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Spillover Impacts of Agricultural Research: A Review of Studies

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Introduction

Measurement of the spillover effects of research has drawn significant attention in recent years. Three aspects of spillover effects — spillover as an input in the research policy debate, as an input to support research management decisionmakers, and as an input in the fine-tuning of research evaluation methodology — are very important to understand (Davis 1991). Consideration of the spillover effects has significant implications for research policy design and evaluation of research benefits. Research systems generate technologies for target environments and commodities. However, the outcome of a research effort often impacts an area wider than the target. Thus, research systems generate two types of benefits for their investors: direct and spillover effects. Conventional research evaluation considers only the direct benefits and ignores the spillover. As a result, output from research is underestimated. So when policymakers decide on the level of investment to be made in research, they are likely to do so on the basis of such underestimated benefits. Therefore, the investment is likely to be less than optimum. If, however, spillover effects were quantified, they would help in making research investment decisions more attuned with the needs. Incorporation of spillover effects in the research policy design would also enhance the transparency of the decision-making process. Research spillover effects also have an impact on the competitiveness of farmers in different regions and countries. National research planning tends to underestimate returns to research by not considering spillover effects and, therefore, tends to underinvest in research. International research support, whether bilateral, regional or multilateral, is normally designed to complement national research activities and to generate maximum international rather than national research benefits. It selects research portfolios with an explicit consideration of the likely spillover benefits for countries with similar agroclimatic and socioeconomic environments.

Research Spillover Effects: Concept and Types

A technological breakthrough in agriculture often leads to increased yields, or improves the quality of output, or enhances the efficiency of input use. If a new technology has applicability beyond the location or commodity for which it was generated, such an effect is commonly referred to as a spillover effect (Bantilan and Davis 1991). Three types of spillover effects have been identified: across-location, across-commodity, and price spillover effects. The first two types are direct effects and the last indirect.

Across-location Spillover Effect

Across-location or across-environment spillover effects refer to a situation in which a technology developed for a particular crop at a specific location can be adapted to improve the production efficiency of that crop at other locations. However, the degree of applicability may vary across locations due to agronomic, climatic, and ecological differences in the production environments. One example of across-environment research spillover is the ICRISAT-developed sorghum variety ICSV 112 (SPV 475). It was primarily intended for India, but was also released in Mexico (UNAL 1-87), Nicaragua (Pinoleso), and Zimbabwe (SV1). This variety matures in 115-120 days and yields 3.4 t ha^{-1} at Patancheru, India (ICRISAT 1990).

Evenson (1989) described across-location spillover effects as interlocational spillover and explained it with a generalization of the role of geoclimatic inhibitors to spillover (Figure 1). The horizontal axis depicts an index of a particular set of geoclimatic factors, e.g., water stress. The

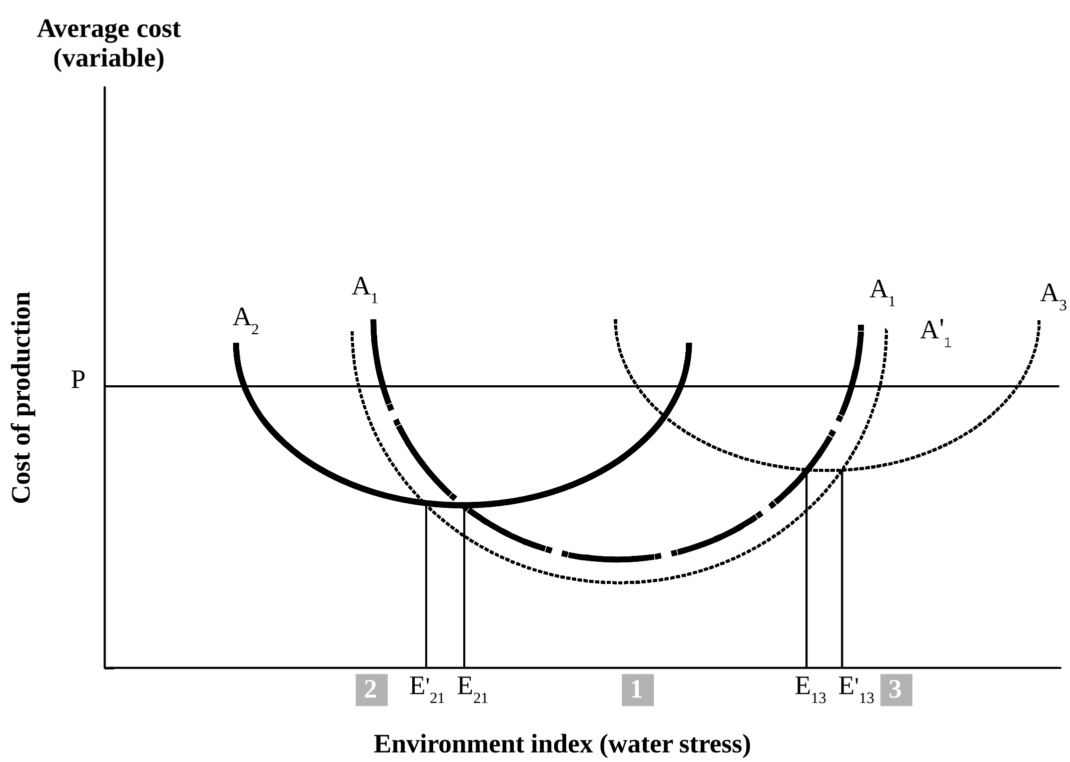

Figure 1. Generalization of the role of geoclimatic inhibitors of spillover effects (Evenson 1989).

vertical axis indicates the variable cost of production per unit of product. Suppose that three research programs are located, respectively, in environments 1, 2, and 3. Environment 1 is the 'best' suited for production. The technology employed there has been targeted to location 1. When this technology is used in environments other than 1, its performance is diminished by environmental interactions. The diminution in performance is greater for the program more tightly targeted to environment 1. Research programs in locations 2 and 3 similarly target technology to their respective environments.

The real cost advantage of the technology developed for environment 1 (relative to the technology for environments 2 and 3) declines when the technology is transferred to locations dissimilar to location 1. Its absolute advantage (over type 2 or 3 technology) is shown to be limited to the range E_{21}–E_{13}. Now consider an improvement in technology produced by research in location 1 (depicted as the A_1' curve). The direct spillover of this technology is limited to the environment range E'_{21}–E'_{13}. However, when comparable technology improvements occur in locations 2 and 3, the range of direct spillover from 1 to the other locations would be narrowed. If more locations were to build targeted research programs, the range of direct spillover would be further narrowed. Thus, the specification of direct spillover research requires consideration of the general research design of a system including the range of locations in which the technology is applicable.

Evenson (1994) defined the potential spillover for a biological technology as $S_{ij} = Y_{ij}/Y_{jj}$, where Y_{jj} is the yield in environment j of varieties developed for that environment and Y_{ij} is the yield of the same group of varieties in environment i. Byerlee (1995) reported that the extent of spillover, i.e., the size of S_{ij} depends on various factors: agroecological similarity between the originating and the receiving region, local food tastes and preferences, factor prices, and institutional factors (land tenure, intellectual property rights, etc.). He also mentioned that realization of the potential spillover is influenced by other factors such as historical and cultural links between countries, geographical proximity, complexity of the problem, and other institutional factors (the research networks and the level of intellectual property rights).

Across-commodity Spillover Effect

Across-commodity spillover effects occur when the technology developed has applicability across commodities. For example, a cultural management technique specially developed for sorghum production may also have the potential of improving the efficiency of production of millets and other cereals. Across-commodity spillover has been termed by Evenson (1989) as intercommodity spillover. He proposed that for some technologies the spillover mechanism would not be confined to a single commodity. Resource- or input-based technology may be relevant to several commodities. Pretechnology science findings may spill over across commodities because they enhance the invention potential of several commodity technology programs. For example, programs to control insects or correct a soil problem will spill over across commodities. A screening technology developed for sorghum may equally be useful for pearl millet screening. Research on biological control of *Helicoverpa* in chickpea and pigeonpea may equally be applicable in cotton and sorghum.

Price Spillover Effect

Price spillover occurs when a technological change for a particular commodity at a specific location increases supply and changes the price of that commodity in other locations through trade. It may also significantly affect the price of a related commodity in the same location. This is particularly relevant for products with low demand elasticity, and/or when the rate of product transformation among commodities is significant (Bantilan and Davis 1991).

Price spillover can be seen as a case of intersectoral spillover as discussed by Evenson (1989). He elaborates that most private (and public) firms in an economy conduct two types of research programs. The first is directed toward process improvements in the sector itself (usually within the firm). Such research does not have a spillover effect on another sector except by way of price. The second type of research is directed toward product improvement. Such research can result in real and accounting spillover because, when product quality changes, it is almost impossible to account for the quality change in terms of the price. When a manufacturer introduces a new machine and sells it at a price that is 10% higher than the price of an existing machine, accounting methods will measure the new machine as providing 10% more real service to the agricultural sector. However, there are at least two reasons why the new machine is likely to be providing more than an increase of 10% in the real service. First, the manufacturer will have to provide a real discount to farmers to sell the new machine. Second, competition and expected competition from other manufacturers will lead him to give a real discount to farmers. Such real discounts associated with the introduction of new products from the farm-input supply sector constitute a research spillover to the agriculture sector.

Evenson (1989) also discusses another type of spillover: interfoci spillover. He defines it in the context of research system design, which is characterized by a set of hierarchical research foci. He relates this to most agricultural research programs where investment occurs in three stages: (a) pretechnology science; (b) technology invention and development; and (c) technology development and subinvention. These stages correspond to specific specializations, which lead to locational specialization. Invention and development of new technology, i.e., stage b, is the central objective of national agricultural research systems (NARSs) as well as international agricultural research centers (IARCs). It is well-recognized that technology development rests on the twin pillars of science and technology which together define the invention potential of a national program. Almost all national and international research institutions invest in pretechnology science research programs, i.e., stage a, to build invention potential. Genome mapping techniques (such as RFLP mapping and polymerase chain reaction) and genome transformation activities at ICRISAT are examples of pretechnology science research which immensely helps in technology generation and development for a group of crops rather than a single one. By enhancing invention potential, pretechnology science research has a spillover effect on programs within the given system as well as on other national and international research programs. Technology developed in one nation may enhance the invention potential in another even if it is not directly transferable. Plant varieties, for example, may be valuable as germplasm in the breeding programs of another nation or state. Another example of interfoci spillover is the ongoing genome transformation activity at ICRISAT—which relates to research stage b—which is likely to make an immense contribution to prevention of fungal diseases in sorghum.

Most national research programs, especially those of small countries, concentrate on adaptive development and subinvention, i.e., stage c. Typically, they are technologically dependent on the international research institutes, and receive direct and indirect research spillin[1] from them. For example, Bangladesh has released six chickpea varieties; of these, four were drawn from ICRISAT crosses after screening and adaptive research trials. The other two were also from crosses provided by other international research centers.

Thus, Evenson's (1989) interfoci research spillover is really an indirect type of across-location spillover.

1. 'Spillin' and 'spillover' refer to the same phenomenon of externality. The terms are used interchangeably depending on whether a research program is receiving or producing the externality.

Spillover Measurement Techniques

Two types of measurement techniques—subjective and objective—have been used to assess the spillover effects in agriculture. The techniques vary according to the type of spillover measured.

Subjective estimates are based on value judgments rather than experimental or farm yield/cost data. They are often arrived at through elicitation from experts. Objective estimates, on the other hand, are based on hard data and evidence reflecting the extent of applicability of a new technology across environments or commodities beyond the research target. Data requirement and methods of analysis for objective estimates vary, depending on the type of spillover to be assessed.

Spillover impact measurement techniques can be discussed under three categories: (a) across-location/environment; (b) across-commodity; and (c) price spillover measurement techniques.

Subjective and objective estimates are available for across-location spillover for some crops. Bantilan and Davis (1991) developed a theoretical model for across-commodity spillover estimation but no empirical studies have yet been done to estimate it. Price spillover is estimated in conjunction with across-environment technology spillover.

Measurement Techniques for Across-location/Environment Spillover

Most of the early empirical studies relating to impact evaluation of agricultural research ignored technology spillover. Later studies in the 1970s and 1980s incorporated spillover across states within a country and across countries utilizing agroclimatic zones (e.g., Evenson and Kislev 1975; White and Havlicek 1981; Evenson 1989). In these studies, research spillover was estimated as a function of the 'research stock', which was typically measured in terms of expenditure or publications aggregated by agroclimatic zone. This research spillover variable was incorporated in an aggregate productivity or production function specification which estimates the relationship between expenditure on research in one agroclimatic zone and output in another. Notationally, the typical form of this specification [developed by Evenson (1968) and refined by Welch and Evenson (1989)] was:

$$R_i^* = R_i + b\,R_i^{ss} + c\,R_i^{sr}$$

Where R_i is the research stock, based on research conducted in state i;

R_i^{ss} is the research conducted in similar neighboring subregions;

R_i^{sr} is the research conducted in similar neighboring regions; and

b and c indicate the spillin to region i from the research activities conducted in similar subregions and similar regions, respectively.

These studies used a simple iterative procedure to estimate b and c. For defining the agroecological zones, the US studies used 16 regions and 45 subregions which were developed by the USDA 1957 Year Book of Agriculture (Evenson 1989).

Aggregate-type studies such as these usually provide information that is useful in general research policy discussions. However, the major problem with such studies is related to the aggregation. The appropriate level of aggregation of any analysis clearly depends on the type of decision to be made from the generated information. Research systems usually require information about the performance of different research programs and projects to justify allocation of resources. The aggregative nature of aggregate-type models and nonavailability of accurate disaggregated data limit these studies in generating such information, which in turn restricts their utility for resource allocation decisions and priority setting in a given environment for a given type of research (Davis 1991).

Several case study analyses have identified spillover benefits from research (e.g., Brennan 1989; Brennan and Bantilan 1999; Yapi et al. 1999; Yapi et al. 1999; Rohrbach et al. 1999). These studies provide meaningful estimates of actual spillover benefits of particular technologies by measuring the impact of technologies imported from an external source. Such estimates are, however, specific to a region or institution and not generalizable at a national or international level.

In terms of the generally accepted economic surplus type research evaluation models, Edwards and Freebairn (1981, 1982, 1984) developed a two-region trade model which included a 'spillover matrix' to model spillovers between two regions. The regions were geographically/politically defined, in their case one country and the rest of the world. Mullen et al. (1989) also used a similar two-region spillover model to look at processing sector research. In both cases, hypothetical guesses of a zero to one spillover index were used to weight the unit cost reduction estimates and were subjectively estimated.

Edwards and Freebairn's two-country model was able to incorporate research spillover effects transmitted in two ways: (i) when research in a significant producing country (or region) affects world supply directly as to change world prices; and (ii) when in addition to or instead of (i), research in one country (or region) has relevance in others such that their supply schedules also are affected, thus lowering both domestic and world prices. The Edwards and Freebairn model is discussed with the help of Figures 2 to 6.

In Figure 2, we see a two-country scenario under a closed economy model. Suppose that two countries—A and B—comprise the world and that they have no trade between them and there are no research activities going on in either. D_{a0} and S_{a0} are the demand and supply curves, respectively, of Country A (Fig. 2a). The equilibrium quantity and price are fixed at Q_{a0} and P_{a0}, respectively. On the other hand, the demand and supply curves of Country B are represented by D_{b0} and S_{b0}, respectively (Fig. 2b). The equilibrium price and quantity for Country B are fixed at P_{b0} and Q_{b0}, respectively. It can be observed that the price of the commodity is higher in Country B than in Country A. Due to this price difference, there may be a tendency towards international trade between the two countries.

Now suppose that the two countries have international trade but there is no ongoing research in either of them. This scenario is shown in Figure 3. Because of the lower price in Country A, the country would export the commodity and Country B would like to import it. Let us assume that the trade occurs through a world market. The curves ED_0 and ES_0 represent, respectively, the excess demand curve of Country B and excess supply curve of Country A (Fig. 3b). Due to the demand-supply interaction in the world market, we can see that the world price is determined at P_{w0} and the equilibrium level of export and import at Q_{w0}. Under assumptions of no transport costs or distortion of prices due to tariffs, subsidies, taxes or quotas, P_{w0} is the domestic price in both countries and therefore determines the quantities produced and consumed in each. Q_{w0} quantity of the commodity is exported by Country A to Country B. As a consequence of international trade, consumers in Country A consume less of the commodity than they would without the international trade while consumers of Country B consume more. The price of the commodity in Country A has gone up (Fig. 3a) while the price in Country B has gone down (Fig. 3c). However, the total economic benefit in the two countries is higher with international trade than without it.

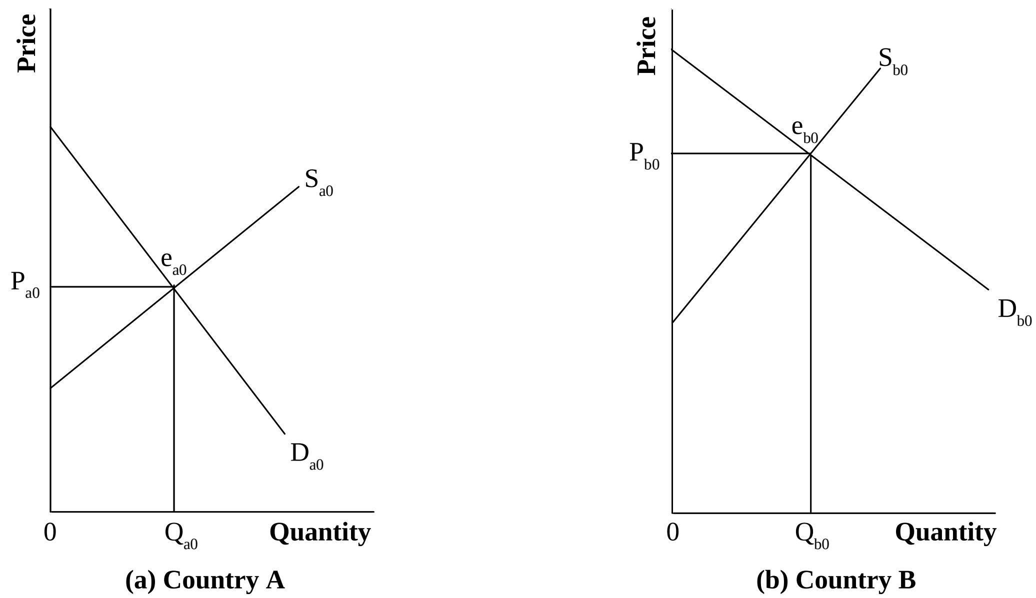

Figure 2. Two-country trade scenario, with both countries having closed economies and no research.

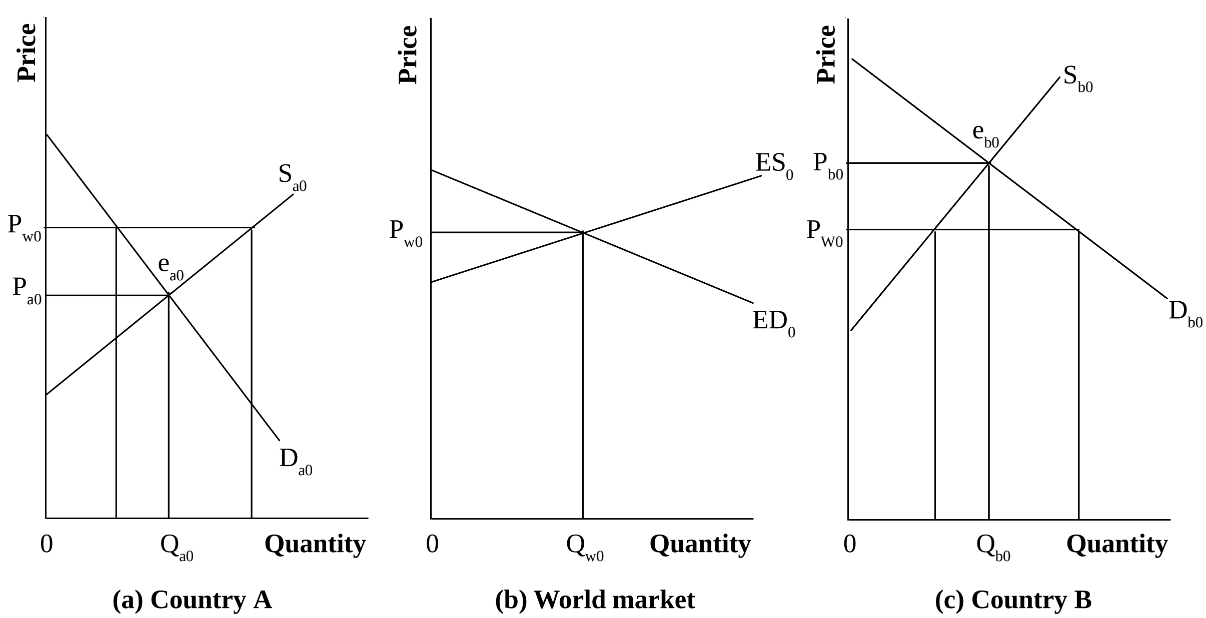

Figure 3. Two-country trade scenario with both countries having international trade but no research.

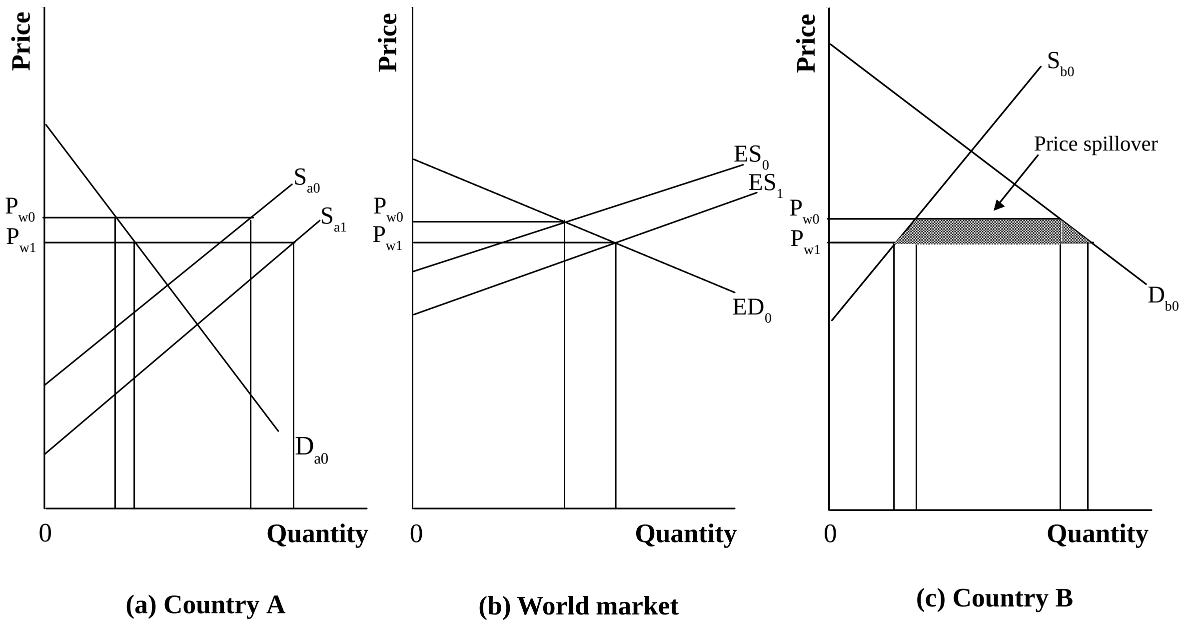

Figure 4. Price spillover in a two-country trade scenario with research in the exporting country but no technology spillover into the importing country.

Suppose country A (the exporting country) has its own research program but country B has none. The technology developed by country A has no applicability for increasing production or reducing costs in country B. In other words, there is no technology spillover from country A to country B. What would this mean for countries A and B? This is explained with the help of Figure 4. Since the research activities are conducted in Country A, the generated technologies would increase the supply at a lower cost, i.e., the supply curve (S_{a0}) of country A would shift toward the right (Fig. 4a). Let's call the altered supply curve S_{a1}. On the other hand, the supply curve in Country B would remain unchanged. As a result of this, the excess supply curve in the world market too would shift toward the right, from ES_0 to ES_1 (Fig. 4b), keeping the excess demand curve (ED_0) unchanged. Since the supply in the world market has increased without a change in demand, there would be a fall in the price, from P_{w0} to P_{w1}. Because of the technological innovation in country A and the consequent decrease in world price, there would be a price spillover from country A to country B. The amount of price spillover would be equal to the shaded area in Figure 4c.

If the research were conducted in the importing country (Country B) rather than the exporting country—again without any technological spillover—then the situation would be different. This scenario is shown in Figure 5. It can be seen that the supply curve in Country B has shifted toward the right, due to the technological innovation accruing from research (Fig. 5c). On the other hand, the supply curve in Country A remains unchanged (Fig. 5a) since there is no research in that country and the technology developed in Country B has no applicability in Country A. Due to the increased supply in Country B, there would be a decrease in the excess demand in Country B, which is reflected in the shift in the excess demand curve, from ED_0 to ED_1, in the world market (Fig. 5b). As a result of this shift in excess demand, there would be less export from Country A to Country B. In other words, there would be a negative price spillover from Country B to Country A. The amount of negative price spillover is represented as the shaded area in Figure 5a.

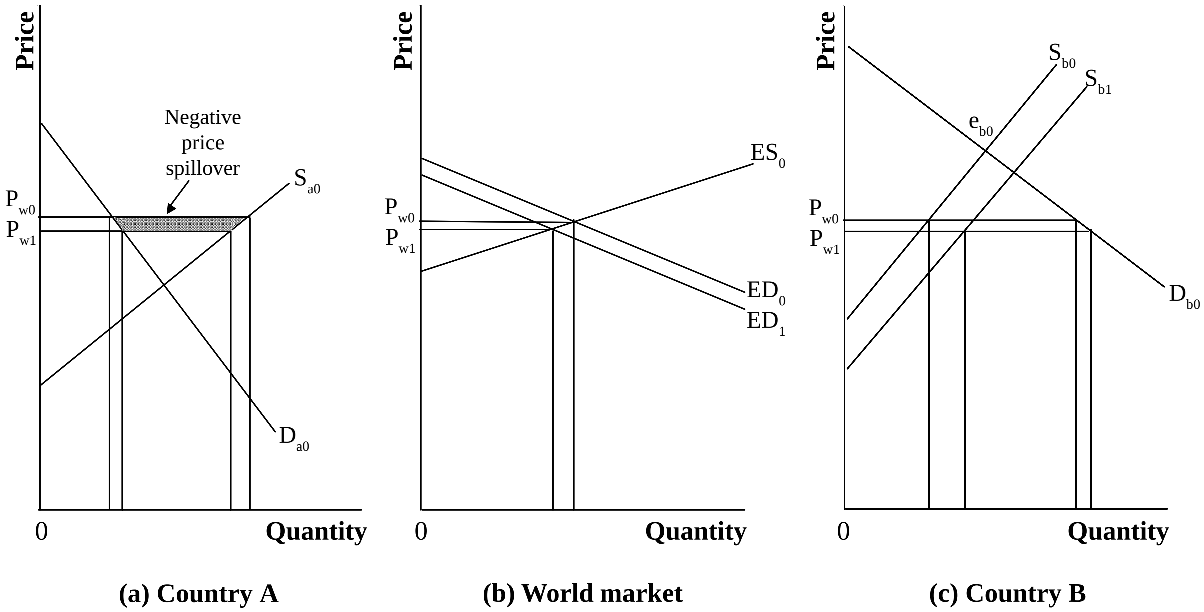

Figure 5. Price spillover in a two-country trade scenario with research in the importing country but no technology spillover into the exporting country.

If research technology generated in one country is applicable in another, i.e., if there is technology spillover, the situation would be different. This situation of technology and price spillovers occurring together is shown in Figure 6. As mentioned earlier, Country A is an exporter and Country B an importer. Research is conducted in Country A and there is technology spillover to Country B. Both countries have free trade. In this scenario, the situation would be as follows: investment in research in Country A would lead to a shift in the supply curve from S_{a0} to S_{a1} (Fig. 6a). Because of the technology spillover, the supply curve in Country B would also shift toward the right (Fig. 6c). The actual magnitude of the shift would depend on the degree of applicability of the technology in Country B. Since the technology is generated for Country A and it has spilled over into Country B, it is likely that the shift in the supply curve in Country B would be less than in Country A. In this example, the unit cost-saving effect, measured by 'K_{ba}', in the country receiving the spillover, i.e., Country B, is assumed to be approximately half of the effect, i.e., 'K_{aa}', in the country undertaking the research, i.e., Country A.

Suppose that the shift in the supply curve in Country B due to technology spillover is from S_{b0} to S_{b1}. The initial impact of this spillover is a shift in Country B's excess demand in the world market from ED_0 to ED_1. It should be noted that some technologies may produce a greater shift in the supply curve in Country B than in Country A, if they perform better in Country B than Country A. Due to the technology spillover, there would be two types of gains for Country B: technology spillover and price spillover, the extent of which is shown as the shaded area in Figure 6c. The total benefit to Country B would be the sum of the price and technology spillovers. Consumers in both countries would gain from the spillover and, because of the steeper price fall, receive a higher share of the total benefits. Similarly, producers in Country A gain but, because of the greater reduction in the world price caused by the reduced world market (excess) demand from Country B, receive a smaller share of the benefits. Producers in Country B would stand to gain rather than lose. However, the gain need not necessarily occur since with certain values of 'K_{ba}' relative to 'K_{aa}' and different supply and demand conditions these producers could in fact still lose from research in Country A.

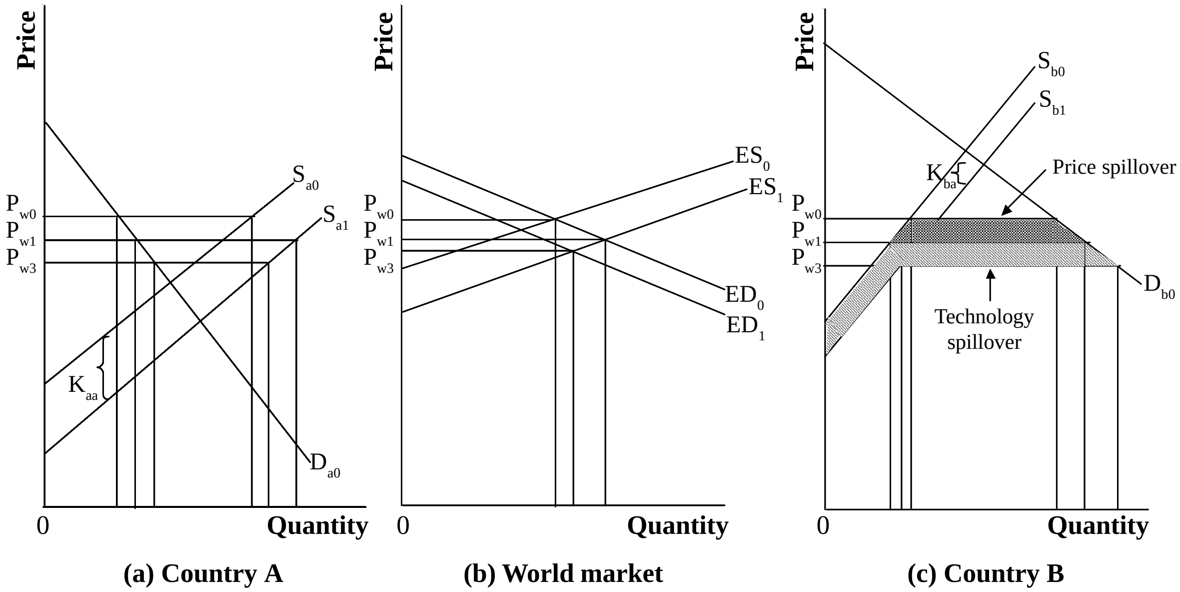

Figure 6. Technology and price spillovers in a two-country trade scenario with research in the exporting country.

Davis et al. (1987) extended the Edwards and Freebairn two-country model to build a multi-country model. In a multicountry situation with several exporters and importers, the implications postulated for a two-country model still hold but with the possibility of a larger number of outcomes. Research spillover effects, 'K_{ba}', may be zero for some exporters and importers thus resulting in differences between national and global total benefit estimates and also differences in the distribution of benefits between consumer and producer groups in different countries.

The Davis et al. (1987) extension has been referred to as the 'Partial equilibrium trade model for spillover estimation'. Both efficiency and distributive considerations were incorporated into this model. The extension of the two-country model to a multicountry situation was characterized by: (a) a more detailed and comprehensive specification of spillover effects; (b) emphasis on the capabilities of research systems in developing countries and therefore the probability of these systems achieving successful research output; and (c) likely differences in the ceiling levels of adoption of research results in different countries. Davis et al. (1987) used agroclimatic zonation to identify agricultural production environments. Similarities in these environments were used to subjectively assess spillover effects (again on a zero to one index) for different commodities. Here too, spillover estimates were derived for geographical/political regions—in most case countries.

Estimation of the benefits from research on a particular commodity undertaken in a particular country or region in the presence of technology spillover is governed by the following formulations. Details of the derivation of these formulae can be obtained in Davis et al. (1987). The gross international benefits from research on a particular commodity undertaken in country 'y' were estimated on the basis of equation 1:

$$E[PV(G_w^y)] = \sum_{t=1}^{T}\sum_{f=1}^{n} \frac{p_{yt}\, x_{ft}\, k_{fy}}{e_{ft}(1+r)^t}\, Q_{sft}$$

$$+$$

$$\sum_{t=1}^{T}\sum_{f=1}^{n} \frac{p_{yt}\, \beta_f\, e_{ft}(\sum_{i=1}^{n} \beta_i\, x_{it}\, k_{iy})^2}{2(1+r)^t[\sum_{i=1}^{n} e_{it}(\beta_i + b_i)]^2}$$

$$+$$

$$\sum_{t=1}^{T}\sum_{f=n+1}^{N} \frac{p_{yt}\, x_{ft}\, k_{fy}}{(1+r)^t\, e_{ft}}\, Q_{sft}$$

$$+$$

$$\sum_{t=1}^{T}\sum_{f=n+1}^{N} \frac{p_{yt}\, \beta_f\, e_{ft}\, x_{ft}\, k_{fy}}{2(1+r)^t}\, [\frac{\sum_{i=1}^{n} \beta_i\, x_{it}\, k_{iy}}{\sum_{i=1}^{n} e_{it}(\beta_i + b_i)}]^2$$

$$+$$

$$\sum_{t=1}^{T}\sum_{f=n+1}^{N} \frac{p_{yt}\ b_f\ \beta_f\ x_{ft}^2\ k_{fy}^2}{2(1+r)^t\ e_{ft}\,(\beta_f + b_f)} \qquad (1)$$

Where

$E[PV(G^y_w)]$	is the expected present value of the total international benefits from research in country 'y' on the commodity of interest summed over 't' years (t = 1 ... T);
p_{yt}	is the probability of success of research undertaken in country 'y' in year 't' ($0 \le p_{yt} \le 1$);
x_{ft}	is the expected ceiling level for adoption in country 'f'' in year 't' ($0 \le x_{ft} \le 1$);
k_{fy}	is the cost-reducing effect in country 'f' (f = 1… N) from research undertaken in country 'y'. In the country where the research has taken place, 'k_{yy}' is the direct effect of research; in the remaining N-1 countries producing and/or consuming the commodity, k_{fy} is the spillover effect of research. In many countries this value is likely to be zero;
e_{ft}	is the exchange rate in year 't' between the currency of country 'j' and the currency used as a standard measure of value;
r	is the social rate of discount in real terms;
Q_{sft}	is the quantity of the commodity produced in country 'f' in time period 't' without research, i.e., the initial equilibrium output;
b_f and b_i	are the slope parameters (dQ/dP) of the demand function in the i^{th} or f^{th} country/region. Note that $b_i = e_{di}\,[Q_{dit}/P_{it}]$, where e_{di} is the elasticity of demand for the commodity in country 'i' evaluated at the original equilibrium prices and quantities, Q_{dit} and P_{dit}. Note that because negative signs are included in the demand specification, the absolute values for these parameters are entered in the formulae;

β_f and β_i	are the slope parameters (dQ/dP) of the supply function in the i^{th} or f^{th} country/region. Also note that $\beta_i = e_{si}\,[Q_{sit}/P_{it}]$, where e_{si} is the elasticity of supply;
N	is the total number of 'homogeneous' countries/regions;
n	is the number of countries/regions where the commodity of concern is produced or consumed and internationally traded; and
N-n	is the number of countries/regions where the commodity is only traded domestically.

The benefits for country/region 'f'' from research undertaken in country 'y' with an international trading environment (f = 1... n) were computed on the basis of equation 2:

$$E[PV(G_{yf})] = \sum_{t=1}^{T}\sum_{f=1}^{n}\frac{p_{yt}\,x_{ft}\,k_{fy}}{e_{ft}(1+r)^t}\,Q_{sft}$$

$$+$$

$$\sum_{t=1}^{T}\frac{p_{yt}(Q_{dft}-Q_{sft})\sum_{i=1}^{n}\beta_i\,x_{it}\,k_{iy}}{(1+r)^t\,\sum_{i=1}^{n}e_{it}(\beta_i+b_i)}$$

$$+$$

$$\sum_{t=1}^{T}\frac{p_{yt}\,b_f\,e_{ft}\,(\sum_{i=1}^{n}\beta_i\,x_{it}\,k_{iy})^2}{2(1+r)^t[\sum_{i=1}^{n}e_{it}(\beta_i+b_i)]^2}$$

$$+$$

$$\sum_{t=1}^{T}\frac{p_{yt}\,\beta_f\,e_{ft}}{2(1+r)^t}\left[\frac{x_{ft}\,k_{fy}}{e_{ft}}-\frac{\sum_{i=1}^{n}\beta_i\,x_{it}\,k_{iy}}{\sum_{i=1}^{n}e_{it}(\beta_i+b_i)}\right]^2 \qquad (2)$$

To calculate consumer benefits in country/region 'f' from research undertaken in country 'y' with an international trading environment (f = 1... n), equation 3 was used:

$$E[PV(G_{cfy})] = \sum_{t=1}^{T}\frac{p_{yt}\,Q_{dft}\sum_{i=1}^{n}\beta_i\,x_{it}\,k_{iy}}{(1+r)^t\,\sum_{i=1}^{n}e_{it}(\beta_i+b_i)}$$

$$+$$

$$\sum_{t=1}^{T}\frac{p_{yt}\,b_f\,e_{ft}(\sum_{i=1}^{n}\beta_i\,x_{it}\,k_{iy})^2}{2(1+r)^t\,[\sum_{i=1}^{n}e_{it}(\beta_i+b_i)]^2} \qquad (3)$$

Benefits to producers in country/region 'f' from research undertaken in country 'y' with an international trading environment (f = 1... n) were estimated on the basis of equation 4:

$$E[PV(G_{gfy})] = \sum_{t=1}^{T}\frac{p_{yt}\,Q_{sft}}{(1+r)^t}\left[\frac{x_{ft}\,k_{fy}}{e_{ft}}-\frac{\sum_{i=1}^{n}\beta_i\,x_{it}\,k_{iy}}{\sum_{i=1}^{n}e_{it}(\beta_i+b_i)}\right]$$

$$+$$

$$\sum_{t=1}^{T} \frac{p_{yt} \beta_f e_{ft}}{2(1+r)^t} \left[\frac{x_{ft} k_{fy}}{e_{ft}} - \frac{\sum_{i=1}^{n} \beta_i x_{it} k_{iy}}{\sum_{i=1}^{n} e_{it}(\beta_i + b_i)} \right]^2 \quad (4)$$

National benefits to country/region ‘f’ from research undertaken in country ‘y’ with no international trading environment (f = n+1... N) were estimated using equation 5:

$$E[PV(G_{yf})] = \sum_{t=1}^{T} \sum_{f=1}^{n} \frac{p_{yt} x_{ft} k_{fy}}{e_{ft}(1+r)^t} Q_{sft}$$

$$+$$

$$\sum_{t=1}^{T} \frac{p_{yt} \; b_f \; \beta_f \; x_{ft}^2 \; k_{iy}^2}{2(1+r)^t e_{ft}(\beta_i + b_i)} \quad (5)$$

To estimate consumer benefits in country/region ‘f’ from research undertaken in country ‘y’ with no international trading environment (f = n+1... N) equation 6 was used:

$$E[PV(G_{cyf})] = \sum_{t=1}^{T} \frac{p_{yt} \; \beta_f \; x_{ft} \; k_{fy}}{(1+r)^t \; e_{ft}(\beta_f + b_f)^2} Q_{dft}$$

$$+$$

$$\sum_{t=1}^{T} \frac{p_{yt} \, b_f \, \beta^2{}_f \, x_{ft}^2 \, k_{fy}^2}{2(1+r)^t \; e_{ft}(\beta_f + b_f)^2} \quad (6)$$

Producer benefits in country/region ‘f’ from research undertaken in country ‘y’ with no international trading environment (f = n+1... N) were estimated using equation 7:

$$E[PV(G_{gyf})] = \sum_{t=1}^{T} \frac{p_{yt} \; b_f \; x_{ft} \; k_{fy}}{(1+r)^t \; e_{ft}(\beta_f + b_f)} Q_{sft}$$

$$+$$

$$\sum_{t=1}^{T} \frac{p_{yt} \; \beta_f \; b_f^2 \; x_{ft}^2 \; k_{fy}^2}{2(1+r)^t \; e_{ft}(\beta_f + b_f)^2} \quad (7)$$

In the estimation of Davis et al. (1987), the direct effect of research was denoted by the ‘k_{yy}’ value or the cost-reducing effect of the research on the supply of a commodity in country ‘y’ where research takes place. The value ‘k_{fy}’ (f = 1… N-1) represents the cost-reducing effects that the research results have on the supply of the commodity in each of the other countries/regions. Subjective estimates of the spillover effects were applied in the empirical estimation.

The research benefit estimation formulae developed in Davis et al. (1987) estimate the final monetary value of the spillover unit cost reduction. In Edwards and Freebairn (1984) and the empirical application by Davis et al. (1987), a spillover index vector or matrix is used. If the analysis covers many regions, this approach reduces the data changing task in case different cost reduction analyses are required. Notationally, this extra component can be represented as

$$K = K^{*}S \qquad (8)$$

where

K is a matrix of monetary direct and indirect spillover unit cost reductions. K is an $n \times n$ matrix where n is the number of geographical regions in the analysis. K_{ij} is then the unit cost reduction in region 'j' resulting from research undertaken in region 'i';

K* is a diagonal matrix of base-rate cost reductions for each region. K^{*}_{ii} is the expected rate cost reduction in region 'i' where the research is undertaken. $K^{*}_{ij} = 0$; and

S is a matrix of research spillover indices or weights. In most cases it is expected that $0 < s_{ij} < 1$, although this is not a necessary condition.

As indicated earlier, Edwards and Freebairn (1984) used values for s_{ij} that were arbitrarily chosen. Davis et al. (1987) used subjectively determined values for s_{ij}, although these were based on detailed information regarding the production environments and their distribution for each commodity. Given the large number of regions (countries) involved and the diversity of production environments within some of these, this subjective weighting process often involved taxing mental calculations (Davis 1991). The need for a less subjective weighting process became apparent as the application of the analysis progressed.

One important point that is noticeable in all of these studies is that they have implicit assumptions regarding the production environment focus of the research. These studies used the Food and Agriculture Organization (FAO)-determined agroecological zones (AEZs) to represent the production environment. FAO has divided the world into 15 AEZs (Appendix A). The FAO-AEZ methodology is based on land suitability assessment characterized by temperature, moisture conditions, and length of the growing period. Therefore, the production environment defined in these studies represents the potential suitability of a crop rather than actual land utilization for any given crop. However, for research spillover estimation, the actual area devoted to the crop in each agroecological zone in each country is required. The FAO/AEZ studies tried to provide some guidelines on this matter but obtaining satisfactory data on the distribution of crops and livestock on the basis of AEZs remains a problem. This limitation was recognized by the studies considered in this paper. Therefore, a reassessment of geographical spillover is required (Davis 1991). To overcome the problem, Davis (1991) successfully modified the model of Davis et al. (1987) by transforming geographical/political boundary-based available data to homogenous agroecological units. The revised procedure for estimating regional spillover developed by Davis (1991) related spillover modeling to production environment factors. Expansion of the subjective estimation procedure required the following:

(i) Choosing an appropriate production environment classification system from the existing agroclimatic classification systems depending on the commodity to be studied. The important considerations include:
   - applicability of possible technologies (too much detail is likely to be redundant, too little likely to result in aggregation errors);
   - substitutability to preferences of decisionmakers who are likely to use the information (if they currently relate and decide on the basis of a simple system, then use of a complex system may provide information in a wrong form); and
   - information and computational requirements may limit the level of disaggregation.

(ii) Estimation of 'production environment to production environment' spillover. Notationally this matrix has been termed the 'C' matrix, an $m \times m$ matrix where 'm' is the number of production environments. It is a matrix of the spillover indices briefly outlined earlier. The elements of this matrix, $c_{tw,}$ can be interpreted with the help of Figure 6. Instead of viewing each supply/demand diagram as a country, it was viewed as a homogenous production environment. The c_{tw} values were found by using the ratios of the k_{ij}s. For example, for the production environment, say 'a', for which the technology was developed,

$$c_{aa} = k_{aa}/k_{aa} = 1 \quad (9)$$

On the other hand, in production environment 'b', for research undertaken in 'a',

$$c_{ab} = k_{ab}/k_{aa} \quad (10)$$

The interpretation of k_{ab} is important. It is the unit cost reduction in production environment 'b' if the technology developed specifically for 'a' was used in 'b'. For k_{ab} to be positive, the technology must be superior to the best already available for production environment 'b'. Note that this could be a different technology than the preresearch technology in 'a'. In most cases it was expected that $c_{ab} < 1$, i.e, the cost reduction is less in a production environment for which the technology was not specifically designed. However, Davis (1991) did not inject this as a restriction to the model.

This notion of a 'production environment to production environment' spillover introduces many issues. According to Davis (1991), these are:

- The 'C' matrix is unlikely to be unique. For example, the elements might change depending on the type of research, say plant breeding versus plant protection or soil management. It may even be required to have a weighted average of individual estimates depending on the decision-making environment to be supported;
- Research may be undertaken with a view to maximizing the cost reduction for a specific production environment or perhaps be interpreted as aiming at increasing the size of the 'C' matrix elements. The latter could be viewed as reducing the production environment sensitivity of a crop; and
- Estimation of these parameters could be through elicitation from technical experts or procedures developed to make use of research trial results.

(iii) Estimating the 'region to region' spillover. Aggregation of the 'C' matrix to give the 'S' matrix or 'region to region' spillover requires two additional sets of information. These include:

- The production environment production shares for each commodity. This is given the notation of an 'F' matrix which is an $m \times n$ matrix (where 'm' is the number of production environments and 'n' the number of regions). For each region this is the proportion of production in each production environment.
- The production environment focus of the research. The notation for this information is an 'R' matrix which is an $n \times m$ matrix. It specifies the share of research focused on each production environment in a region. If a region (country) has production in eight environments, research decisionmakers will need to determine whether the research will focus on all production environments or a subset; and whether varying levels of emphasis should be given to the production environments. To assist aggregate-level decision-making applications, the assumption that the research effort is focused in proportion to the production in each production environment has been maintained. In matrix notation,

assume that R = F. Clearly, a range of alternatives is possible so that the model can generate a rich set of information regarding possible decisions and their potential impact on research applicability (spillover).

With the above sets of information, the aggregated 'region to region' spillover is obtained by using:

$$S = R\ C\ F \qquad (11)$$

This set of information has been used in the multiregional research evaluation model to estimate possible research benefits associated with different options.

Davis (1994), Pardey and Wood (1994), and Evenson (1994) discuss the need for improving the subjective estimates of spillover matrices employed by previous studies and suggest methods for quantitative assessment. Evenson (1994) provides empirical procedures for estimating spillover coefficients from research trial data. There is a vast amount of yield trial data that can be used to assess the potential transferability of varietal technology. However, with the exception of Englander (1991) and Evenson (1994), such data have not been exploited to estimate spillover matrices.

Englander (1991) used an econometric approach to measure the 'technology transfer frontier' of wheat varieties. Basically, this is an estimate of the potential spillover of wheat varieties across countries. His model was of the following form:

$$Y_{ij} = f\,(E_j, T_i, G_{ij}) + \text{error term}$$

Where

Y_{ij} is the yield of wheat variety 'i' in location 'j';

E_j is a vector ($E_{j1}, E_{j2},\ldots, E_{jm}$) characterizing the environment at location 'j';

T_i is a vector ($T_{i1}, T_{i2},\ldots, T_{in}$) characterizing the technology embodied in variety 'i'; and

G_{ij} is a vector ($G_{ij1}, G_{ij2},\ldots, G_{ijq}$) characterizing the interactions between the technology and the environment.

For empirical estimation of the model, he used the yield trial data of Centro de Mejoramiento de maïz y del Trigo (CIMMYT). In his empirical model, per hectare yield is the dependent variable. Independent variables were related to climate, treatments, and varietal-technological characteristics. The climate-related variables were: dummy for countries where the varieties were sown, dummy for climate of the location, absolute value of the latitude where the variety was sown, and elevation of the location in meters above the sea level. The treatment-related variables were: dummy for use of nitrogen fertilizer, dummy for phosphorus fertilizer use, and dummy for potash fertilizer use. To represent varietal-technological characteristics he included: dummy to indicate whether the variety was sown in the country in which it was developed or not; dummy variable to indicate the initial trial in which a variety was entered; a set of dummy variables to indicate whether a variety was traditional, a local cross using a CIMMYT variety, a local reselection of a CIMMYT variety, or a CIMMYT variety; a set of dummy variables to indicate the country where the variety was developed; dummy variable to indicate the variety was bred by CIMMYT; and a set of dummy variables to indicate each of the Mexican-bred CIMMYT varieties.

Evenson (1994) provided empirical procedures for estimating spillover coefficients from research trial data. He specified the actual research spillin (R_i^{sp}) from another region as:

$$R_i^{sp} = \Sigma_j\, A^{\alpha}_{ij}\, R_j\, PR_{ij}$$

Where

A_{ij} is the 'advantage index' and is defined as ($A_{ij} = Y_{ij}/Y_{jj}$) the ratio of the yield of a variety (developed primarily for environment 'j') in environments 'i' and 'j'. A_{ij} can be interpreted as the biological potential for spillover of a variety generated for environment 'j' to environment 'i';

α is a modifying coefficient and Ri and Rj are research-stock variables defined as the cumulated sum of past research expenditures in each region. The cumulation was done through time weight; and

PR_{ij} is the expenditure of the program designed to facilitate and enhance transfer from region 'j' to region 'i'.

Maredia et al. (1996) also used an econometric approach to estimate the coefficients of global spillover matrices for wheat improvement research based on yield trial data. They demonstrated the value of national and international yield trial data in estimating the spillover effects of an international wheat improvement research system. They were able to address the extent of environmental specificity of wheat varietal technology, i.e., the degree of yield advantage of varieties (developed for a particular environment) in other environments, and the implications of the findings for the design of national and international wheat research systems.

Maredia et al. (1996) assumed that the performance of a variety was a function of environmental variables (location dummy, year dummy) and technology variables (vintage and origin of the variety). Technology variables were included to represent characteristics of varietal technology. They used the following regression model to estimate the spillover matrix:

$$Y^j_{hgt} = a + b_h DLOC_h + c_t DYEAR_t + v\, VINT + w_i DORIG_i + r\, MR + \in_{hgt} \text{ for } j = 1,2,\ldots,n \quad (12)$$

where

j is the test megaenvironment in which the yield data point is observed;

Y^j_{hgt} is the observed yield (kg ha^{-1}) of the g^{th} entry at the h^{th} trial location in environment 'j' and t^{th} trial year;

$DLOC_h$ is a vector of dummy variables equal to 1 if data point belongs to location 'h', 0 otherwise;

$DYEAR_t$ is a vector of dummy variables equal to 1 if data point belongs to year 't', 0 otherwise;

VINT is a variable to reflect the vintage of a variety approximated by the trial year in which the g^{th} variety first appeared;

$DORIG_i$ is a vector of dummy variables equal to 1 if the g^{th} variety belongs to the origin group 'i', 0 otherwise;

MR is the inverse Mill's ratio; and

$\in$ is the error term.

To estimate the model they used international wheat yield trial data (panel data). To factor out the site and time effects (such as different levels of management) on the observed trial, they included location and year dummies (DLOC and DYEAR). To correct probable selection bias related to the correlation between varietal attrition and experimental response (i.e., yield) of nonrandomly missing varieties in the trials conducted over a number of years, they included the variable MR (inverse Mill's ratio). The model was estimated separately for each megaenvironment and, therefore, the coefficients for DORIG represented the performance of varieties of different environmental origins in a given megaenvironment relative to the 'home varieties'[2]. The varietal groups originating from the test megaenvironment were considered as the benchmark variable (i.e., dummy variable $DORIG_j$ was

2. Home varieties are the best performing varieties presently cultivated in the area. In other words, the controls used in the yield trials.

dropped from the equation for each megaenvironment). Therefore, the coefficients of $DORIG_i$ are the differential yields defined as ($w^j_i = Y_{ij} - Y_{jj}$). These coefficients were used to estimate Y_{ij}/Y_{jj} to give the elements of the spillover matrix, C_{ij}, based on the constant Y_{jj} (approximated by the arithmetic mean) for each megaenvironment.

Measurement Techniques for Across-commodity Spillover

Across-commodity spillover was systematically studied first by Bantilan and Davis (1991) although an analysis of welfare change due to research in a multiproduct environment was done earlier by Alston (1990). Bantilan and Davis (1991) showed that across-commodity spillover effects of technical change find their way into a firm's cost structure via changes in product substitution among the firm's outputs. While technical change specific to the production of one commodity, say y_1, reduces the marginal cost of producing that commodity, further welfare gains are actually achieved by the firm if such technology has some applicability such that production efficiency of other products also improves.

Let the transformation function (eq. 13) reflect the limits of the technical possibilities in a multioutput, multiinput farm:

$$Q\,(y_1,\ y_2,\ldots,\ y_m) = I(x_1, x_2, \ldots, x_n) \qquad (13)$$

where y_1, y_2,...., y_m represent the amounts produced of each of the m outputs, and x_1, x_2, ..., x_n the amounts used of each of the n inputs. The boundary relationship given by equation 13 expresses the constraints that limit the firm's transformation of a set of inputs into a set of final products. It indicates the substitutability of one input for another (while total output is held constant) as well as the substitutability of one output for another (while holding the total usage of inputs fixed).

The transformation function (eq. 13) constrains the firm's ability to choose combinations of inputs and outputs, and the optimal production decisions of a producer may be determined with the assumption of profit maximization. Thus, the derivation of optimal input demand and output supply levels may logically start from a consideration of a short-run profit function given by

$$\Pi = \sum_{i=1}^{m} p_i\, y_i - \sum_{j=1}^{n} w_j\, x_j - FC \qquad (14)$$

where
p_i = price of output 'i',
w_j = price of input 'j'; and
FC = fixed cost.

In other words, in the context of producing farms, optimal input and output levels implied by the technical transformation function and the necessary conditions are equivalently obtained by the optimization of its dual profit function.

A solution to the constrained maximization problem was derived through the use of the Lagrangean function. The necessary conditions for maximization, as they derived, are:

$$\frac{\frac{\partial Q}{\partial y_1}}{p_1} = \ldots = \frac{\frac{\partial Q}{\partial y_m}}{p_m} = \frac{\frac{\partial I}{\partial x_1}}{w_1} = \ldots = \frac{\frac{\partial I}{\partial x_n}}{w_n} = \frac{1}{\lambda} \qquad (15)$$

In principle, the m + n equations implied by equation 15 plus the constraints represented by equation 13 are the basis for the optimal values of the m outputs, n inputs, and the shadow price, which maximize the firm's profits. The cost structure of the firm can be translated in terms of the transformation function defined in equation 13. To do this, take the total differential of the transformation function to obtain

$$\sum_{i=1}^{m} \frac{\partial Q}{\partial y_i} dy_i = \sum_{j=1}^{n} \frac{\partial I}{\partial x_j} dx_j \quad (16)$$

From equation 16, $\partial Q / \partial y_i dy_i$ is obtained, i.e.,

$$\frac{\partial Q}{\partial y_i} dy_i = \sum_{j=1}^{n} \frac{\partial I}{\partial x_j} dx_j - \sum_{k=1,k\neq i}^{m} \frac{\partial Q}{\partial y_k} dy_k$$

so that

$$dy_i = \frac{1}{\frac{\partial Q}{\partial y_i}} [\sum_{j=1}^{n} \frac{\partial I}{\partial x_j} dx_j - \sum_{k=1,k\neq i}^{m} \frac{\partial Q}{\partial y_k} dy_k] \quad (17)$$

Substituting equation 15 into equation 17 gives

$$dy_i = \frac{1}{\frac{\partial Q}{\partial y_i}} [\sum_{j=1}^{n} \frac{w_j}{\lambda} dx_j - \sum_{k\neq i}^{m} \frac{\partial Q}{\partial y_k} dy_k] \quad (18)$$

Taking the total cost function expressed by

$$TC = \sum_{j=1}^{n} w_j x_j + FC$$

the total differential of TC is obtained, i.e.,

$$dTC = \sum_{j=1}^{n} w_j dx_j \quad (19)$$

By dividing equation 19 by equation 18,

$$\frac{dTC}{dy_i} = \frac{\sum_{j=1}^{n} w_j dx_j}{\sum_{j=1}^{n} \frac{w_j}{\lambda} dx_j - \sum_{k\neq i}^{m} \frac{\partial Q}{\partial y_k} dy_k} \frac{\partial Q}{\partial y_i}$$

$$= \lambda \frac{\partial Q}{\partial y_i} \frac{1}{1 - \frac{\frac{\sum_{k=1,k\neq i}^{m} \partial Q}{\partial y_k} dy_k}{\sum_{j=1}^{n} \frac{w_j}{\lambda} dx_j}} \quad (20)$$

$$= \lambda \frac{\partial Q}{\partial y_i} \delta \qquad (21)$$

where

λ	=	shadow price of the resources implied by the Lagrangian function;
$\partial Q/ \partial y_i$	=	marginal input required for an incremental change in output 'i'; and
δ >1	=	opportunity cost multiplier.

The interpretation of $\partial Q/ \partial y_i$ comes from solving the transformation function, i.e.,

$$\frac{\partial Q}{\partial y_i} = \frac{\partial I(x_1, x_2, .., x_n)}{\partial y_i}$$

$$= \sum_{i=1}^{n} \frac{\partial I}{\partial x_j} \frac{\partial x_j}{\partial y_i}$$

In other words, $\partial Q/\partial y_i$ is the sum of the marginal changes in inputs required to produce an increment of output y_i. In short, $\partial Q/\partial y_i$ is a composite measure of the marginal input required for output i.

From equations 15 and 20,

$$\delta = \frac{1}{1 - \dfrac{\sum_{k=1,k\neq i}^{m} \dfrac{\partial Q}{\partial y_k} dy_k}{\sum_{j=1}^{n} \dfrac{\partial I}{\partial x_j} dx_j}}$$

and using equation 16, we have

$$\beta = \frac{\sum_{k=1,k\neq i}^{m} \dfrac{\partial Q}{\partial y_k} dy_k}{\sum_{j=1}^{n} \dfrac{\partial I}{\partial x_j} dx_j} < 1.$$

Based on the derivation above, dTC/dy_i or the marginal cost resulting from an increase in one output 'y_i' is equal to the marginal input required for output 'i', i.e., ($\partial Q/\partial y_i$), valued by the shadow price 'l', and adjusted by an index of opportunity cost 'd', whose value is nonnegative and has a magnitude which depends on

$$\beta = \frac{\sum_{k=1,k\neq i}^{m} \dfrac{\partial Q}{\partial y_k} dy_k}{\sum_{j=1}^{n} \dfrac{\partial I}{\partial x_j} dx_j}.$$

Note that in a one-output production environment, dTC/dy_i is equivalent to $\partial Q/\partial y$, i.e., $\delta = 1$. However, when a firm's production decision involves two or more products, then the opportunity costs incurred due to the possibility of producing other products out of the available set of inputs x_j, j = 1, ..., n, are relevant. In other words, the marginal input requirements of the other products in proportion to the total change in total cost cannot be ignored.

The above formulation of the marginal cost function allows a more general analysis of the output supply decisions in a multiple-product, multiple-input production environment. An additional perspective provided by this framework is that it makes explicit consideration of the opportunity cost incurred when decisions are made in favor of the production of one product versus another.

In the context of the framework presented earlier, Bantilan and Davis (1991) examined the implications of technological change for the firm's production decision and cost structure, and thereby, the across-commodity spillover effect of a new process or technique developed for one commodity.

In terms of equation 21, the marginal cost of the firm is measured by the value of the marginal input required for every incremental change in y_1. In a monoculture (one-product) environment, the opportunity cost multiplier, δ, is equal to 1.

The corresponding analysis for a multiple-output, multiple-input environment is illustrated by using a two-output, three-input production scenario, where the transformation function is represented by

$$Q(y_i, y_k) = I(x_1, x_2, x_3) \tag{22}$$

By equation 21, the production constraints given by equation 22 are incorporated in the following marginal cost function given by:

$$\frac{dTC_i}{dy_i} = \lambda \frac{\partial Q}{\partial y_i} \frac{1}{1 - \dfrac{\frac{\partial Q}{\partial y_k}\, dy_k}{\sum_{j=1}^{3} \frac{\partial I}{\partial x_j}\, dx_j}} \, .$$

It is noted that the marginal cost in this multiple-product scenario is significantly higher if the opportunity cost of producing the alternative output is substantial, i.e., $dTC/dy_i > l^* \partial Q/\partial y_i$. This relationship about the firm's marginal cost reflects the change in the total cost incurred by the firm when it decides to increase production of output by y_i by one unit. The change in total cost involves the marginal input (index) required to produce an incremental increase in output y_i valued at the shadow price, 'l', with adjustments made to account for the opportunity cost involved when one product is produced in favor of another. This result has important implications. The first is that as a result of technological change, the marginal cost declines due to the improvement in the efficiency of input use as $\partial Q/\partial y_i$, which measures the marginal input required for an incremental increase in output 'i', goes down. Second, if the new process designed for one product, say output 'y_i', produces a spillover effect on other products, i.e., the technology is also applicable to another product, say output 'k', then $\partial Q/\partial y_k$ declines due to the enhancement in the efficiency of input use brought about by the new process. This circumstance allows a decline in the opportunity cost 'd'. Thus, the marginal cost incurred by a multioutput producer is effectively less in a positive 'across-commodity spillover' regime compared to the case where the technology is exclusively applicable only to one product. Third, in a neutral technological change environment, the relative marginal productivities of the inputs do not change, i.e., the marginal rate of technical substitution of one input for another along a fixed-input proportion remain unchanged so that the relative shares are not affected. However, in the case of biased technical change, the marginal product of one or more inputs is increased relative to the marginal product of others. This means that the producer will have incentive to use more of some inputs relative to others. This is tantamount to saying that the relative share of some inputs accordingly increases while others decline.

The change in the relative input prices effectively changes the firm's cost structure. If the relative share of the inputs for which prices increase is large, then the marginal cost may shift substantially upwards. Effectively, the cost structure under a neutral technology change regime deviates from the cost structure under a biased technologically changed environment because of the possible 'input price spillover' that may occur.

In summary, a reexamination of the linkage between the firm's production response function and the corresponding cost structure within the context of a multiproduct production environment indicates that the usual marginal cost formulation is deficient: it underestimates the marginal cost. It is clear that this deficiency arises from the fact that the usual analysis ignores the opportunity cost of producing alternative products using the same input. This is equivalent to setting the opportunity cost index equal to 1, when in fact, it is necessarily greater than 1 in a multiproduct environment. The framework developed by Bantilan and Davis (1991) is a more general formulation that accommodates positive externalities like across-commodity spillover effects.

Summary and Conclusion

Three types of research spillovers—across-environment, across-commodity, and price—have been dealt with in empirical literature. Studies have quantified spillover impacts using economic surplus models, subjectively and objectively. Subjective estimates quantified the spillover coefficient matrix based on expert elicitation while objective estimates were based on data derived through multilocational trials. The quantification of spillover benefits from germplasm research conducted at ICRISAT would be very useful for research evaluation and policy planning.

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Appendix A

List of FAO agroclimatic zones.

Climatic zone	Abbre-viation	Growing season: Description	Growing season: Name	Abbre-viation
Warm Tropics	WT	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Moderately Cool Tropics (Tropical highlands)	CLT1	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Cool Tropics (Tropical highlands)	CLT2	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Cold Tropics	CDT	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A

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Climatic zone	Abbre-viation	Growing season Description	Name	Abbre-viation
Warm Moderately Cool Subtropics (Summer rainfall)	WST1	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Warm Subtropics (Summer rainfall)	WST2	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Warm Subtropics (Summer rainfall)	WST3	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Moderately Cool Subtropics (Summer rainfall)	CLST1	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A

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Climatic zone	Abbre-viation	Growing season Description	Name	Abbre-viation
Cool Subtropics	CLST2	365 days	Perennially wet	PW
(Summer rainfall)		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Cool Subtropics	CDST	365 days	Perennially wet	PW
(Summer rainfall)		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Cool Subtropics	STW	365 days	Perennially wet	PW
(Winter rainfall)		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Cool Subtropics	STCW	365 days	Perennially wet	PW
(Winter rainfall)		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A

Continued.....

Climatic zone	Abbre-viation	Growing season Description	Name	Abbre-viation
Cool Temperate (Winter rainfall)	CCT1	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Cool Temperate (Winter rainfall)	CCT2	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A
Transitional	TN	365 days	Perennially wet	PW
		364-330 days	Wet	W
		329-270 days	Humid	H
		269-210 days	Seasonally dry	SD
		209-150 days	Semi-arid	SA1
		149-90 days	Semi-arid	SA2
		89-0 days	Arid-irrigated	A