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# On the economics of agricultural production\*

Jean-Paul Chavas<sup>†</sup>

Agriculture is in the business of using ecosystem services to produce food. Examining how agro-ecosystems function provides useful insights into the economics of agriculture. Of special interest are the presence and nature of scale effects, complementarity effects and convexity effects in ecosystem functioning. Implications for agricultural productivity and the economics of agriculture are evaluated. At the farm level, this helps to better understand the current trend toward greater specialisation. Current challenges for agricultural contracts, markets and policy are explored.

**Key words:** agricultural production, structure, technology.

## 1. Introduction

Agriculture is in the business of using ecosystem services to produce food. The process of food production has changed significantly over time and over space. Such changes have been influenced by the dynamic interactions between improved technologies and increasing human population (Boserup 1965). The evolving organisation and structure of agricultural production remain subjects of considerable interest (Boserup 1965; Binswanger *et al.* 1993; Binswanger and Deininger 1997). At the microeconomic level, the prevalence of the family farm as a socio-economic unit of agricultural production is of special interest (e.g. Schmitt 1991). The trend toward greater product specialisation is also of interest. In developed countries, this can be seen today through the development of large specialised animal production units in broiler, dairy or pork production (which contrasts with the more traditional mixed crop-animal farms). This raises a number of basic questions. Why are traditional farms typically diversified? and why are large farms often less diversified? It is useful to try to answer these questions in the context of the functioning of agro-ecosystems. But the complexity of agro-ecosystems has hindered our ability to understand the underlying economics.

The objective of this article is to explore the economics of agro-ecosystems, with the objective of obtaining better insights on the economics of agriculture. In general, it is clear that agro-ecosystems use resources (land, labour, capital, management) to transform ecosystem services (including plants and animals)

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into food. The process through which ecosystem services are being used is at the heart of the economics of agriculture.

Historically, agriculture has been very successful in improving ecosystem productivity to feed a growing human population. In general, this has been a great success story. However, the improved productivity of agro-ecosystems has been associated with massive changes in technology and in the structure of agriculture. Among other factors, genetic improvements, mechanisation and rural migration have contributed to rapid productivity growth in agriculture in many countries. Yet, many questions remain. One of these questions is: Why have agro-ecosystems become so specialised? While ecologists tend to see ecological diversity as desirable, this seems to counter the current trend toward greater specialisation in agriculture. Below, we will explore how our understanding of agro-ecosystem functioning can help us better assess the economics of agriculture.

## 2. Assessing agro-ecosystem productivity

Agro-ecosystems are complex processes. They involve multiple inputs (including ecosystem services) to produce multiple outputs. The productivity of an agro-ecosystem can be assessed along three different dimensions: scale effects, complementarity effects and convexity effects. First, it may depend on its scale of operation. This is the traditional concept of returns-to-scale. The underlying technology exhibits increasing (IRTS), constant (CRTS) or decreasing (DRTS) returns-to-scale when average productivity rises, is constant, or declines with the scale of operation (see Baumol *et al.* 1982). Second, ecosystem productivity can depend on complementarity effects and their implications for economies of scope (as discussed below). In a multi-output context, complementarity arises when an activity increases the marginal productivity of another. Third, ecosystem productivity depends on the convexity of the feasible set. Convexity of the feasible set corresponds to the traditional concept of diminishing marginal productivity. This reflects resource scarcity where, for a given resource set, obtaining higher outputs becomes increasingly difficult. Note that scale effects differ from convexity effects (e.g. local IRTS can apply with or without local convexity). In general, scale, complementarities and convexity effects can all affect ecosystem productivity.

In addition, agro-ecosystems evolve over time. Their dynamics can be very important. First, the technological progress has been quite large, contributing to significant increases in agro-ecosystem productivity. Second, short-term effects can differ significantly from long-term effects. For example, situations where positive short run payoff accompany negative longer run payoff raise questions about the sustainability of current practices (e.g. soil erosion).

Finally, agro-ecosystems typically exhibit significant uncertainty. For example, unanticipated weather effects and pest damages can have large effects on agricultural production. These effects can be in the short run (e.g.

adverse effects of a drought) as well as long run. This latter case is associated with ecosystem resilience, reflecting its ability to recover from adverse shocks. Ecologists have argued that more diverse ecosystems tend to exhibit greater resilience.

## 2.1 Technological progress

Over the last few decades, productivity growth has been the principal factor responsible for economic growth of agriculture in developed countries (Ball 1985; Mullen and Cox 1995; OECD 1995; Ball *et al.* 1997; Mullen 2007). The growth has been driven by rapid technological progress in agriculture. For example, over the last few decades, Australian agriculture has seen an increase in productivity of 2.5 per cent a year (Mullen and Cox 1995; Mullen 2007). This indicates that technical progress (i.e. significant improvements in land and labour productivity) contributed to most of the increase in farm output. Such remarkable results apply to most developed countries (OECD 1995). On average, productivity growth in agriculture has been larger than in many other sectors (e.g. see Jorgenson and Gollop 1992; Mullen 2007). This stresses the importance of agricultural technical change in developed countries. However, the extent and nature of agricultural productivity growth in developing countries has been less uniform. Over the last three decades, land productivity and labour productivity have increased significantly in most countries (Craig *et al.* 1997). However, Sub-Saharan Africa has seen stagnation in its agricultural labour productivity (Craig *et al.* 1997).

There is evidence that technological progress tends to respond to relative resource scarcity. This is the induced innovation hypothesis (Binswanger 1974; Hayami and Ruttan 1985). It states that relative resource scarcity tends to guide technological change toward using additional inputs that are plentiful and inexpensive, while saving on scarce and expensive inputs. This is consistent with labour-saving technological change being stimulated by higher wages. This is also consistent with fertiliser-using technological change found in North American, European and Asian agriculture in the 1960s and 1970s (Binswanger 1974; Hayami and Ruttan 1985). It involved the development of high-yielding varieties (through genetic selection) of corn, wheat, and rice that were particularly responsive to nitrogen fertiliser. The incentive to develop and adopt these new varieties came in part from technological progress in the nitrogen fertiliser industry, which reduced the market price of nitrogen fertiliser. This combination of low-cost fertiliser with high-yielding varieties contributed to large crop yield improvements in developed agriculture, and to the success of the 'green revolution' in developing countries.

Over the last century, advances in agricultural technology typically came from some combinations of private and public institutions that made significant investments in agricultural research and development (R&D). Historically, the payoff from both private and public R&D investments in agriculture has been high. On average, their estimated rate of return has been in the range of

20–30 per cent in developed countries (e.g. Griliches 1960; Hayami and Ruttan 1985; Huffman and Evenson 1993; Mullen and Cox 1995; Chavas and Cox 1997; Mullen 2007). For both private and public R&D, there is evidence of significant lags between the timing of investment and its effects on farm productivity, the lag varying between 10 and 30 years. The empirical evidence suggests that private R&D investments appear to generate their returns in the intermediate run (after about 8–15 years), while public R&D investments seem to payoff in the longer run (after 15–25 years) (e.g. Huffman and Evenson 1993; Chavas and Cox 1997). This is consistent with the 17-year legal patent protection, and the fact that private research tends to be more ‘applied.’ In contrast, public research tends to be more ‘basic’ with longer-term and more uncertain payoff. However, the relative role of public vs. private agricultural research is changing. In the US agriculture, investments in private research have increased faster than in public research. Although Australia’s agricultural research remains dominated by public institutions (Mullen and Cox 1995; Mullen 2007), a move toward greater privatisation of agricultural research is observed in many countries around the world (OECD 1995). With the current developments in biotechnology, this involves a redefinition of the relationships between private research and public research.

Part of the increase in farm productivity over the last few decades has been associated with increased specialisation. In many developed countries, at the beginning of the 20th century, most farm households were small and greatly diversified. Being strongly motivated by food self-sufficiency motives, they attempted to produce most of the household food consumption needs. This changed with the growth of agricultural markets, which facilitated the development of specialisation in agriculture at the farm level, the regional level, as well as the national level. Greater specialisation reduced the scope of activities and increased the need for market exchange for each farm and each region. It allowed farm managers to focus their skills on just a few enterprises, thus improving their production control and efficiency. It also allowed farm and food marketing firms to become better organised spatially, thus contributing to lower transportation and marketing costs.

## 2.2 Economies of scale

Issues related to the structure of agriculture and to the survival of the family farm have always been subjects of interest. At the centre of this debate is the relationship between farm size and economic efficiency: Are large farms more efficient than small farms? Is it possible to identify an optimal farm size? The nature of returns-to-scale in production can shed some light on these issues (Chavas 2001).

Returns-to-scale reflect the relationship between average production cost and firm size. Increasing (decreasing) returns-to-scale correspond to an average cost (per unit of output) being a decreasing (increasing) function of output; and CRTS mean that average cost is unaffected by firm size.

Alternatively, finding that larger firms exhibit a lower (higher) average cost identifies the presence of economies (diseconomies) of scale. In agriculture, it often appears relevant to consider land as a fixed factor of production. Then, returns-to-scale can be alternatively measured in terms of the properties of the average return per unit of land: increasing (constant, decreasing) returns-to-scale correspond to the average return per unit of land being an increasing (constant, decreasing) function of farm acreage. In this context, the average return per acre is the Ricardian rent, measuring the return to land after all other factors of production have been remunerated (e.g. Chavas 1993).

In agriculture of developed countries, the empirical evidence shows that the average cost function has a typical L shape: average cost tends to decline for small farm sizes, and then reach a lower plateau for average to large farm sizes (e.g. Hall and Leveen 1978). This suggests three points. First, economies of scale seem to exist for small farms. Second, there is no strong evidence that diseconomies of scale exist for large farms. Third, there is a fairly wide range of farm sizes where average cost is approximately constant. This has focused some attention on the 'minimum efficient' farm size, that is, the smallest farm size that can capture the benefits of economies of scale. Knowing this minimum efficient size is particularly relevant for the evaluation of the efficiency of farm structure and land reform policy.

One problem is that there is no clear consensus on what the 'minimum efficient' farm size is. Why? First, farmers have the option to choose among different technologies, each one adapted to particular farm sizes. The typical situation is that, for a given technology, average cost tends to decrease with size, up to some capacity beyond which average cost increases. As firm size increases, a switch can take place from one technology to another better adapted to larger sizes (e.g. through capital investment and mechanisation), so that the region of DRTS is often not observed. Also, the minimum average cost of each technology may be fairly constant across technologies. This implies that the lower-bound envelope of the minimum average cost across technologies (the 'long-run average cost' function) is rather flat (e.g. Hall and Leveen 1978; Matulich 1978). This suggests that, while IRTS may well be present for a given technology, the situation of CRTS may be approximately satisfied across technologies for a wide range of farm sizes. This would help explain why there is empirical evidence of both increasing returns and CRTS appearing to coexist in agriculture. Also, it helps explain why farm size can vary over such a wide range, both within a country and across countries. This indicates that, as long as farms have access to a technology adapted to their size, efficiency gains from changing farm sizes or from land redistribution schemes may be limited.

Second, the empirical estimation of returns-to-scale often depends on the measurement of cost. In agriculture, the measurement of the cost of family labour is problematic. Family labour is often valued at its opportunity cost, often assumed to be the wage rate (e.g. Hall and Leveen 1978; Singh *et al.* 1986). However, this is not appropriate when household work generates

direct utility to the household (in a way similar to leisure in the neoclassical household model). For example, this would happen whenever family members enjoy working on the farm. In this case, the shadow price of family labour is less than the wage rate, the difference reflecting the value of 'enjoying farm work.' Supporting empirical evidence in agriculture is presented by Lopez (1984). This is relevant on 'hobby' farms, where agricultural activities are also seen as 'leisure' activities. It also seems to characterise part-time managers typically found on small farms. This suggests that the valuation of family labour may in fact change with farm size: *ceteris paribus*, the shadow value of labour on some small farms may be lower than on larger farms because of the enjoyment of farm work by 'hobby farmers' and some part-time farmers. This also means that the wage rate is an upward-biased estimate of the shadow price of family labour on some small farms. In this case, finding high average production cost on small farms may simply reflect this measurement bias (rather than the existence of IRTS). This indicates that most farms are scale efficient, i.e. that economies of scale do not provide a strong incentive for farms to become larger. In this case, finding that even small farms can be scale efficient helps explain the prevalence of the family farm.

### 2.3 Economies of diversification

Farms are typically multi-product firms. Most produce more than one output, either implementing crop rotation practices or using an integrated crop-livestock production system. Yet the extent of farm specialisation varies both over time and across space. In general, there is a tendency for commercial farms to be more specialised than subsistence farms, with an overall trend toward increased specialisation. The fact that most farms are multi-product firms suggests that the benefits of diversification are significant in agriculture. These benefits take two forms: the presence of economies of scope reflecting the reduced cost associated with producing multiple outputs, and the risk-reducing effects of diversification.

#### 2.3.1 *The role of risk*

Risk and risk aversion provide incentives for farmers to reduce their risk exposure. To the extent that different activities are influenced differently by weather conditions or pest problems, diversification can be an effective way of reducing farmers' risk exposure. There is empirical evidence that risk reduction is a significant motivation for farm diversification (e.g. Lin *et al.* 1974).

Being in general risk averse (e.g. Lin *et al.* 1974; Binswanger 1981; Chavas and Holt 1996), farmers are made worse off by being exposed to risk. In this context, a risk premium can be used as a measure of the implicit cost of private risk bearing. In situations where the variance of farm revenue is proportional to the square of expected output, one expects the average risk premium to increase with farm size (Chavas 1993). This suggests that risk exposure would give some economic advantage to smaller farms. This would

provide a disincentive for increasing farm size. Alternatively, larger farms may have access to better risk management strategies that can help reduce their risk exposure. As a result, it is not clear where risk plays a significant role in explaining why larger farms tend to be more specialised.

### 2.3.2 *Economies of scope*

The cost function has provided the standard basis for measuring economies of scope. In this context, Baumol *et al.* (1982) have defined economies of scope (diseconomies of scope) as situations where it is less costly (more costly) to produce the aggregate outputs from an integrated firm as compared to specialised firms. This has stimulated empirical analyses of the benefit (or cost) of producing from an integrated multi-output firm. The analysis of economies of scope can be extended in the context of the underlying technology: economies of scope exist when the production of multiple outputs in an integrated manner increases productivity (Chavas and Kim 2007). This is relevant in the evaluation of ecosystem productivity (where ecosystem services are often non-market inputs).

Economies of scope in agricultural activities appear to be significant (e.g. Fernandez-Cornejo *et al.* 1992; Chavas and Aliber 1993). Economies of scope come in part from complementarities among outputs. Complementarity between two activities arises when one activity increases the marginal productivity of the other. In agriculture, crop rotations give a well-known illustration. Crop rotation allows different crops to better exploit the fertility of the soil. For example, corn planted after soybean benefits from the soybean's ability to fix nitrogen. Also, crop rotations contribute to lowering pest populations, thus reducing the need for pesticides. Finally, integrated crop-livestock systems can involve forage production that helps improve land fertility and reduce soil erosion, while manure can ameliorate soil quality and increase crop yields.

## 2.4 Benefits of diversification

The above discussion indicates that farm diversification is motivated by both risk effects and complementarity/scope effects. The latter effects are associated with productivity improvements. How does diversification help ecosystems to be more productive? Compared to natural ecosystems, agro-ecosystems tend to be very specialised. The main reason is that agricultural production is dominated by just few species. More than 70 per cent of farmland is planted in cereals, which provide more than 50 per cent of human calorie consumption (Heiser 1990, p. 64); and just four crops (wheat, maize and rice) constitute 80 per cent of world cereal production. Current agricultural crops evolved from a long process of selection from wild varieties that started at the dawn of agriculture about 10 000 years ago. The process focused on just few crops, but generated large productivity gains that contributed to the spread of agriculture around the world. The process is still going on today. Modern genetic selection and biotechnology have generated even larger productivity gains, providing new ways of feeding a growing world population.

It is notable that these productivity gains have been associated with a trend toward more specialised agro-ecosystems. Why? Managing simpler agro-ecosystems is typically easier. This can be explained in the context of 'bounded rationality'. Bounded rationality means that decision makers implement decision rules that are 'best', subject to their ability to process information (Simon 1955). While this may not be relevant in simple systems, this becomes important in the management of complex systems. Ecosystems are typically very complex and still poorly understood. This means that bounded rationality plays a role in the management of agro-ecosystems. To the extent that specialisation is associated with lowered complexity, it means that specialisation generates productivity gains, implying an incentive to specialise (Chavas and Barham 2007). This suggests the presence of 'increasing returns' to specialisation for geneticists as well as farmers. In addition, technological change outside agriculture may be influencing the trend toward increased specialisation in agriculture. For example, improvements in communications and transportation technologies mean that farmers can obtain easier access to specialists, thus allowing them to reduce the scope of their managerial activities.

### **3. Trade-off between diversity and specialisation**

On the one hand, economies of scope and the risk benefits associated with farm diversification suggest strong incentives for farms to be multi-product enterprises. On the other hand, under bounded rationality, specialisation can generate productivity gains. Intuitively, this latter effect means that a specialist can perform a task better than a general manager. For example, a veterinarian is expected to better manage animal health problems on a farm than a general farm manager. The productivity benefits of specialisation can help explain the historical decline in diversity of agro-ecosystems, and the recent trend toward more specialised farms.

Note that this does not imply the absence of complementarity/scope or risk effects. Complementarity/scope and risk effects work against specialisation benefits. The fact that most farms are still multi-output enterprises indicates that the specialisation benefits do not dominate. The relative importance of complementarity/scope and risk effects in agriculture may actually be an important characteristic that distinguishes it from other industries. Together with the absence of strong economies of scale, this would help explain why the structure of agriculture continues to be dominated by small family farms (instead of large corporate firms). Yet, the trend toward greater farm specialisation indicates that recent technological advances may be changing the balance in favour of specialisation. A rise in specialisation benefits from genetic selection as well as farm management would contribute to larger productivity gains obtained when farms are less diversified. In this case, while the diversification benefits (driven by risk and complementarity effects) may still exist, they can become dominated by specialisation benefits. This suggests the need to evaluate the trade-offs between diversification and specialisation.

### 3.1 Technology development

The trend toward more specialised agro-ecosystem started some 10 000 years ago, as agriculture replaced a more diversified ecosystem supporting an economy based on hunting and gathering. This points to the role of technological progress. In agriculture, genetic selection has been at the heart of very large productivity growth. Historically, this was done by farmers through observations and judicious seed selection. Combining luck with time, this eventually generated the genetic material constituting modern crops. Over the last century, the genetic selection has benefited from scientific developments in genetics and more recently in genetic engineering. The growing role of genetics was associated with the rise of specialised research institutions either public (funded by the taxpayers) or private (funded by foundations and/or patent royalties). These institutions have been the engine of rapid technological progress in agriculture. Among the success stories were the development of corn hybrid in the first part of the 20th century, and the 'green revolution' of the 1960s and 1970s that greatly benefited Asia and Latin America. A notable failure was the failure of the green revolution to reach Africa. Biotechnology now offers good prospects for further increases in agricultural productivity.

While technological progress has come with greater specialisation in agriculture, does it have some downside? Is there a cost associated with diversity loss? The question has been asked with respect to the implications of loss in genetic diversity. Could it be that some useful genes are being lost before being discovered? By reducing prospects in genetic selection, it could have adverse effects on future productivity growth. This has stimulated the creation of gene banks to preserve as many of genes as possible. Another issue is whether declining diversity in agro-ecosystems could have broader adverse effects on the functioning of earth ecosystems. Such concerns have stimulated research on the functioning of ecosystems and the effects of environmental diversity. Finally, there is been some concern that diversity loss may be associated with greater risk exposure. These issues are further discussed below.

### 3.2 Farm management

We have just reviewed the presence of trade-off between integration and specialisation in agriculture. What are the implications for farm management? As discussed above, we have seen that economies of scope and risk effects provide an incentive for small farms to diversify. Chavas and Di Falco (2008) find that complementarity effects contribute to economies of scope, and there is evidence that economies of scope tend to decline with farm size (Chavas and Aliber 1993). This means that large farms have some incentive to specialise.

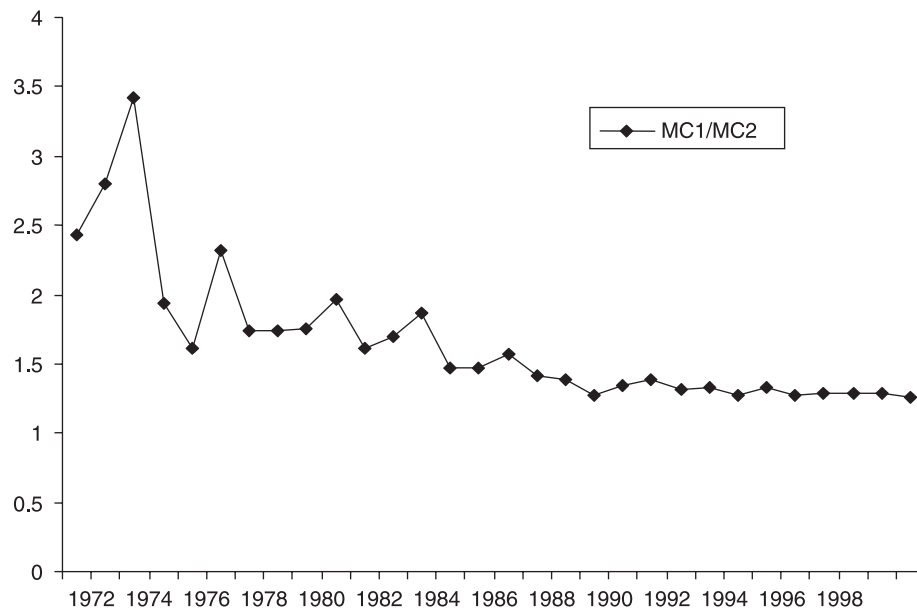
There is evidence of significant complementarity effects among crops. They imply that the benefits from integrated cropping systems are significant. For

example, crop rotation can improve soil fertility (e.g. corn-soybean) and help reduce pest populations. In such cases, farm technology is 'joint' as crop diversity contributes to enhanced productivity (Di Falco and Chavas 2006). Concerning livestock, there is also evidence that economies of scope are important in integrated crop-livestock systems (Chavas and Aliber 1993). The interaction between crop and livestock can take several forms. One example is how manure can enhance soil fertility and increase crop yield. In the context of mixed-dairy farms, the evidence that economies of scope decline with farm size is instructive (Chavas and Aliber 1993). It suggests that specialised management may become profitable only on larger farms. Often, the benefits of specialisation can be obtained only beyond some minimal scale of operation. This shows the existence of important trade-off between farm size and diversification. As farm size increases, the benefits of specialisation and the associated enhanced productivity rise, which can counterbalance the benefits of diversification mentioned above. This is supported by empirical evidence of a negative relationship between economies of scope in agriculture and farm size (e.g. Fernandez-Cornejo *et al.* 1992; Chavas and Aliber 1993). This provides an economic rationale for why larger farms tend to be more specialised than smaller farms, as the former are in a better position to capture the benefits of specialisation. It also suggests that the trend toward more specialised farm production systems is in large part motivated by productivity gains.

### 3.3 Risk management

Diversification can be an effective way of reducing risk exposure. This suggests that a more diverse agro-ecosystem can contribute to lower risk exposure. Most farmers being risk averse, this means that risk provides a general incentive for farm diversification (e.g. Lin *et al.* 1974; Chavas 2004). In addition, most individuals are averse to 'downside risk', i.e. to losses associated with unfavourable events (e.g. Binswanger 1981; Chavas and Holt 1996). This means that a reduction in downside risk exposure (e.g. the probability of crop failure) is in general desirable. Can diversification help? There is some evidence that crop diversification also contributes to a significant reduction in downside risk exposure (Di Falco *et al.* 2007). This strengthens the role of risk as a motivation for farm diversification. An additional issue is the linkage between diversity and resilience, i.e. the ability of an agro-ecosystem to respond to shocks. Di Falco and Chavas (2008) provide evidence that diversity does help an agro-ecosystem to recover from an adverse weather shock quicker. All these arguments stress that risk management helps motivate diversification strategies.

This raises the question of possible interactions between technology and risk management. Such interactions appear to be present. For example, the development of drought resistant varieties helps reduce unpredictable weather effects on yields, thus reducing production risk. Improved production



**Figure 1** Relative marginal cost of US farm output comparing 'bad state' (MC1) with 'good state' (MC2).

and marketing management can also help reduce risk exposure. Kim and Chavas (2003) and Chavas (2008) found empirical evidence that technological and managerial innovations contribute to reducing risk exposure. This is illustrated in Figure 1, which reports the impact of technological progress on the marginal cost of production in US agriculture, conditional on the state of nature. Figure 1 shows that the ratio of marginal costs under a 'bad state' vs. a 'good state' has been significantly reduced over the last few decades. This indicates that technological progress in US agriculture has contributed to reducing risk exposure (presumably due to both genetic advances and improved management). By weakening the effects of risk on diversification strategies, this means that technological progress may indeed be the driving force toward greater specialisation in agriculture.

#### 4. Implications for agro-ecosystem management

Farms are involved in agro-ecosystem management. As noted above, the presence of complementarities provides incentives for diversification. These complementarities are positive externalities among activities. Alternatively, agro-ecosystem functioning can involve negative externalities (e.g. diseases) with adverse impact on productivity. In either case, these externalities are subject to management. When the externalities are local, they can be managed locally. This is the scenario where the Coase theorem applies: maximising the

value of ecosystem services can generate efficient allocations (Coase 1960). This means that farm management can deal effectively with local externalities that arise within the boundary of the farm. An example is given by the positive externalities obtained from crop rotation. In this context, farm-level diversification can capture the associated complementarity benefits and generate an efficient use of the agro-ecosystem.

The issue becomes more complex if the externalities are non-local, i.e. beyond the boundaries of the farm. Examples include the cases of contagious diseases or of invasive species. In such situations, local management is not sufficient to achieve an efficient allocation. The Coase theorem still applies. But it identifies the need for some coordination scheme that would maximise the aggregate value of ecosystem services. Such schemes require innovations in both markets and policies. This raises some significant challenges. First, the efficient way to internalise an externality always depends on the exact nature of the externality. This means that there is no panacea to externality management. Second, identifying the magnitude of these non-local externalities remains a significant challenge.

One issue is that the effects of externalities often depend on the current institutional context. For example, the functioning of markets can interact with external effects. This is relevant in the current wave of globalisation and trade liberalisation, motivated by associated efficiency gains. In a second best world, this can be a problem when liberalised markets tend to exacerbate the adverse effects of externalities. Such arguments have sometimes been used against globalisation policies. This occurs when current markets and policies contribute to the destruction of ecological capital. These are scenarios where current strategies are profitable in the short run but not in the longer run, implying a lack of sustainability and a threat to future ecosystems productivity. However, blaming globalisation can hide the main issue: the efficient management of externalities.

The Coase theorem states that externality management requires some coordination schemes among the individuals affected by the externalities. This can be done through contracts. When the number of individuals is small (e.g. at the level of a watershed), private contracts can be effective. Alternatively, when the number of individuals is large, more centralised coordination schemes may be needed. This can apply at the regional level, the national level or the international level depending on the nature and extent of the externalities. Evaluating the boundary between private contracts and centralised coordination is useful. But such boundaries are evolving depending on the nature of transaction costs. In agriculture, lower transaction costs have contributed to a growth of private contracts that help support greater product differentiation. This is exemplified by the recent growth in organic agriculture, typically supported by contracts between farmers and food wholesalers/retailers/consumers. While this implies a very different vertical organisation of food industry, it allows for explicit linkages between food prices and agro-ecosystem management.

Agricultural policy can also play a role. This occurs when government agencies are seen as the appropriate coordination agents dealing with externalities. Examples include the management of contagious diseases or of invasive species. The challenge is that agricultural policy often faces multiple objectives. They include capturing the benefits of globalisation, supporting farm income, and managing non-local externalities. This becomes problematic when the objective of managing externalities conflict with other objectives.

We have argued that productivity growth has played a major role in influencing specialisation strategies. This raises the question: what are the linkages between research policy and diversification? The answer depends in part on the type of research. Private research is motivated mostly by shorter-term profitability. Public research can work on longer term emerging technologies, sometimes with lower odds of success. The geographical focus of the research is also of interest. Local research is relevant on agricultural technology that is adapted to local agro-climatic conditions. At the other extreme, international research is relevant for technology that can be applied across various agro-climatic zones, and where research efforts exhibit significant scale economies. In between are national research efforts that typically focus on specific crops and agro-climatic conditions. In general, the presence of scale economies works against adaptation to local agro-climatic conditions. This was the case of 'green revolution' research on sorghum and millet: most of the sorghum-millet research initially centralised in India in the 1960s proved to be poorly adapted to African agro-climatic conditions. This contributed to the failure of the green revolution in Africa. Another issue is the difficulty to deal with regions of the world facing very specific agro-ecosystems. An example is the case of teff (a food grain) that is grown mostly in Ethiopia. The regional specificity of this crop has generated relatively little attention from research institutions, contributing to low agricultural productivity growth in the Highlands of Ethiopia.

Overall, technological progress has generated large improvements in farm productivity. Biotechnology is currently generating good prospects for further improvements in agro-ecosystem productivity. However, rapid genetic improvements have focused on a limited number of crops and animals. This contributes to a trend toward greater specialisation as farmers have an incentive to adopt the few varieties/breeds that benefit from genetic progress. This means that, while emerging technologies contribute to productivity gains, they also decrease the incentive to diversity. This applies at all levels: at the farm level, the regional level, the national level, and the international level. This creates special challenges to agro-ecosystem management. At the local level, farmers have stronger incentives to specialise (e.g. as they adopt the few varieties/breeds benefiting from biotechnology). This works against the incentive to capture local complementarities. This is efficient as long as the complementarities remain local. However, this can become problematic in the presence of non-local externalities. As discussed above, this implies the

need for coordination schemes to internalise these externalities and the appropriateness of these schemes depends on the nature and geographical extent of the externalities (i.e. regional, national and international).

Another issue is whether the trend toward greater specialisation means greater risk exposure. This is consistent with the risk-reduction effects of diversification strategies. But, as discussed above, new technologies (e.g. the development of drought resistant varieties) and improved management can also help reduce risk exposure. But there remains much uncertainty about how agro-ecosystems evolve over time. How resilient are they to small shocks? To large shocks? In the short run? In the long run? This remains a significant challenge to both technology development and management. Historically, humans have been very good finding technology and management solutions to resource scarcity problems. This indicates that we need to remain vigilant in adapting to our changing environment. However, some caution here may be appropriate. There may be some adverse changes that are rapid and large enough to overwhelm our ability to adjust. This is particularly relevant in situations of irreversibility where agro-ecosystems reach some 'bad states' that are difficult to reverse. Under such scenarios, application of the precautionary principle to agro-ecosystem management may be warranted.

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