Induced technical and institutional change in tropical agriculture

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Abstract: The author employs a model in which the direction of technical change is induced by changes in relative resource endowments to interpret the trajectories of technical change in both developed and developing country agriculture. An international agricultural research system, an institutional innovation supported by the Consultative Group on International Agricultural Research (CGIAR), has become an important source of advances in yield enhancing biological technology. National agricultural research systems in a number of developing countries have been strengthened. Concern is expressed about the failure of national governments and international donors to sustain investment in agricultural research capacity.

Keywords: agricultural research; institutional change; resource endowments; technical change.

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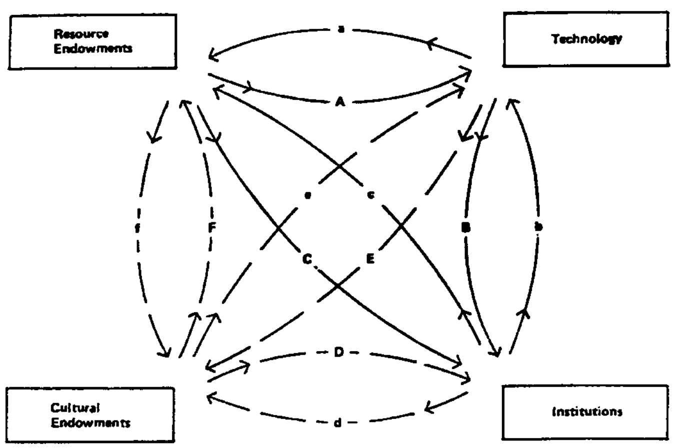
1 Introduction

Beginning in the early 1970s. Hayami and Ruttan and Binswanger and Ruttan formulated a model of agricultural development in which technical change was treated as endogenous – as induced by differences and changes in relative resource endowments. This model was later adapted and extended to interpret the process of institutional change.

In our more recent work, we have treated the process of induced technical change as embodied in a model that maps the relationships among resource endowments, cultural endowments, technology and institutions (Figure 1). Change in any one element in the system will induce lagged responses by other elements in the model. For example, technical change in agricultural production induced by changes in relative resource endowments may in turn induce change in land tenure and labour relations (Ruttan and Hayami, 1984).

Figure 1 Interrelationships between changes in resource endowments, cultural endowments, technology and institutions



Source: Fusfeld, 1980

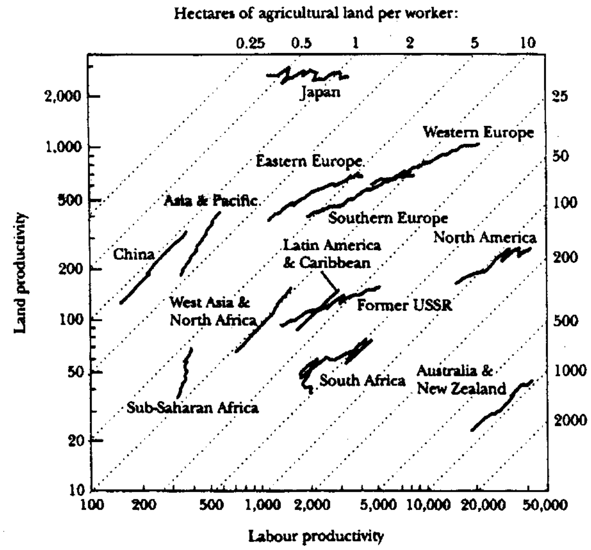
In this paper, I present several examples of the process and impact of induced technical and institutional change in tropical agriculture. In a final section, I trace the implications for the development of agricultural research systems in the tropics.

2 Induced technical change

There is now a substantial body of agriculture research documenting the process of induced technical change in both tropical- and temperate-region agriculture (Thirtle and Ruttan, 1987).

Alternative technological trajectories have been developed to facilitate the substitution of relatively abundant (hence cheap) factors for relatively scarce (hence expensive) factors (Figure 2). Two kinds of technology generally correspond to this taxonomy: mechanical technology to 'labour saving' and biological (and chemical) technology to 'land saving'. The former is designed to substitute power and machinery for labour. The latter is designed to substitute intensive production practices or industrial inputs for land. This substitution may be accomplished through increased recycling of animal (including human) and green manures; through use of chemical fertilizers; and through husbandry practices and management systems.

Figure 2 International comparison of agricultural land and labour productivities by region, 1961 to 1990



Notes: AgGDP in normal local currency units was first deflated to base year 1980 using country–specific AgGDP deflators and then converted to US dollars using agricultural output PPPs. The number of countries on which the regional (weighted averages area based is as follows: sub-Saharan Africa (17), Asia & Pacific (11), Latin America & Caribbean (18), West Asia & North Africa (9), Europe (13), and North America (2)
[a]Hectares of agricultural land per economically active member of the agricultural population
[b]Hectares of agricultural land includes arable plus permanently cropped and permanently pastured land
[c]Agricultural workers is here defined as economically active agricultural production

Source: Craig et al., 1997

The distinction between mechanical and biological technology may be somewhat overdrawn. All mechanical innovations are not necessarily motivated by incentives to save labour, nor are all biological innovations necessarily motivated by incentives to save land. In Japan, horse ploughing was initially to raise yields by deep cultivation. In the USA tomatoes have been developed which have a sturdier skin and ripen at the same time to facilitate mechanical harvesting.

2.1 *Mechanical processes*

The mechanisation of farming has been intimately associated with the industrial revolution. Although progress in agricultural and industrial mechanisation represents a response to the same set of fundamental economic forces, the mechanisation of agriculture cannot be treated as simply the adaptation of industrial methods of production to agriculture. The spatial dimension of crop production requires that the machines suitable for agricultural mechanisation must be mobile – they must move across or through materials that are immobile (Brewster, 1950: pp.69–81; Johnson and Ruttan, 1994).

The seasonal characteristic of agricultural production requires a series of specialised machines – for land preparation, planting, pest and pathogen control, and harvesting – specifically designed for sequential operations, each of which is carried out only for a few days or weeks in each season. This also means that it is no more feasible for workers to specialise in one operation in mechanised agriculture than in pre-mechanised agriculture. A major economic force leading to the greater use of mechanical equipment in both crop and animal production has been the growth in demand for labour in the urban–industrial sector.[3]

2.2 Biological and chemical processes

In agriculture, biological and chemical technology and processes are more fundamental than machine processes. Until the 1960s 'green revolution' – the development and diffusion of modern high yielding varieties of wheat, maize and rice – a typical treatise on economic development passed over innovation in biological technology with a quick reference to the need for better seeds and improved methods of cultivation.

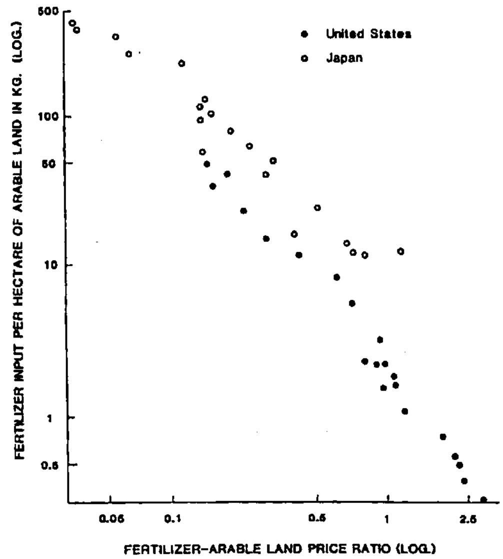
In crop production, advances in biological and chemical technology have typically involved one or more of the following three elements:

- land and water resource development to provide a more satisfactory environment for plant growth
- modification of the environment by the addition of organic and inorganic sources of plant nutrition to the soil to stimulate plant growth and the use of biological and chemical means to protect plants from pests and disease
- selection and breeding of new biologically efficient crop varieties specifically adapted to respond to those elements in the environment that are subject to human control. Similar processes are characteristic of advances in livestock agriculture.

Taiwan represents a particularly illuminating case of biological technology transforming agriculture (Hayami and Ruttan, 1971, pp.198–212). The Japanese administration found it necessary to invest in agricultural research since Japanese rice varieties could not be successfully transferred to Taiwan. The rice varieties developed by Japanese rice breeders in Taiwan first became available in the mid 1920s. By 1940 these Ponlai varieties were planted on half of the total area devoted to rice. The new varieties, combined with the development of the irrigation system, created an opportunity for growth in the use of commercial fertiliser in order to realise the higher yield potential.

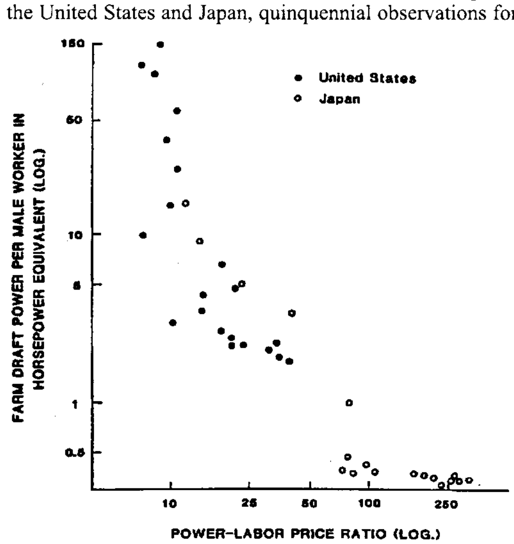
The 'green revolution' has, since its initial development and adoption in South and Southeast Asia in the late 1960s, been the subject of substantial controversy. It has been described, mistakenly, as a Western technology inappropriately introduced into South and Southeast Asia. The initial criticisms suggested that the new technology would have the effect of widening inequities in income distribution and social polarisation in rural communities. Careful studies conducted in the late 1970s and early 1980s indicated that these concerns have been overblown (David and Otsuka, 1988, pp.441–450; Hayami and Ruttan, 1985, pp.336–345).[4] More recent criticisms have focused on the environmental effects of the intensification of agricultural production (Conway, 1997; Conway and Pretty, 1991; Pingali et al., 1997, pp.91–125). Even the most severe critics concede that the green revolution technology has substantially enhanced the rate of growth in agricultural production.[5]

Figure 3 Relation between fertiliser input per hectare of arable land and fertiliser-arable land price ratio (=hectares of arable land which can be purchased by on ton of $N+P_2O_5+K_2O$ contained in commercial fertilisers), the USA and Japan: quinquennial observations for 1880–1980



Source: Hayami and Ruttan, 1985

Figure 4 Relations between farm draft power per male worker and power-labor price ratio (=hectares of work days which can be purchased by one horsepower of tractor or draft animal), the United States and Japan, quinquennial observations for 1880-1980



Source: Hayami and Ruttan, 1985

2.3 Technological trajectories

The theory of induced technical change suggests that countries with different resource endowment will follow different paths or trajectories in technological development (Figures 3 and 4). The data presented in these two figures can be interpreted as representing a dynamic factor-substitution process. Changes of the magnitudes represented in Figures 3 and 4 could only occur as a result of technical change. They are too large to have occurred as a result of simple factor substitution. They were induced, to a significant extent, by the long-term trends in relative factor prices.[6]

Data on land and labour productivity across and over time for a broad group of countries and major geographic regions are also broadly consistent with the induced technical change model (Figure 1). The exceedingly wide differences in output per hectare for any given level of output per worker and the exceedingly wide differences in output per worker for any given level of output per hectare is rather encouraging in terms of the potential for agricultural development in countries such as those in Africa with low land and/or labour productivity. Growth accounting exercises, using cross-country production functions, suggest that in the poorest less developed countries (LDCs), output per worker could be increased by several multiples with adequate investments in research, education and technical inputs, even if the land area per worker continues to decline because of growing population pressure in rural areas.

3 Induced institutional change

It has not been possible to test the induced institutional change hypothesis with the same rigour as the induced technical change hypothesis. It has, however, been possible to draw on a substantial number of case studies that lend plausibility to the hypothesis.

3.1 A Philippine case study

Research conducted by Yujiro Hayami and Masao Kikuchi (2000) in a Philippine village, beginning in the late 1970s, has enabled us to examine in some detail a contemporary example of the interrelated effects of changes in resource endowments and technical change on the demand for institutional change in land tenure and labour relations.

3.1.1 Changes in technology and resource endowments

Between 1956 and 1976, rice production per hectare in the study village rose dramatically, from 2.5 to 6.7 metric tons per hectare per year. This increase resulted from two technical innovations. In 1958, the national irrigation system was extended to the village. The second major technical change was the introduction, in the late 1960s, of high yielding rice varieties. The diffusion of modern varieties was accompanied by increased use of fertiliser and pesticides and by the adoption of improved cultivation practices,such as straight-row planting and intensive weeding.

Between 1966 and 1976 the number of households rose from 66 to 109 and the population rose from 383 to 464. The number of landless labourer households increased from 20 to 54. In 1976, half of the households in the village had no land to cultivate. The average farm size declined from 2.3 to 2.0 hectares. In both 1956 and 1966, 70% of the land was farmed under share tenure arrangements. In 1963, an agricultural land reform code was passed to provide greater incentives to peasant producers of basic food crops. A major feature of the new legislation was an arrangement that permitted tenants to initiate a shift from share tenure to leasehold, with rent under the leasehold set at 25% of the average yield for the previous 3 years. Implementation of the code between the mid-1960s and the mid-1970s resulted in a decline in land farmed under share tenure to 30%.

3.1.2 Induced institutional innovation

The shift from share tenure to lease tenure induced a second change in tenure relationships. Between 1966 and 1976 there was a sharp increase in the number of plots under sub-tenancy arrangements. The sub-tenancy arrangements were usually made without formal consent of the landowner. The most common sub-tenancy arrangement was 50–50 sharing of costs and output between subtenant and operator. Hayami and Kituchi (2000) hypothesised that the incentive for the emergence of the sub-tenancy institution was disequilibrium between the institutional rent paid to landlords under the leasehold arrangement and the economic rent.

To test this hypothesis, market prices were used to compute the value of the unpaid factor inputs (family labour and capital) for different tenure arrangements during the 1976 wet season. The results indicate that the share-to-land was lowest and the operators' surplus was highest for the land under leasehold tenancy. In contrast, the share-to-land was highest and no surplus was left for the operator who cultivated the land under the subtenancy arrangement (Table 1). A substantial portion of the economic rent was captured by the leasehold tenants in the form of operators' surplus. On the land farmed under a sub-tenancy arrangement, the economic rent was shared between the leaseholder and the landlord.

A second institutional change, induced by higher yields and the increase in population pressure, has been the emergence of a new pattern of labour relationship between farm operators and landless workers. According to the traditional system called *hunusan*, labourers who participated in the harvesting and threshing activity received one-sixth of the harvest. By 1976, most of the farmers (83%) adopted a system called *gamma*, in which participation in the harvesting operation was limited to workers who had performed the weeding operation without receiving wages. The emergence of the *gamma* system can be interpreted as an institutional innovation induced by the disequilibrium between the institutionally determined wage rate and the market rate.

To test the hypothesis that the *gamma* system permitted farm operators to equate the harvesters' share of output to the marginal productivity of labour, imputed wage costs were compared with the actual harvesters' shares (Table 2). The results indicate that a substantial gap existed between the imputed wage for the harvesters' labour and the actual harvesters' shares. This gap was eliminated if the imputed wages for harvesting and weeding labour were added. Those results are consistent with the hypothesis that the changes in institutional arrangements governing the use of production factors were induced when disequilibria between the marginal returns and the marginal costs of factor inputs occurred. Institutional change, therefore, was directed toward the establishment of a new equilibrium in factor markets.

Table 1 Factor shares of rice output per hectare, wet season 1976

Factor shares[a]	*Number of plots*	*Area (ha)*	*Rice output*	*Current inputs*	*Land: Landowner*	*Land: Sublessor*	*Land: Total*	*Labour*	*Capital*[b]	*Operator's surplus*
	kg/ha									
Leasehold land	44	67.7	2889 (100.0)	657 (22.7)	567 (19.6)	0 (0)	567 (19.6)	918 (31.8)	337 (11.7)	410 (14.2)
Share tenancy land	30	29.7	2749 (100.0)	697 (25.3)	698 (25.3)	0 (0)	698 (25.4)	850 (30.9)	288 (10.5)	216 (7.9)
Subtenancy land	16	9.1	3447 (100.0)	801 (23.2)	504 (14.6)	801[c] (23.2)	1305 (37.8)	1008 (29.3)	346 (10.1)	-13 (-0.4)

Notes: [a]Percentage shares are shown in parentheses
[b]Sum of irrigation fee and paid and/or imputed rentals of carabao, tractor, and other machines
[c]Rents to subleasors in the case of pledged plots are imputed by applying the interest rate of 40% crop season (a mode in the interest rate distribution in the village)

Source: Hayami and Kikuchi, 1983, pp.111–113

Table 2 Comparison between the imputed value of harvesters' share and the imputed cost of *gamma* labour

	Based on employers' data	*Based on employers' data*
Number of working days of *gamma* labour (days/ha)[a]		
Weeding	20.9	18.3
Harvesting/threshing	33.6	33.6
Imputed cost of *gamma* labour (P/ha)[b]		
Weeding	167.2	146.4
Harvesting/threshing	369.6	369.6
(1) Total	536.8	516.0
Actual share of harvesters:		
In kind (kg/ha)[c]	504.0	549.0
(2) Imputed value (P/ha)[d]	504.0	549.0
(2)-(1)	-32.8	33.0

Notes: [a]Includes labour of family members who worked as *gamma* labourers
[b]Imputation using market wage rates (daily wage=P8.0 for weeding, P11.0 for harvesting)
[c]One-sixth of output per hectare
[d]Imputation using market prices (I kg=P1)

Source: Hayami and Kikuchi, 1982, p.121

A second round of technical and institutional changes occurred in the 1990s. Non-farm employment opportunities have expanded as a result of better transport to the metropolitan Manila area and the location of a small metalcraft industry in the village; wage rates have risen and small portable threshing machines have largely replaced manual threshing. The labour share for harvesting has declined and a new form of labour contract, referred to as *new hunusan* has emerged.

Other examples of indigenous technical and institutional innovation in response to changes in resource endowments could be cited. One that is particularly relevant to Africa is the *groupments naam* movement among the Mossi in Northern Burkina Faso.[7] The effort was lead by a charismatic former extensionist who saw the possibility of building on the social capital of a traditional youth institution, the *kombi-naam* to create a development oriented youth movement, the *groupment naam*. The technical innovation involved the replacement of traditional soil and water retention methods by porous stone dikes that were more stable and more effective in soil and water retention. Beginning in the 1970s, such dikes have been built on hundreds of thousands of hectares in one of the poorest and environmentally degraded areas of Sub-Saharan Africa.

4 Toward a global agricultural research system

Substantial progress was made in the first several decades of the 20th century in initiating agricultural research capacity in Latin America and in the colonial economies of Asia and

Africa. These efforts were typically focused on tropical export crops such as sugar (Box 1), rubber, cotton, banana, coffee and tea.[8]

Box 1 International diffusion of sugarcane

Sugarcane represents a classic example of the international diffusion and transfer of an agricultural technology. It is of interest because the process has evolved from simple transfer of biological materials to the transfer of capacity to develop new sugarcane technology. There have been four stages in the transfer and development of sugarcane.

Stage I. Natural Selection and Diffusion of Wild Canes. Sugarcane was cultivated in India as early as 400 BC. Sugarcane and the art of sugar making were diffused from India to China, to Arabia, and to the Mediterranean region very early. Shortly after 1400 AD, sugarcane was introduced on Madeira and in the Azores. Columbus took it with him to Hispaniola on his second voyage to the New World in 1493. From there it was carried to Cuba and Puerto Rico, and later to Mexico, Peru and Brazil. Throughout this period the cane used in commercial cultivation was one of two closely related thin stemmed varieties. In 1791 Captain Bligh (of *Mutiny on the Bounty* notoriety) collected and introduced a thick-stemmed variety which rapidly replaced the thin-stemmed forms within a few years.

Stage II. Sexual Reproduction. In nature the sugarcane plant produces only asexually. Until methods of sexual reproduction were discovered this limited the selection of superior clones to indigenous cultivated or wild forms. Procedures for the sexual reproduction of sugarcane were discovered at a Dutch research station in Java (in 1887) and at British research station in Barbados (in 1887). By 1920, commercial varieties had been transferred to most of the sugar growing areas of the world. Only simple tests and demonstrations were required for recipient countries to propagate and diffuse the varieties locally.

Stage III. Interspecific Hybridisation. Breeding for disease resistance became an important concern since many of the new varieties were found to be susceptible to local diseases and pests. Disease-resistant varieties were developed by crossing a wild thin-stemmed variety with a high yielding thick stemmed variety. Through a series of crosses and back crosses, new interspecific hybrids were developed that incorporated the hardiness and disease resistance of the wild species with the desirable characteristics of cultivated varieties. Later the Coimbatore station in India developed a series of tri-hybrid disease-resistant varieties which were transferred to every sugar cane producing country in the world. While this transmission was widespread, it was highly dependent on local experimental station capacity for adaptation.

Stage IV. Location Specific Breeding. The Coimbatore (India) station set the stage for modern sugar cane variety development research which emphasises the development of varieties suited to specific soil, climate, disease and management requirements. More than 100 experimental stations around the world are now engaged in the development of locally adapted sugarcane varieties. Very few varieties are transferred internationally for cultivation, although genetic material for use in local development programmes and sugarcane breeding knowledge and technology does continue to be transferred. Meetings of sugarcane research scientists and international consultancies represent an important institution for transferring new scientific and technical knowledge.

Box 1 International diffusion of sugarcane (continued)

An important lesson from the history of sugarcane research is the important role of advances in fundamental knowledge for the productivity of applied research. Each advance in knowledge – sexual reproduction, interspecific hybridisation, and location specific breeding – led to new breeding technology and to the rapid development of new varieties. But over time the gains that could be realised from exploiting the most recent advances in breeding technology declined and the scientific and technical effort, and the cost, of developing new varieties rose.

Source: Evenson, R.E., Houck, J.P. and Ruttan, V.W. (1970) 'Technical change and agricultural trade: three examples – sugar cane, bananas and rice', in R. Vernon (Ed) *The Technology Factor in International Trade*, New York, NY: Columbia University Press, pp.415–480; Evenson, R.E. and Kislev, V. (1975) *Agricultural Research and Productivity*, New Haven, CT: Yale University Press, pp.140–155.

In the immediate post-war years, assistance for agricultural development in the poor countries was conducted largely along the lines implied by the technology transfer model of agricultural development. By the early 1960s, evidence had accumulated that yield enhancing biological technology was highly 'location specific'. Evidence was also accumulated to the effect that only limited productivity gains could be achieved by the reallocation or more efficient uses of the resources available to peasant producers in poor countries. The world's food crises of the 1960s and 1970s induced a series of important institutional innovations. The immediate response was the transfer of large resources, including food aid, to the food-deficit countries (Ruttan, 1996, pp.149–202). The longer-term response was the mobilisation of resources to develop a system of international agricultural research institutes and to strengthen national agricultural research systems in less developed countries.

4.1 An incomplete international system

The initial international institutes focused their research mainly on the major food crops grown in developing countries – rice, wheat, maize, potatoes and cassava. These were joined in the 1970s by centres focusing on livestock production and animal disease, on arid and semi-arid areas, on food policy, and on the conservation of genetic resources and, in the 1990s, by the addition of new centres on banana and plantain, forestry, soils, irrigation and agroforestry. The expansion of the Consultative Group on International Agricultural Research (CGIAR) system was not accompanied by a comparable increase in the resources available to the system. Donor contributions, which amounted to $335–340 million in current dollars in 1998, had declined in real terms from the levels achieved a decade earlier. At donor insistence, research effort was reallocated away from productivity enhancing research to the broader issues of rural development and the environmental impacts of the intensification of agricultural production.

Since the mid-1980s, the managers of several of the CGIAR institutes have been forced to confront the problem of how to revitalise a mature research organisation during a period when it was necessary to make substantial cuts in research and support staff in response to budget reductions. The rapid changes in the technology of crop variety improvement, associated with the advances in molecular biology and genetic engineering combined with recent institutional innovations leading to stronger private property rights in genetic materials, represents a particularly difficult challenge to the ability of the CGIAR system to continue to make advances in biological technology available to the national agricultural research systems of the developing countries.[9]

4.2 National research systems

As the new seed-fertiliser technology generated at the CGIAR centres began to come on-stream in the late 1960s, some donors assumed that the CGIAR centres could bypass the more difficult and often frustrating efforts to strengthen the national agricultural research systems.[10] However, experience confirmed that strong national research centres were essential if the prototype technology developed at the international centres was to be broadly transferred, adapted and adopted. The location-specific nature of biological technology meant that the challenge of constructing a global agricultural research system capable of sustaining growth in agricultural production required the development of research capacities for each commodity of economic significance in each agroclimatic region. A careful analysis of sources and linkages among scientific and technical knowledge is illustrated in Table 3.

Between the early 1960s and the early 1980s, agricultural research budgets and research personnel in developing countries grew rapidly. The global share of agricultural researchers in less developed countries increased from 33 to 58%. China alone accounted for 24% in 1981–1985. However, by the late 1980s, many national research systems, in Africa, Latin America and the Caribbean, were like the international system, experiencing increasing budget stringency.[11]

Beginning in the mid-1950s, Kenya developed a highly productive maize research programme but has not been able to sustain its initial success. In most developing countries there are only weak links between ministry of agriculture research organisations and universities. Research funds flow mainly to ministry research laboratories in spite of the fact that the proportion of university scientists who had received training at PhD level is generally much higher in the universities. In the few countries with significant private sector agricultural research there are typically only weak links with either ministry or university research.

By the mid-1990s, a new and more sophisticated perspective was emerging on the possibilities of transfer of agricultural technologies across agroclimatic zones. Analysis of wheat breeding indicated very substantial spillovers. About two-thirds of all wheat varieties released in developing countries during 1966–1990 were directly or indirectly based on germplasm developed by the CIMMYT-NARS network. The share of these varieties in developing countries has increased to over 80% in the past decade. Furthermore, varieties containing CIMMYT based genetic material had a significant yield advantage relative to varieties containing only locally based genetic material. This experience opens up the possibility of rationalising the international wheat breeding system within the CGIAR-NAR system.

Table 3 Science and technology in the agricultural research and development system

Layer/activity	*User and use types*				
I FINAL USERS/ Sources of clientele problems		Producers	Governments	Consumers	
II. EXTENSION (Public and private)	Resources & environment	Commodity oriented	Management & marketing	Public policy resources	Family & human
		Major areas of science and technology for agriculture			
	Mathematical sciences	Physical sciences	Biological sciences		Social sciences
III. PRODUCTS FROM INNOVATION (Agri-industrial development) innovations	Farm machinery & equipment Farm buildings	Commercial fertilisers Agricultural chemicals Irrigation systems	Crop/plant varieties Horticultural/nursery species	Animal breeds Animal health products	Management systems Marketing systems Institutional
	Computer equipment/ software	Pest control systems	Livestock feed	Food products Child care	Health care
IV. TECHNOLOGY INVENTION (Public and private research)	Agricultural Engineering & design Mechanics Computer design	Agricultural chemistry Soils & soil sciences Irrigation & water Methods	Agronomy Horticulture Plant breeding Applied plant pathology	Animal & poultry sciences Animal breeding Animal & human Nutrition Veterinary medicine	Farm management & marketing Resource economics Rural sociology Public policy studies Human ecology

Table 3 Science and technology in the agricultural research and development system (continued)

Layer/activity	*User and use types*				
			Integrated pest management		
V. PRE-TECHNOLOGY SCIENCES (University and public agency research primarily)	Applied math Applied physics Engineering Computer science	Climatology Soil physics & chemistry Hydrology & water Resources	Plant physiology Plant genetics Phytopathology	Animal & human physiology Animal & human genetics Animal pathology Nutrition	Applied economics Statistics & econometrics Political science Sociology
			Environmental sciences		
VI. GENERAL OR CORE SCIENCES (University and public agency research primarily)	Mathematics Probability & statistics	Atmospherical & meteorological sciences Chemistry Geological sciences Physics	Bacteriology Biochemistry Botany Ecology	Genetics Microbiology Molecular biology Zoology	Economics Psychology

Note: [a]Arrows indicate the direction of linkages, upstream, downstream, or horizontal
Source: Wallace and Huffman, 1993

The emergence of a private sector biotechnology industry in a number of the more advanced developing countries, such as China, India, Malaysia and Brazil, and the emergence of new forms of intellectual property protection for biological technology means that the private sector has become engaged in areas of pre-technology and basic research that in the past have been almost the exclusive province of the public sector. Private sector research in most developing countries continues, however, to rely heavily on public sector, germplasm enhancement.[12]

The national and international public and private sector agricultural research systems are presently being complemented by new less formally structured systems. There is now substantial evidence that non-governmental organisations (NGOs) and agricultural producers themselves are beginning to play an increasingly important role not only in technology diffusion but in technology development.

One example is the development by a Catholic priest in Madagascar of a set of agronomic practices centred on early rice transplanting, now labelled the System of Rice Intensification, that adds upwards of 1000–2000 kg per hectare to the yields of both traditional and modern varieties. The System is now being tested and diffused by international and national research systems and NGOs throughout the tropics (Uphoff, 2000).

A second example, documented in a recent paper I have recently reviewed, is a system used by indigenous producers in Southern Mexico to develop 'Creole' varieties of maize by taking advantage of interplanting and cross-pollination of traditional and modern varieties of maize. The National University of Mexico and CIMMYT are now testing the effectiveness of a somewhat similar method, drawing more directly on modern breeding technology, in Central Mexico.

The implication of such informal research and diffusion is potentially very important. It has been conventional that advances in mechanical technology are based largely on farmer innovations that are then 'engineered' by farm equipment company engineers. This is based on the knowledge of mechanical principles and careful empirical observation by farmers and mechanics. It is possible, as knowledge of general biological and genetic principles and of breeding techniques is acquired by producers, that a larger share of adaptive development of biological technology will be carried out by agricultural producers.

There continue to be several limitations in the present system. There has been an erosion of public sector agricultural research capacity in a number of developed countries and in the member states of the former Soviet Union as well as in many developing countries.[13] Relatively few developing countries in which national systems have achieved the capacity to make effective use of the advances in knowledge and technology that could be made available to them through the international system or through collaboration with the stronger national systems. The private sector agricultural technology supply industry, while growing rapidly, still remains poorly represented in most developing countries. Although the infrastructure of the international agricultural research system remains incomplete, it is far more highly developed than the international infrastructure for health, environmental or industrial research.

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Notes

[1] This paper was prepared for the Conference on Raising Agricultural Productivity in the Tropics, Center for International Development, Harvard University, October 16 & 17, 2000.

[2] For induced technical change see Binswanger and Ruttan (1978) and Hayami and Ruttan, (1970, 1985). For institutional innovation see Binswanger and Ruttan (1978), Hayami and Ruttan (1985) and Ruttan and Hayami (1984).

[3] The pace of mechanisation may also be influenced by soil and topography. For a discussion of the constraints on mechanisation during the transition from shifting cultivation to intensive agriculture in Africa, see Pingali et al. (1987). For a discussion of the transition from land- to labour-saving technology in rice production in Southeast Asia, see Pingali et al. (1997, pp.40–61).

[4] Critics of the green revolution have often failed to distinguish between technical and institutional bias. Although biological technology is generally neutral with respect to scale, the institutional environment into which the new technology is introduced – including tenure arrangements, factor and product markets, and credit institutions – are often biased against small producers. It is important, for purposes of policy reform, to correctly identify whether the source of the bias is technical or institutional (Hayami and Ruttan, 1985, pp.336–345).

[5] The empirical grounding of a number of the critical studies have been so weak that it is hard to avoid the conclusion that they have been ideologically motivated. For two of the more egregious examples, see Pearse (1980) and Shiva (1991).

[6] For a more rigorous test of the induced technical change hypothesis against Japanese and US agricultural history see Hayami and Ruttan (1985, pp.178–204). See also Binswanger and Ruttan (1978).

[7] The *groupment naam* movement and its accomplishments have been analysed in some detail, drawing on extensive literature and personal experience by Smale and Ruttan (1997).

[8] In this section, I draw heavily on Alston and Pardey (1999), Hayami and Ruttan (1985, pp.264–274) and Ruttan (1982, pp.90–115, 1986).

[9] For a more detailed discussion of the program and financial problems facing the international agricultural research system, see Alston and Pardey (1999) and CGIAR System Review Secretariat (1998).

[10] There is now an extensive literature on the development of national agricultural research systems in developing countries. For comprehensive reviews see Byerlee and Alix (1998) and Pardey et al. (1991) and For a particularly insightful case study see Tendler (1994, pp.146–180).

[11] The first comprehensive set of data on agricultural research expenditures and personnel in developing countries was assembled by Pardey et al. (1989). The data have been more completely analysed in Pardey et al. (1991, pp.197–265).

[12] The most complete body of research on private sector agricultural research in developing countries has been a series of articles and reports by Carl Pray (1987, pp.411–431; Pray and Umali-Deininger, 1998, pp.1127–1148).

[13] I do not, in this paper, attempt to address the problems of transition to sustainable systems of agricultural production in the formerly centrally planned economies of eastern Europe and the former USSR. Prior to 1980, the absence of effective markets had resulted in a technological trajectory that was less efficient than if relative factor–factor and factor–product prices had more accurately reflected relations factor endowment and market demand (Fan and Ruttan, 1992).