Agricultural policy in an uncertain world

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Abstract
This paper briefly reviews the current food situation and provides some historical perspectives on its evolution over time. It documents the important effects of agricultural productivity. It also evaluates the role of externalities, uncertainty and policy in the agricultural sector. The analysis stresses the joint role of uncertainty and externalities in the analysis of efficiency issues in the agricultural sector. Implications for farm management and agricultural policy are discussed.

Keywords: agriculture, efficiency, technological change, uncertainty, policy

JEL classification: Q1, D6, D8

1. Introduction
The role of agriculture in the world is complex. While farming is in the business of using agro-ecosystem services to feed people, it does so in different ways over time as well as across space. This paper briefly reviews the current food situation and provides some historical perspectives on its evolution over time. And it documents the important effects of agricultural productivity. It also evaluates the role of externalities, uncertainty and policy in the agricultural sector. But addressing all the complexities of agriculture cannot be accomplished within a single paper. This means that our analysis must be limited in scope. As a result, we focus only on a subset of the important issues facing agriculture today. In addition, our discussion centres on agriculture in the USA and Europe.

This paper focuses on the joint role of uncertainty and externalities in the analysis of efficiency issues in the agricultural sector. Production uncertainty is an important characteristic of agriculture: unpredictable factors such as

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1 Some important issues we do not cover include food quality, food safety and the dynamics of agro-ecosystem management.

2 Yet, many of the arguments presented in this paper appear relevant to agriculture around the world.
weather effects, diseases and pest damages can have large effects on farm outputs. Agricultural markets can also be unstable, generating large price volatility that can be difficult to anticipate. This stresses the role of risk management in the agricultural sector. In addition, agricultural production involves using ecosystem services to produce food. The functioning of agro-ecosystems is complex and involves significant interactions among many variables (water, nutrients, water, temperature, etc.). These interactions often take forms of externalities that need to be managed. Coase (1960) proposed an approach to identify the efficient management of externalities. Interestingly, he used interactions between crops and livestock to motivate his analysis. The last few decades have seen a rise in ecological concerns with implications for agricultural management and policy. These concerns make Coase’s analysis even more relevant today.

The paper is organised as follows. After presenting a broad overview of the recent history of agriculture, the paper documents advances in farm productivity as well as some challenges facing the food sector (in Section 2). This helps motivate the need to improve the management of both risk and externalities in agriculture. An important contribution of the paper is to extend the Coasian approach to include risk allocation in efficiency evaluations (in Sections 3 and 4). Implications for farm management and agricultural policy are discussed in Section 5. Section 6 evaluates current and future challenges for the economics of agriculture and agricultural policy.

2. Historical perspectives

Agriculture is in the business of feeding people. Figure 1 shows the increase in the human population over the last few centuries. In 2011, the world population reaches 7 billion people. The growth rate in population peaked in the late 1960s (when it exceeded 2 per cent a year) and has now declined to 1.2

![Fig. 1. Evolution of the world population. Source: US Census Bureau (2010).](image-url)
per cent a year. Yet, 1 billion people have been added over the last 11 years. Feeding the growing world population is a significant challenge.

This challenge has generated a debate involving two polar scenarios. On the one hand, increases in human population put pressure on natural resources and the ability of the earth to provide food for all. This is the Malthusian scenario, which associates population increases with rising resource scarcity and the spread of famine. On the other hand, technological progress has greatly increased the productivity of land and labour. Under a positive feedback from the size and density of human population to technological change, productivity growth can help deal with increased resource scarcity. This is the Boserupian scenario, which relies on induced innovations (Boserup, 1965, 1981). The induced innovation hypothesis states that new technologies are likely to develop and be adopted in response to changes in resource scarcity (Hicks, 1932; Binswanger, 1974; Ruttan, 2001; Acemoğlu, 2002; Acemoğlu et al., 2009). For example, it means that increasing (decreasing) the cost of a resource tends to stimulate the development and use of technologies that reduce (increase) the use of this resource.

Agriculture provides a great case study of the induced innovation hypothesis. The rise of agriculture some 10,000 years ago appears consistent with induced innovations. As documented by Boserup (1965, 1981) and Kremer (1993), the historical evidence shows that the switch from hunting-gathering to agriculture did not take place without a rise in population density. The argument is that farming requires more effort than hunting-gathering, implying that no individual would want to switch from hunting-gathering to farming unless the former fails to provide enough food to satisfy human needs. This latter scenario develops when the human population rises beyond some threshold where the ecosystem can no longer feed the human population through hunting-gathering activities alone. It means that the historical rise of agriculture was an induced response to food scarcity associated with a rising population. This includes the cultivation of wheat and barley in Mesopotamia, starting around 8000 BC, of maize in Mexico and of rice in China starting around 5000 BC (Heiser, 1990: 6–8).

### 2.1 Food prices

The evolution of food prices over the last decade is shown in Figure 2 for three agricultural commodities: corn, wheat and rice. It shows very large changes in food prices in 2008. In a period of few months, food prices basically doubled, followed by a very sharp decline. The changes were most dramatic for rice. These rapid price fluctuations are quite unsettling for any market participant. Higher commodity prices benefit sellers (including grain farmers), but they hurt buyers (including consumers, and dairy/livestock farmers who face higher feed cost). Alternatively, lower commodity prices benefit buyers (including consumers), but they hurt sellers. While there are many factors contributing to such large price swings, this market instability makes anticipating future price patterns very difficult. It means the presence of significant price
risk/uncertainty for market participants. This puts a premium on developing management and/or policy schemes that can help deal with this uncertainty.

A longer-term look at agricultural prices is given in Figure 3. It shows the real price of food over the last century for three farm commodities: corn, milk and wheat. The prices are real US prices, defined as nominal prices divided by the US consumer price index (normalised to equal 1 in 1983). By correcting for inflation, these real prices give useful information on the evolving performance of agriculture in feeding the world. They show two important characteristics. First, they exhibit a trend towards a long-term decline in real prices. Over the last 90 years, the average annual rate of change in real price was $-1.8\%$ per cent for corn, $-1.9\%$ per cent for wheat and $-0.8\%$ per cent for milk. For consumers, this reflects a decline in the real cost of food. This is a remarkable fact: agriculture has been able to feed the growing world population at a lower price for consumers. Second, Figure 3 exhibits
much variability in real prices over time. Two periods are particularly noteworthy: the 1930s (during the Great Depression) when food prices were very low; and the early 1970s when food prices were very high. The 1970s was a period exhibiting high population growth and increased resource scarcity. But it was followed by three decades of fairly steady decline in real prices for food. While this may be good news for consumers, it raises the question about what is coming next.

2.2 Agricultural productivity

What is the main source of the long-term decline in real food prices? The short answer is: improvements in agricultural productivity. Figures 4 and 5 illustrate the evolution of agricultural yields over the last few decades. Figure 4 shows how US yields have changed for three commodities: corn, wheat and milk. Over the last 80 years, the average annual growth rate in yield was 2.0 per cent per year for corn and 1.4 per cent per year for wheat, reflecting very large increases in land productivity. Similarly, the last 80 years have seen an average annual growth rate in milk production per cow of 1.9 per cent per year. Figure 5 shows the evolution of yield for selected farm commodities in France. Like Figure 4, it shows a large and steady increase in land productivity over the last 50 years. Since 1930, the average annual growth rate in yield was 2.3 per cent per year for corn and 1.9 per cent per year for soft wheat. These are very large increases that were crucial in increasing food production.

How much of these increases come from technological change? Part of the historical increases in food production came from increased input use (e.g. fertiliser, pesticides, capital). But the evidence shows that most of these increases came from technological improvements (Ball et al., 1997; Gardner, 2002; Fuglie, 2008). For example, Ball et al. (1997) documented that US agricultural production grew at an average rate of 2 per cent annual rate over the last few

![Fig. 4. Evolution of agricultural yields, USA, 1913–2010. Source: ERS, USDA (2010).](image-url)
decades, most of it (1.94 per cent) coming from productivity growth (as measured by a total factor productivity TFP index). Remarkably, such changes took place while US agricultural labour input was declining at an average rate of 2.7 per cent a year (reflecting both rural–urban migration and increased mechanisation). In addition, Fuglie (2008) found that, over the last four decades, agricultural productivity has been growing at fairly high rates in most regions of the world. This reflects the important role played by innovations in farming systems, fertiliser use, pest control methods, mechanisation and genetic selection. It means that technological change has been the principal factor responsible for increased food production around the world. And at this point, there is no strong evidence of a general slowdown in agricultural productivity growth.

2.3 Some lessons from history

Agriculture has been associated with large increases in food production per hectare. Rising agricultural productivity has played a major role in improving the ability of agro-ecosystems to feed a growing world population. Yet, dealing with increased resource scarcity was not always easy. History reminds us that there were also difficult times. This includes the 1315–1317 great famine in Europe, the 1849–1850 Irish potato famine and the 1958–1961 great famine in China (where 30 million people died of starvation). This indicates that, while high population can stimulate technological progress, it can also test the ability of the human race to sustain itself. Below, we reflect on these challenges through three historical examples: the Irish
potato famine, the near extinction of the North American buffalo and the Dust Bowl.

2.3.1 The Irish potato famine

The potato, a native of South America, was introduced in Ireland in the late sixteenth century. The following two centuries saw a rapid increase in its production and consumption in Ireland. By the early nineteenth century, potato was the dominant staple in the diet of the Irish peasant class. This was made possible by a remarkable characteristic: potato is one of the very few foods that is high in calories, protein, minerals and vitamins (except for vitamins A and D). As such, it can function as the main source of individual nutrition over an extended period of time (Davies, 1994). In addition, potato productivity was generally good: it could produce more nutrients on less land than other crops (including wheat and corn). As a result, the early 1800s saw Ireland solve its problem of feeding a growing population by planting more potatoes, as both production and consumption became highly specialised in potato, especially for the Irish poor.

The great Irish famine was triggered in 1845 by a potato disease (the potato blight) which destroyed nearly half of the potato crop. This was followed by continued widespread crop failures and food shortages in the following few years. During the period 1846–1850, the devastation led to 1 million Irish people starving to death, and as many others emigrating to the UK, the USA, Canada and Australia.

The Irish potato famine was a tragedy of historical proportion. It stimulated academic interest in at least three directions. First, it documented the danger of extreme forms of specialisation, especially in food systems that are subject to unanticipated production shortfalls. This is a lesson that remains valid today. Second, the Irish potato famine identifies the role of migration as an important response to adverse shocks. Moving can provide an effective relief to people affected by unforeseen adversity. But this raises the question: in situations of adversity, to what extent would the migration option still be available today? Third, the Irish potato famine stimulated interest into the type of economic behaviour that may arise during periods of distress. Of special interest has been the nature of subsistence-driven behaviour and its implications for food demand (e.g. Davies, 1994; Rosen, 1999). Could it be that potato was a Giffen good in Ireland, i.e. an inferior good with negative income effects that were strong enough to generate upward-sloping demand curve (Davies, 1994)? There is the possibility that poor individuals would indeed exhibit Giffen behaviour. Could it apply also at the market level? This would indicate that the price of potato could actually rise during a production shortfall, thus reducing the purchasing power of the poor and making the famine even worse. The empirical evidence does not support this hypothesis at the market level during the Irish potato famine (Rosen, 1999). Yet, the nature of consumption behaviour under situations of poverty and malnutrition remains of interest. For example, Jensen and Miller (2008) found evidence of Giffen consumption behaviour among the poor in China. While the demand for food has typically
been found to be price inelastic, such inquiries indicate that the elasticity of demand of food may be even lower in situations of malnutrition. This is important since it would suggest that unanticipated supply shocks generating food shortfalls could also contribute to large price swings. This is one of the key contributing factors to price instability in agricultural markets.

2.3.2 The near extinction of the North American buffalo
In the sixteenth century, there were about 25–30 million buffalos in North America. By 1890, only about 100 remained wild in the US Great Plains. About 10–15 million were killed during a rather short period of time from 1870 to 1880. This is one of the more notable environmental disasters in American history. This slaughter did stimulate the implementation of US conservation policies in the early twentieth century (e.g. the creation of the US National Park system). But what caused it? Taylor (2007) has recently examined the reasons for this conservation failure. He documents the economic factors that contributed to this environmental disaster. He stresses three key factors: (i) open-access conditions in the Great Plains, with no regulation of the buffalo kill; (ii) technological progress in tanning that greatly stimulated the demand for buffalo hides; and (iii) free trade in the 1870s and 1880s and a very elastic demand in buffalo hides (mostly from Europe). The first factor stresses the importance of institutions and policy in resource management (e.g. Ostrom, 1990). The second factor reminds us that, while in general beneficial, technological progress can have adverse effects on resource use. And the last factor indicates that, under some circumstances, free trade can contribute to resource depletion. In summarising the implications of his analysis, Taylor (2007) writes:

The story of the buffalo has as much relevance today as it did 130 years ago. Many developing countries in the world today are heavily reliant on resource exports, and few have stringent regulations governing resource use. The slaughter on the plains tells us that waiting for development to foster environmental protection can be a risky proposition: In just a few short years, international markets and demand from high income countries can destroy resources that otherwise would have taken centuries to deplete.

2.3.3 The Dust Bowl
The Dust Bowl was one of the most severe US environmental disasters of the twentieth century. Severe drought followed by extreme levels of wind erosion hit the US Great Plains in the 1930s. Strong winds swept top soil in massive dust storms, reducing substantially the land’s potential for agricultural production. This ecological disaster was created by the interactions between adverse weather patterns and farm practices used.

Over the previous decades, grassland in the US Great Plains had been ploughed to plant wheat. When the rainfall was sufficient, this generated good yields which stimulated more settlements and cultivation. The drought started in the early 1930s, generating crop failures. As the drought deepened,
the ground cover that held the soil in place disappeared, leaving the soil exposed to wind erosion. Starting in 1933, strong dust storms stripped topsoil and blew it sometimes thousands of miles towards the Eastern USA, causing extensive damage. The catastrophic conditions stimulated a large migration: by 1940, 2.5 million people had moved out of the US Great Plains.

What lessons can we learn from the Dust Bowl experience? First, we now know that farming practices used at the time were not sustainable. Hansen and Libecap (2004) have documented that externalities were involved: while farmers could prevent wind erosion by fallowing land or converting cropland into grasslands, much of the benefits would be captured by neighbouring farms. Such externalities were not well managed at the time, stressing the need for the development of appropriate coordination and policy schemes. Second, the Dust Bowl showed the presence of significant interactions between poor land conservation practices and adverse weather shocks: the severe and prolonged drought exacerbated the effects of mismanagement, turning them into a full-scale disaster. Such interactions between unforeseen events and poor environmental and resource management remain valid today. Third, while the Dust Bowl stimulated the development of US conservation policies, its longer-term effects remain of interest (Hornbeck, 2009). As noted above, an important effect was massive outmigration. But how important were the adjustments in agricultural land use? Hornbeck (2009) showed that such long-term adjustments in land productivity were in general slow and partial, as they recovered only 14–28 per cent of the initial decline. In this case, besides migration, local adaption to environmental destructions proved to be limited.

3. Economic efficiency

The above discussion has identified four important factors that influence the performance of agriculture: technology, uncertainty, trade and environmental externalities. This section attempts to integrate these factors in the evaluation of efficiency.

3.1 Pareto efficiency

The concept of Pareto efficiency is well known in economics. It identifies allocations that maximise aggregate benefit across all individuals in society. To illustrate, consider a society composed of $S$ individuals. Following Luenberger (1995), define the benefit function of the $s$th individual as his/her willingness-to-pay starting from a bundle of goods $z_s$ to reach a utility level $U_s$, $s = 1, \ldots, S$. Denote the corresponding aggregate benefit in society by $B(z, U)$, where $z = (z_1, \ldots, z_S)$ and $U = (U_1, \ldots, U_S)$. Let $Z(T)$ be the feasible set for $\sum_{s=1}^{S} z_s$, where $T$ is a technology index and $\sum_{s=1}^{S} z_s \in Z(T)$ means that aggregate goods $\sum_{s=1}^{S} z_s$ can be produced under technology $T$. As shown by Luenberger (1995), Pareto efficient allocations are allocations satisfying the
following two conditions: (i) \( V(U, T) = \text{Max}_z \{ B(z, U); \sum_{s=1}^{S} z_s \in Z(T) \} \); and (ii) choose a \( U \) that satisfies \( V(U, T) = 0 \). The first condition is intuitive: it states that Pareto efficiency implies maximising aggregate benefit. The second condition states that once maximised, aggregate benefit \( V(U, T) \) must be totally re-distributed among the \( N \) individuals in society (with the set \( \{ U; V(U, T) = 0 \} \) defining the Pareto utility frontier).

This simple characterisation is very general. It applies in a general equilibrium context, allowing for complex interactions/externalities across sectors and economic agents (e.g. see Luenberger, 1995). It applies under uncertainty when one defines commodities to be ‘state-contingent’ (see Debreu, 1959; Chambers and Quiggin, 2000). It applies under any technology, including technologies exhibiting non-convexity (Chavas and Briec, 2011). And it applies with or without markets. While this is very nice, this characterisation has two limitations: (i) it does not tell us how aggregate benefit should be distributed among individuals in society; and (ii) it does not help us identify the role of markets versus non-market institutions. Both limitations are relevant in the analysis of government policy.

The evaluation of market versus non-market institutions is a difficult one. We know that markets can generate Pareto efficient allocations under the following conditions (Debreu, 1959): (i) no externality; (ii) convex technology; and (iii) complete and competitive markets. Then, market-clearing prices are social prices (measured as the aggregate benefit generated by one more unit of the corresponding goods), and efficiency is obtained under decentralised decision-making and free markets (including free trade). This generates two important results. First, free trade can support an efficient allocation. Alternatively stated, trade liberalisation can generate efficiency gains (as further discussed below). Second, technological progress increases aggregate welfare. Indeed, any improvement in technology from \( T \) to \( T' \), with \( Z(T) \subset Z(T') \), implies a rise in aggregate benefit: \( V(U, T') \geq V(U, T) \). Note that this does not say how the associated welfare gains get distributed in society. The issue of the distribution of benefits from technological improvements is relevant in agriculture (as further discussed below).

Knowing that competitive markets can be efficient is useful. But this does not identify any role for government pricing policy. It suggests that government economic policy needs to be motivated in situations where some of the Debreu conditions are not satisfied and/or there are concerns about distribution issues across individuals.³

### 3.2 Efficiency in agriculture

Below, we discuss efficiency in the agricultural sector. As motivated above, we focus on two important characteristics: the presence of externalities; and the fact that risk is important in agriculture and risk markets are typically

incomplete. Assuming that farmers are price-takers, our analysis proceeds at
the sector level, taking prices as given.4

Consider an agricultural sector involving \( Q \) farms.5 The \( Q \) farms are part of
a farming system in a given agro-ecological region. The \( q \)th farm uses \( N \) inputs
\( x_q = (x_{1q}, \ldots, x_{Nq})' \) to produce \( M \) outputs \( y_q = (y_{1q}, \ldots, y_{Mq})' \). Let \( x = (x_1, \ldots, x_Q) \) and \( y = (y_1, \ldots, y_Q) \). Let \( e \) be a vector of random variables representing
production uncertainty, and let \( T \) be a technology index. The production possi-
bility set of the agro-ecosystem is represented by \( F(T, e) \), where \( (x, y) \in F(T, e) \) means that inputs \( x \) can produce outputs \( y \) under technology \( T \) and state \( e \).
Because of production lags, we assume that inputs are chosen ex ante, while
outputs are chosen ex post. This means that, while the choice of \( x_q \) does not
depend on \( e \), our discussion below implicitly allows the choice of \( y_q \) to
depend on \( e \). Note that the feasible set \( F(T, e) \) is quite general: it allows for
production uncertainty and any technology, including possible productivity
interactions among outputs as well as externalities across farms. It will be con-
venient to represent the underlying technology by the aggregate production
function

\[
 f(x, y_{2:M}, T, e) = \max_{y_1} \left\{ \sum_q y_{1q} : (x, y) \in F(T, e) \right\}
\]

if a maximum exists,

\[
 = -\infty \text{ otherwise,}
\]

(1)

where \( y_1 = (y_{11}, \ldots, y_{1Q}) \) and \( y_{2:M} = \{y_{2q}, \ldots, y_{Mq} : q = 1, \ldots, Q\} \). Let
\( (y^+_{11}(x, y_{2:M}, T, e), \ldots, y^+_{1Q}(x, y_{2:M}, T, e)) \in \arg\max_{y_{1q}} \left( \sum_q y_{1q} : (x, y) \in F(T, e) \right) \) in the maximisation problem (1), with \( f(x, y_{2:M}, T, e) = \sum_q y^+_{1q}(x, y_{2:M}, T, e) \). Given \( (x, y_{2:M}, T, e) \), equation (1) defines \( f(x, y_{2:M}, T, e) \)
as an aggregate stochastic production function measuring the largest possible
aggregate quantity of the first output, where feasibility \( (x, y) \in F(T, e) \) implies
that \( \sum_q y_{1q} \leq f(x, y_{2:M}, T, e) \). In addition, assuming that the maximisation in
equation (1) has a unique solution, \( y^+_{1q}(x, y_{2:M}, T, e) \) can be interpreted as a
stochastic production function for the \( q \)th farm, \( q = 1, \ldots, Q \). Again, this pro-
vides a generic representation of the technology, allowing for production
uncertainty and possible productivity interactions among outputs as well as
externalities across farms.

The agricultural sector is part of a market economy where inputs \( x \) and
outputs \( y \) are market goods. We assume that each of the \( Q \) farms is a family

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4 Focusing on a single sector makes the analysis simpler (compared with a general equilibrium
approach assessing the allocation and prices in all sectors). Taking prices as given means that
our analysis of efficiency would remain valid provided that prices are social prices. Note that
this neglects issues related to price inefficiency (when prices depart from social prices).

5 By focusing on the farm sector, our analysis can address the management of externalities
among farms. When the externalities go beyond the farm sector, the analysis would need to
be extended to include all economic agents affected by the externalities.
farm where the owner, the manager and the farm worker are the same person, i.e. where there is no separation of ownership and control. Let \( p = (p_1, \ldots, p_M) > 0 \) be the vector of uncertain prices for outputs, and \( r = (r_1, \ldots, r_N) \) be the vector of input prices. Letting \( w_q \) be exogenous income, denote the net income of the \( q \)th farm by \( p\pi_q + p'y_q - r'x_q \). Under incomplete risk markets, assume that each farmer maximises expected utility. For the \( q \)th farmer, this is denoted by \( EqU_q(\pi_q) \), where \( Eq \) is the expectation operator based on the subjective probability distribution of \( (p, e) \) reflecting the information available at decision time, and \( U_q(\pi_q) \) is a utility function representing the farmer’s risk preferences. Under non-satiation, we assume that \( U_q(\pi_q) \) is a strictly increasing function.

For the \( q \)th farmer, define the certainty equivalent as the sure amount of money \( CE_q(x_q, y_q, \cdot) \) satisfying

\[
EqU_q(\pi_q) = U_q(CE_q),
\]

where \( q = 1, \ldots, Q \). Equation (2) shows that the certainty equivalent \( CE_q(x_q, y_q, \cdot) \) provides a general welfare measure for the \( q \)th farmer, where ‘\( \cdot \)’ denotes other arguments (such as prices, risk preferences, risk exposure, etc.). In addition, under non-satiation, it implies that maximising \( EqU_q(\pi_q) \) is equivalent to maximising the certainty equivalent \( CE_q(x_q, y_q, \cdot) \). We want to characterise an efficient allocation in situations that include both uncertainty and possible externalities across farms. Following Coase (1960), this can be done by maximising the aggregate welfare of all \( Q \) farmers:

\[
W(T, \cdot) = \operatorname{Max}_{x, y} \left\{ \sum_q CE_q(x_q, y_q, \cdot) : (x, y) \in F(T, e) \right\},
\]

Assuming the maximisation in equation (1) has a unique solution, equation (3) can be alternatively written as (see the proof in the appendix):

\[
W(T, \cdot) = \operatorname{Max}_{x, y} \left\{ \sum_q CE_q(x_q, y_{1q}(x, y_{2:M}, T, e), y_{2:M,q}, \cdot) \right\},
\]

where \( W(T, \cdot) \) is an aggregate welfare measure for the \( Q \) farmers under technology \( T \). Equation (4) shows that the production functions \( \{y_{1q}(x, y_{2:M}, T, e) : q = 1, \ldots, Q \} \):

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6 As noted above, the analysis treats the prices \( (p, r) \) as given. For market goods under competition, these prices are treated as market equilibrium prices. In situations where \( (y, x) \) include non-market goods, \( p \) would denote the marginal benefit of \( y \), and \( r \) would denote the marginal cost of \( x \).

7 Note that we allow for active learning where the \( q \)th farmer’s subjective probability distribution of \( (p, e) \) can depend on information-gathering activities in \( x_q \). This active learning can vary across farmers.

8 For simplicity, we assume that income is the only source of utility for farmers. Note that the analysis could be extended to include other arguments in the utility function (e.g. leisure, environmental quality).
q = 1, \ldots, Q) summarise all the relevant information about the stochastic production technology. Letting \( p = (p_1, p_{2:M}) \), which means that the certainty equivalent \( \text{CE}_q \) in equation (2) can be alternatively written as

\[
\text{CE}_q(x_q, y_{2:M,q}, T, \cdot) = U_q^{-1} E_q U_q[w_q + p_1 y_{1q}(x_q, y_{2:M}, T, \cdot) + p_{2:M} y_{2:M,q} - r'x_q],
\]

where \( q = 1, \ldots, Q \).

Following Pratt (1964), the implicit cost of risk for the \( q \)th farmer can be measured by the Arrow–Pratt risk premium \( R_q(x, y_{2:M}, T, \cdot) \) defined as the sure amount of money \( R_q \) satisfying

\[
\text{CE}_q(x_q, y_{2:M,q}, T, \cdot) \equiv E_q[w_q + p_1 y_{1q}(x_q, y_{2:M}, T, \cdot) + p_{2:M} y_{2:M,q} - r'x_q]
\]

where \( \text{CE}_q(x_q, y_{2:M,q}, T, \cdot) \) is defined in equation (2'). The risk premium \( R_q(x, y_{2:M}, T, \cdot) \) is the smallest sure amount of money the \( q \)th farmer is willing to pay to replace the random income \( \pi_q \) by its mean \( E_q(\pi_q) \). We assume that each farmer is risk averse, where \( U_q(\cdot) \) is a strictly concave function and the cost of risk is positive: \( R_q(x, y_{2:M}, T, \cdot) > 0, q = 1, \ldots, Q \).

Substituting equation (5) into equation (4) and using \( f(x, y_{2:M}, T, \cdot) = \sum_q y_{1q}(x, y_{2:M}, T, \cdot) \) yield

\[
W(T, \cdot) = \text{Max}_{x,y} \left\{ E_q \left[ \sum_q w_q + p_1 f(x, y_{2:M}, T, \cdot) \right.ight.

+ p_{2:M} \left( \sum_q y_{2:M,q} \right) - r' \left( \sum_q x_q \right) \left. \right] - \sum_q R_q(x, y_{2:M}, T, \cdot), \right\}
\]

which has solution \((x^*, y^*)\). \( W(T, \cdot) \) in equation (4') is an aggregate welfare measure of production decisions under risk (including both price and production risk). It identifies efficient decisions that maximise the aggregate certainty equivalent of all farmers, allowing for uncertainty and externalities. It includes two terms: aggregate expected profit, \( \sum_q E_q(\pi_q) \), minus the aggregate cost of risk as measured by \( \sum_q R_q \).

### 4. Assessing agricultural efficiency

#### 4.1 The role of expected profit

The maximisation of aggregate expected profit in equation (4') is a standard part of economic analysis. First, it stresses the role of technical efficiency. Indeed, equation (4') implicitly assumes that \( y_1 = f(x, y_{2:M}, T, \cdot) \), or equivalently that \( y_{1q} = y_{1q}(x, y_{2:M}, T, \cdot), q = 1, \ldots, Q \). It means that efficient
decisions must be made in such a way that inputs and outputs are located on the upper bound of the production possibility set, i.e. on the production frontier. Any decision that does not satisfy this condition would be deemed technically inefficient.

Second, expression (4′) applies under externalities. This is reflected in the production function
\[ f(x, y_{2:M}, T, e) = \sum_{q} y_{1q}^+(x, y_{2:M}, T, e), \]
showing that the stochastic production function for the \( q \)th farm, \( y_{1q}^+(x, y_{2:M}, T, e) \), can depend on the inputs and outputs of other farms, \( (x_{q'}, y_{2:M}, q') \), for \( q' \neq q \). This allows for positive as well as negative externalities among farms (depending on whether \( y_{1q}^+(x, y_{2:M}, T, e) \) is positively or negatively affected by \( (x_{q'}, y_{2:M}, q') \) for \( q' \neq q \)). Importantly, in the presence of externalities, equation (4′) shows that the expected profit of all farms affected by externalities become relevant in making efficient decisions. Doing so is crucial to ‘internalise’ the externalities and to achieve an efficient allocation (Coase, 1960). Alternatively, failing to do would generate an inefficient allocation.

This stresses that efficiency requires some coordination scheme among all farms affected by the externalities. As noted by Coase (1960), this can be achieved through private contracts among the affected parties. Interestingly, in the paper that earned him the Nobel Prize, Coase (1960) used the example of a farmer and a cattle-raiser, where the externality comes from straying cattle that destroy the farmer’s crops. This may work well when the number of affected farmers is small. But when the number of farmers becomes large, the private contracting solution may become difficult to implement (e.g. because of economies of scale in obtaining and processing information about the externalities). Then, the required coordination scheme may come from government policy. In this case, government policy would try to manage the externalities in a way consistent with equation (4′). Importantly, externalities imply that decentralised decision-making would be inefficient. Indeed, equation (4′) shows that the maximisation of the \( q \)th farmer’s expected utility can be efficient only in the absence of externalities (when the \( q \)th farm stochastic production function becomes \( y_{1q}^+(x_q, y_{2:M}, q, T, e) \)).

Our analysis started from a characterisation of technology at the aggregate level. By allowing some farms to produce nothing, it implicitly treats the number of active farms as endogenous. This means that equation (4′) can also be used to evaluate the efficient structure of agriculture. Yet, the presence of externalities across farms depends on the identity of each farm. For example, if an externality (either positive or negative) exists between two farms, then a merger between these two farms would basically make this externality disappear. By internalising the externality under a single management, this would eliminate the need for a coordination scheme between the two farms. Does that mean that a merger would always be a desirable solution to an externality problem? Not necessarily. This would depend on the quality of management in the merged farm versus the quality of a coordination scheme implemented between the two original farms. There are three possible scenarios. First, if the quality of management in the merged farm is excellent,
then merger would be an efficient solution implemented in market economy under a decentralised system. This is the ‘market solution’. Second, if the quality of coordination implemented between the two original farms is excellent, then private contracts between the two farms would provide an efficient solution to the externality. This is the ‘contract solution’ applied to the original farm structure, where the terms of the contract correspond to a ‘Coasian bargain’ consistent with equation (4’). Third, if many farms are involved and a contract solution proves difficult to implement, then agricultural policy may provide an efficient solution to the externality problem. This is the ‘government solution’.

Choosing between a market solution, a contract solution and a government solution can be challenging. Proponents of either the market solution or the contract solution typically point to the difficulties facing government agencies in developing refined coordination schemes among many agents (difficulties often referred to as ‘government failures’). But such difficulties may also be present no matter what solution is proposed. In the context of contracts, these difficulties typically take the form of ‘incomplete contracts’ that limit the effectiveness of coordination between the interested parties, thus making contracts a less attractive option. And when externalities involve many farms, the merger solution may not be attractive for two reasons. First, it could lead to a very concentrated industry, which may no longer have a competitive structure. Second, in the presence of extensive externalities among many farms, the manager of merged farms would likely be facing the same difficulties as a central planner. He/she may then fail to internalise the former externalities, in which case technical and/or allocative inefficiencies would arise as his/her decisions differ from equation (4’). Such difficulties applied to either the market solution or the contract solution are often referred to as ‘market failures’. In all cases, the issue focuses its attention on the managerial abilities of the decision-makers as reflected by their abilities to obtain and process information about the relevant externalities. Good farm-level access to information is necessary to support a decentralised scheme (in either the market solution or the contract solution). Alternatively, the presence of economies of scale in acquiring and using information may favour more centralised schemes (including government policy). Choosing the appropriate solution to an externality problem should be guided by which institution comes closest to satisfying equation (4’).

The above discussion makes it clear that the presence of externalities depend on the definition of each farm and its boundary. This indicates that a narrow focus on externalities appears misplaced. Agriculture is in the business of using agro-ecological systems to produce food. These systems are complex as the production of food involves significant interactions among solar energy, plants, soil, water, pest populations and other factors. These interactions exist at all levels: at the plot level, at the farm level, at

9 Recall that our model allows for active learning by each farmer, with possible heterogeneity in acquiring and using information across farms.
the regional level and at the earth level. To illustrate, at the plot level, there are productivity gains from crop rotation (that helps keep pest population down). At the farm level, there are productivity gains from crop diversification (that eases bottleneck in labour demand during planting and harvesting) and from crop-livestock integration (as the use of manure improves soil productivity). At the regional level, there are productivity gains from preventing soil erosion or from establishing irrigation networks. And at the world level, there are productivity gains from identifying local plants and animals that can be used (possibly in other parts of the world) to help feed a growing population. This stresses the need to assess the performance of agriculture at a global level, including its effectiveness in using agro-ecological services in producing food. Yet, many decisions are made at the farm level. Expression \( (4') \) shows how both local and global levels are relevant. It means that the management of agro-ecological services is also important at the farm level, as farm managers face the challenge of managing agro-ecological services and their local interactions. The efficient management of these interactions generates farm-level economies of scope. How good are farmers at managing their local agro-ecosystems? It depends in part on farmers’ managerial abilities. The fact that agriculture has evolved to transform and dominate many ecological systems around the world is an indication of the relative success of farming practices. Yet, this does not mean that current practices are necessarily efficient. More empirical work is needed to evaluate these issues and to identify improved management strategies for farming systems.

4.2 The role of risk

Expression \( (4') \) also shows that the aggregate cost for risk \( \sum q R_q \) is subtracted from expected profit. Going beyond the analysis presented by Coase (1960), this makes it clear that the cost of risk should be included in efficiency analysis. It stresses the welfare effects of risk exposure among risk-averse farmers. In general, an efficient allocation should try to reduce the aggregate cost of risk. This can be done in at least three ways. First, the \( q \)th farmer wants to take actions \( (x_q, y_q) \) to reduce his/her risk exposure. This can take the form of increasing the use of inputs that are ‘risk decreasing’ (e.g. irrigation or pest control, where \( \partial R_q / \partial x_{iq} < 0 \)) and decreasing the use of inputs that are ‘risk increasing’ (e.g. fertiliser, where \( \partial R_q / \partial x_{iq} > 0 \)). This can also take the form of diversification schemes that can be an integral part of an efficient allocation when they contribute to reducing risk exposure. Second, the cost of risk for the \( q \)th farmer, \( R_q(x, y_{2:M, T, \cdot}) \), can depend on the actions of his neighbours, \( (x_{q'}, y_{2:M, q'}) \) for \( q' \neq q \). In this case, the \( q \)th farmer’s risk exposure involves an externality that needs to be managed. As discussed above, short of merger, its efficient management requires implementing coordination schemes among the affected parties (using contracts and/or government policy). Third, the aggregate cost of risk \( \sum q R_q \) in equation \( (4') \) can be reduced through risk-transfer mechanisms. By re-distributing the risk away
from the individuals that face a high cost of risk (as measured by \( R_q \)),\(^{10}\) such mechanisms can reduce the aggregate cost of risk and are an integral part of implementing an efficient allocation of risk.\(^{11}\) This can be done using private insurance schemes, risk markets (e.g. hedging on futures markets) and/or government policy. Each of these institutions has been involved re-distributing risk in the agricultural sector. In the USA, the role of agricultural policy in risk re-distribution started during the Great Depression (e.g. price support programmes which reduce price risk were first put in place in the 1930s when farm income was low and price volatility was high). The role of agricultural policy in re-distributing risk continues to this day (e.g. disaster payments, or the subsidisation of crop and income insurance) (Gardner, 2002; Peterson, 2009). Given the extensive price risk and production risk found in agriculture, a significant puzzle remains: agricultural insurance markets remain uncommon without extensive government subsidies. Why? This seems to reflect both market failures (as agricultural insurance markets have been slow to develop) and government failures (from the apparent need for large subsidies). Yet, over the last few decades, new risk management tools have developed in the financial sector. In particular, the increasing availability of option contracts related to price risk and weather risk has created new opportunities for risk management in agriculture.

5. Assessing technological change

Besides characterising efficiency, expression (4') also shows how the technology index \( T \) affects welfare \( W(T, \cdot) \). Consider the effects of a small change in \( T \). Under differentiability, applying the envelope theorem to expression (4') gives

\[
\frac{\partial W}{\partial T} = E \left[ p_1 \left( \frac{\partial f}{\partial T} \right) \right] - \frac{\partial (\Sigma_q R_q)}{\partial T},
\]

(6)
evaluated at the optimal \( x^* \) and \( y^* \). When \( f > 0 \), this can be alternatively written as

\[
\frac{\partial W}{\partial T} = E \left[ (p_1 f) \frac{\partial \ln(f)}{\partial T} \right] - \frac{\partial (\Sigma_q R_q)}{\partial T}.
\]

(6')

Consider the case where \( T \) represents time. Then, for a given \( \epsilon \), it follows that \( \partial \ln(f)/\partial T \) is the rate of technological change (measured at the aggregate level)

\(^{10}\) In our model, risk re-distribution would take place by treating exogenous income, \( w_q \) in equation (4'), as state dependent.

\(^{11}\) Note that risk preferences can introduce income effects in the evaluation of the cost of risk. In particular, following Pratt, under decreasing absolute risk aversion, the risk premium \( R_q \) would decline with income \( w_q \), meaning that any income re-distribution would typically affect both the cost of risk and production decisions in equation (4'). This is a scenario where income distribution issues are no longer separable from efficiency considerations.
from one time period to the next. It measures the rate of change in aggregate output \( \sum q y_q \) due to a change in \( T \). For given prices, equation (6′) evaluates the welfare effects of technological progress in a simple and intuitive way. It shows that welfare change (\( \partial W/\partial T \)) is increasing with productivity gains (as measured by the rate of technological change, \( \partial \ln(f)/\partial T \)). It also shows how welfare change (\( \partial W/\partial T \)) is impacted by risk: positively if \( \partial (\sum_q R_q)/\partial T \) < 0 (i.e. if technological change reduces the aggregate cost of risk); but negatively if \( \partial (\sum_q R_q)/\partial T \) > 0 (i.e. if technological change increases the aggregate cost of risk). Note that these results are very general: they apply under any risk preferences, any risk exposure (with both price risk and production risk) and any technology. They point out that technological change can help reduce the cost of risk (e.g. the case of breeding drought-resistant varieties).

Expression (4′) identifies the optimal supply decisions. For the \( q \)th farm, denote the supply decisions by \( y_q^*(T, e, \cdot) \), which in general depend on the technology index \( T, q = 1, \ldots, Q \). In a market economy, it means that \( T \) also affects prices. Here we focus our attention on the effects on output prices \( p \). Denote the corresponding aggregate supply functions by \( Y^S(T, e, \cdot) = \sum q y_q^*(T, e, \cdot) \). And let \( Y^D(p, \cdot) \) denote the aggregate excess-demand for outputs. The market prices \( p^*(T, e, \cdot) \) are then the prices \( p \) satisfying the market equilibrium conditions:

\[
Y^S(T, e, \cdot) = Y^D(p, \cdot).
\]

When an increase in \( T \) stimulates aggregate supply (\( \partial Y^S/\partial T > 0 \)) and when demand functions are downward sloping, equation (7) implies that the technological progress is associated with a decrease in prices \( p^* \): \( \partial p^*/\partial T < 0 \). This means that consumers benefit from technological progress. And this impact becomes stronger (weaker) when the demand function \( Y^D \) is less (more) responsive to price. Note that similar arguments apply to the effects of production uncertainty \( e \): unanticipated production shocks would have a stronger (weaker) effect on market equilibrium prices \( p^*(T, e, \cdot) \) when the demand function \( Y^D \) is less (more) responsive to price.

In this context, the market equilibrium aggregate welfare of farmers is

\[
W^*(T, \cdot) = W(p^*(T, \cdot), T, \cdot).
\]

Under differentiability and using equation (6′), the welfare effects of

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12 For simplicity, we assume that input prices are constant, i.e. input markets face an infinitely elastic supply.

13 In local markets, \( Y^D \) would just be the demand from local markets. Alternatively, in global markets, \( Y^D \) would be the aggregate excess demand from the rest of the world.
technological change are given by

$$\frac{\partial W^*}{\partial T} = E \left[ (p_1 f) \left( \frac{\partial \ln(f)}{\partial T} \right) \right] - \frac{\partial \left( \sum q R_q \right)}{\partial T} + \left( \frac{\partial W}{\partial p} \right) \left( \frac{\partial p^*}{\partial T} \right).$$

(9)

The first two terms in equation (9) are the effects given in equation (6′): the productivity effect $E((p_1 f) \left( \frac{\partial \ln(f)}{\partial T} \right))$ minus the risk effect $\frac{\partial \left( \sum q R_q \right)}{\partial T}$. The last term is the market equilibrium effect associated with the induced adjustment in prices $p$. In general, we expect $\frac{\partial p^*}{\partial T} < 0$ as technological change typically stimulates supply. It means that, while technological progress tends to benefit consumers, its induced price effects tend to reduce producers’ welfare. Thus, at the aggregate level, farmers gain from technological progress ($\frac{\partial W^*}{\partial T} > 0$) when the productivity gain $E((p_1 f) \left( \frac{\partial \ln(f)}{\partial T} \right))$ is large and the induced price effect $\left( \frac{\partial W}{\partial p} \right) \left( \frac{\partial p^*}{\partial T} \right)$ is small. But farmers can lose from technological progress ($\frac{\partial W^*}{\partial T} < 0$) when the induced price effect $\left( \frac{\partial W}{\partial p} \right) \left( \frac{\partial p^*}{\partial T} \right)$ is negative and large. As noted above, this can happen when the demand function $Y^D$ exhibits a low responsiveness to price. Since the demand for food typically exhibits a low elasticity of demand, this is a likely scenario for agriculture. It means that, while technological progress can generate large benefits to consumers and society in general, farmers can actually be made worse off by adopting a new technology. This is a peculiar characteristic of food markets: through induced price adjustments, they can re-distribute the benefits of technological progress in a way that does not reward the agents that implemented it in the first place.

### 6. Assessing agricultural policy

The last few decades have seen a move towards increased trade in global markets. Interestingly, market globalisation is not new. A wave of market globalisation took place in the period of 1860–1914, led by Great Britain (Frieden, 2006: 28–55). While Great Britain implemented mostly protectionist trade policies during the industrial revolution (Chang, 2008: 40–48), it pushed for trade liberalisation in the late nineteenth century. This included the 1846 repeal of the British ‘Corn Laws’ (which protected British wheat prices from international competition). In the following decades, Great Britain reduced tariff barriers and stimulated the development of global markets for many commodities (including agricultural commodities). This globalisation period basically ended with World War I. The period between World War I and World War II was characterised by growing protectionism around the world and economic difficulties (including the Great Depression of the 1930s). The current period of globalisation started in 1945 and was led by the USA. The last five decades have seen a move towards reducing trade barriers, rapid economic growth and an increasing importance of international trade (Frieden, 2006: 39–55). The reduction in trade barriers was facilitated by bilateral free trade agreements (FTA) and international institutions such as the World Trade Organization (WTO). But this time,
agriculture was not part of this trend. Indeed, protectionist trade policies remain common in agriculture (using import tariffs, import quotas and/or export subsidies). The resistance to reducing trade barriers in agriculture has come from the USA as well as Europe. This was at the heart of the failure of recent WTO trade negotiations. Yet, countries like Brazil and India have pushed for trade liberalisation in agricultural markets. For example, Brazil would gain from being able to export sugar to the currently protected European and US markets.

This raises the question: what are the benefits of trade liberalisation? Economic theory shows that trade generates aggregate efficiency gains. The arguments date back to Adam Smith and Ricardo, who argue that protectionist policies can retard economic growth by preventing productivity-enhancing specialisation in global markets. Setting aside risk issues, there is a general consensus that specialisation can contribute to increased productivity.

While this identifies economic gains from globalisation, two questions remain. First, how large are the benefits from market liberalisation and globalisation? And second, how are these benefits distributed? Economic models of trade have shown that the aggregate benefits of trade are positive and in the range of 2–3 per cent of GDP (Bhagwati, 2002: 33). Compared to the productivity gains discussed earlier, these benefits appear relatively small. It seems that a few years of technological change can generate greater aggregate benefits than trade liberalisation. But the aggregate impacts of trade policy often hide large distributional impacts. Trade typically generates gainers and losers. And in the absence of compensations for the losers, some groups can benefit significantly from trade policy. In general, producers in exporting countries gain from trade liberalisation. Alternatively, producers in importing countries gain from trade restrictions. As producer groups tend to be well organised politically, these distributional effects seem to be driving the political economy of trade policy: trade liberalisation is typically favoured for commodities that a country exports, while protectionist policy is favoured for commodities that a country imports. In the latter case, distributional effects may well motivate trade restrictions, while efficiency-loving economists lament that protectionist policies often amount to rent-seeking behaviour by producer groups with adverse effects on aggregate efficiency.

Other issues related to agricultural policy are: How extensive is agricultural policy? And what is its cost to society? In developed countries, agricultural policy is extensive. Besides trade policy (discussed above), domestic policy involves large government subsidies to the farm and food sector [including subsidies on a number of inputs and outputs, price support programmes and income support; see Gardner (2002), Peterson (2009) and OECD (2010)]. Peterson (2009: 105–116) reports that the annual cost of agricultural policy around the world amounts to USD 365 billion a year, or USD 1 billion per day. Most of this cost comes from high farm subsidies in developed countries, especially the EU (USD 153 billion a year), the USA (USD 100 billion a year) and Japan (USD 45 billion a year). That is a lot of money. One must surely wonder whether this is money well spent.
One argument is that agricultural policy is mainly to support the income of family farms in developed countries. Indeed, agricultural policies in the USA and Europe were put in place during periods of important rural–urban migrations, when the average income of rural households lagged significantly behind their urban counterparts. Also, as noted above, technological progress in agriculture greatly benefited urban households (in the form of lower food prices) with possible adverse effects on farmers’ income. In this context, farm subsidies in developed countries could be seen as an income re-distribution scheme from high-income urban households towards lower-income rural households. This characterisation may have been fairly accurate 40 years ago. But it appears less accurate today. For example, Gardner (2002) has documented the evolution of the income distribution in the USA over the last century. He found that the income gap between urban and rural households in the USA has greatly diminished over the last two decades. It means that, on average, the income of rural households has basically caught up with the income of their urban counterparts. Interestingly, this is true for large farms as well as small farms: while small farm households still have lower average farm income, their increased reliance on off-farm income allowed them to make up the difference (Gardner, 2002: 339–349). This documents a rising and more equally distributed standard of living for US farm households. This is a very positive aspect in the performance of US agriculture. But the disappearing income gap between urban and rural households raises renewed questions about the political justifications for current farm subsidies.

Finally, we may want to evaluate the performance of agriculture in terms of its effects on consumer welfare. On this point, the overall evaluation must be positive (e.g. Gardner, 2002: 339–343). As discussed above, the increased availability of food at a lower real price is a significant achievement of agriculture over the last few decades. Most of this is due to rapid technological change and strong productivity growth. The social benefits from productivity improvements appeared to have dominated the overall performance of the agricultural sector.

7. Challenges for the future

Over the last few decades, agriculture has been characterised by high and sustained productivity growth. Overall, this is an amazing achievement to help meet the increased demand for food (as fuelled by population growth). What about the future? The recent developments in biotechnology offer good prospects for continued technological progress. Hopefully, agricultural innovations will come fast enough to deal with current and future resource scarcity. Yet, significant challenges lie ahead.

Rising concerns about climate change indicate that the next few decades will see significant changes in agriculture around the world. Changing patterns in rainfall and temperature will be good for agriculture in some regions but bad in others. Weather uncertainty will likely increase. How will people
adjust? Improved agricultural technology and improved management can help. This stresses the need for refined risk management schemes at all levels: the farm level, the national level and the international level. Yet, we should be careful not to overestimate our ability to adjust to unforeseen adverse events. First, migration options will likely not be as effective as they were in the past (e.g. as in the case of the Irish potato famine or the Dust Bowl). Second, without migration, adjusting to persistent shocks may prove difficult (e.g. as evidenced by a slow adaptation to the long-term effects of the Dust Bowl). Mitigating the effects of climate change may well be one of the most important challenges for agriculture in the twenty-first century.

Also, rising concerns about environmental issues are and will continue to reshape agriculture and agricultural policy. These issues are at all levels: local, regional and global. At the local level, our analysis stresses that farm managers are in the business of managing their local agro-ecosystem. It means that solutions to environmental issues must involve farmers. Alternatively, for environmental issues that are global, agricultural policy must play a role and be an integral part of broader environmental policy.

Sustainability issues are also on the rise. Our analysis has focused on a static analysis. Sustainability is about preserving the future. This identifies the need to introduce dynamics in our analysis. Combining markets and government policies will be needed. This will require refining our understanding of the dynamics of agro-ecosystems and of the long-term effects of current farm management practices.

Finally, addressing emerging issues in agriculture will require refined empirical research. We need to continue the evaluation of agricultural technology and its effects on resource scarcity and environmental management. More research is required to improve our understanding of how environmental services get transformed into supporting and feeding the human race. This includes estimating the economic value of multifunctionality in agriculture. We need refined analyses to assess risk exposure (especially exposure to unfavourable events) and to evaluate the associated cost of risk. This is crucial to improve risk management in agriculture at all levels, including refinements in agricultural policy. Finally, we need empirical investigations of the resilience of agro-ecosystems as they adjust in a changing world.

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References


Appendix

Proof of equation (4): From equation (1), since \((x, y) \in F(T, e)\) implies that \(\sum_q y_{1q} \leq f(x, y_{2:M}, T, e)\), it follows that \(F(T, e) \subset \{(x, y): \sum_q y_{1q} \leq f(x, y_{2:M}, T, e)\}\). Letting \(y_q = (y_{1q}, y_{2:M,q})\) and assuming that the maximisation in equation (1) has a unique solution, we obtain

\[
\begin{align*}
\max_{x,y} \left\{ \sum_q CE_q(x_q, y_q, \cdot) : (x, y) \in F(T, e) \right\} \\
\leq \max_{x,y} \left\{ \sum_q CE_q(x_q, y_q, \cdot) : \sum_q y_{1q} \leq f(x, y_{2:M}, T, e) \right\} \\
= \max_{x,y} \left\{ \sum_q CE_q(x_q, y_q, \cdot) : \sum_q y_{1q} \leq \sum_q y^+_{1q}(x, y_{2:M}, T, e) \right\} \\
\text{since } f(x, y_{2:M}, T, e) = \sum_q y^+_{1q}(x, y_{2:M}, T, e) \text{ from equation (1)} \\
= \max_{x,y} \left\{ \sum_q CE_q(x_q, y_q, \cdot) : y_{1q} = y^+_{1q}(x, y_{2:M}, T, e), q = 1, \ldots, Q \right\}
\end{align*}
\]
since $CE_q(\cdot)$ is increasing in $y_{1q}$

$$= \text{Max}_{x,y} \left\{ \sum_q CE_q(x_q, y^+_{1q}(x, y_{2:M}, T, e), y_{2:M,q}, \cdot) \right\}.$$ We now need to show that the reverse inequality holds:

$$\text{Max}_{x,y} \left\{ \sum_q CE_q(x_q, y_q, \cdot) : (x, y) \in F(T, e) \right\} \geq \text{Max}_{x,y} \left\{ \sum_q CE_q(x_q, y^+_{1q}(x, y_{2:M}, T, e), y_{2:M,q}, \cdot) \right\}.$$ Under non-satiation, this inequality clearly holds when $f(x, y_{2:M}, T, e) = \sum_q y^+_{1q}(x, y_{2:M}, T, e) = -\infty$. Next, consider the case where $f(x, y_{2:M}, T, e) > -\infty$. Then, from equation (1), there exists a point $y_1 = (y_{11}, \ldots, y_{1Q})$ satisfying $(x, y) \in F(T, e)$ and $y_{1q} = y^+_{1q}(x, y_{2:M}, T, e), q = 1, \ldots, Q$. Evaluated at that point, we obtain

$$\text{Max}_{x,y} \left\{ \sum_q CE_q(x_q, y_q, \cdot) : (x, y) \in F(T, e) \right\} \geq \sum_q CE_q(x_q, y^+_{1q}(x, y_{2:M}, T, e), y_{2:M,q}, \cdot),$$

which concludes the proof.