the poor and the unfortunate. The objective then is to reduce the probability of individuals falling below some threshold level of food access. Barrett (1999) identifies three key elements to successful food security strategies: 1 stable employment, income growth, and high labour productivity; 2 access to finance, food markets, and storage; and 3 private and public safety nets providing transfers to those in needs. Over the last few decades, economic growth has contributed to large improvements in global food security (Duncan 1999). Yet, food insecurity remains significant and tends to be concentrated in areas where both government and markets are weak (e.g. North Korea in the 1990s). Many non-government organisations (NGOs) have proved very effective in developing emergency feeding programs worldwide. But the role of government policy remains significant in providing food assistance both domestically and internationally (Barrett 1999; Drèze and Sen 1993; Pinstrup-Andersen 1993; Ruttan 1995). This includes food aid for famine relief, sometimes triggered by 'early-warning systems'. In government food programs, transfers in kind often receive greater political support than cash assistance, presumably because they support only the particular expenditures deemed worthy of assistance. Also, restricted food transfers (e.g. food stamps) have been found to increase nutrient intake at two to ten times the rate of an equivalent cash transfer (Chavas and Keplinger 1983; Barrett 1999). Thus, in-kind food transfers can be effective ways of dealing with food insecurity, provided that they are properly targeted toward those at nutritional risk. These are strong arguments in favour of targeted in-kind food assistance programs. For example, narrowly targeted programs (such as the US WIC program targeted toward women, infants, and children at nutritional risk) have been found highly effective in improving beneficiaries' nutritional status and physical well-being (Chavas and Keplinger 1983; Barrett 1999). Yet, because of high administrative cost and/or difficulties in identifying individuals facing food insecurity, targeting is not always feasible. In developed countries, targeting is often done at the household level on the basis of income, family size, and work status (e.g. the US food stamp program). This neglects intra-household variations in food security (e.g. children versus adults). This is a reminder that, nutritional status being fundamentally an individual characteristic, any aggregation (e.g. to the household or regional level) suppresses within-group variability, leading to downward-biased estimates of food insecurity (Drèze and Sen 1993; Pitt *et al.* 1990). This stresses the need for a better understanding of distribution issues both inter- and intra-households. In developing countries, administrative targeting is less common, largely due to high implementation cost. Rather, 'self-targeting' programs are more common. They are designed so that mostly food-insecure individuals have an incentive to participate. They include subsidies for 'inferior foods', and food-for-work schemes (Barrett 1999). In general, in-kind food transfers yield greater additional nutritional intake and are often better targeted. Alternatively, cash transfers reduce administrative costs, but are less effective in improving food security.

5. Conclusion

This article has presented a microeconomic model relevant to the analysis of food security. Since malnutrition and starvation are inherently individual characteristics, our model is developed at the individual level. This is more disaggregated than the traditional household-level analysis. Special attention is given to income as well in-kind transfers. The analysis is general in the sense that it incorporates dynamics, uncertainty and learning, along with the basic characteristics of human nutrition and health.

The approach evaluates individual behaviour under alternative situations of food insecurity, including malnutrition and starvation. It provides useful insights on how markets and entitlements influence individual food security. First, it helps identify the conditions that generate food insecurity. Second, it shows how income and nutritional education can interact in their effects on individual nutritional status. Finally, it shows how policy instruments commonly used in the management of food security (e.g. market transaction costs, cash transfers, in-kind transfers, improved infrastructure) relate to individuals' nutritional and health status. This stresses the need to understand better the institutional relationship between individuals and their socio-economic environment, including intra-household allocation rules, inter-household contractual arrangements, and food policy design. A good understanding of these rules along with their influence on resource allocation and human survival appears crucial in the effective policy management of food security issues.

Appendix

Proof of Proposition 1: Consider the case where all state variables y_t are observed at time t (condition 1 in proposition 1). This is the case of perfect state information where equation 3 becomes $z_t = y_t$ (i.e. where $g_{t+1}(y_{t+1}, x_t, v_{t+1}) = y_{t+1}$ in equation 3), and where $V_{t+1}(I_t, z_{t+1}, x_t)$ becomes $V_{t+1}(y_{t+1})$ (see equation 12′). In this context, assuming that the marginal utility of income is positive, and after dropping irrelevant constraints from (17), the solution $x^c_{fc,t}(N)$ of equation 17 can be obtained by solving the following problem:

$$\mathrm{Min}_{x_{fc,t}\geq 0}\{p_{f,t}x_{fc,t}: N = N_t(x_{fc,t});\ y_{o,t+1} = f_{o,t+1}(y_t, x_{fc,t}, x_{nc,t}, e_t)\}.$$

Comparing this problem with equation 16, it is clear that they have identical solutions ($x^d_{fc,t}(N) = x^c_{fc,t}(N)$) if $x_{fc,t}$ is not an argument of the function $f_{o,t+1}(\cdot)$. This is the case if the state variables $y_{o,t+1}$ are not affected by food consumption $x_{fc,t}$ (condition 2 in proposition 1).

Proof of Proposition 2: Result 1 follows directly from proposition 1 under assumption A6 and perfect state information. To prove result 2, note that, $N_t(x_{fc,t})$ being linear, equation 16 becomes a standard linear programming problem with m constraints. From linear programming, the number of non-zero variables in the optimal solution cannot exceed m. Result 2 then follows from result 1.

Finally, given the definitions of B'_t and B''_t, note that the feasible set $X_t(B''_t)$ is at least as large as the feasible set $X_t(B'_t)$: $X_t(B''_t) \supset X_t(B'_t)$. With B'_t defined such that $X_t(B'_t) = M_t(B'_t)$, moving from B'_t to B''_t tends to enlarge the feasible set and offers new opportunities for the feasible set $X_t(B''_t)$ to be larger than the malnutrition set $M_t(B''_t)$: $X_t(B''_t) \supset M_t(B''_t)$. But without $X_t(B''_t) = M_t(B''_t)$, assumption A6 no longer holds and condition 2 in proposition 1 may no longer be satisfied, implying that $x^*_{fc,t}(B''_t)$ may no longer be the minimal cost diet. This implies result 3.

Proof of Proposition 3: Noting that F^s_t is the complement of F^d_t in the feasible set X_t, assume the contrary: $x^*_t \notin F^s_t$, or equivalently, $x^*_t \in F^d_t$. This means that the individual chooses to die at time $(t+1)$, with $y_{h,t+1} = y^a_h$ with probability one. From assumptions A2 and A5, the utility obtained after the time of death is a strict lower-bound on all possible utility levels. Thus, as long as the set F^s_t is non-empty, the optimal choice x^*_t from equation 12 cannot be an element of the set F^d_t. By contradiction, this implies $x^*_t \in F^s_t$.

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