Technological Change and Technological Diffusion in Agricultural Development: How have Proprietary Rights Contributed?

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<u>Abstract:</u>

The chapter examines three phases of R&D in agricultural development: traditional plant breeding, the modern hybrid crop experience and the future of genetic use restriction technologies. These three phases are more important for the proprietary right systems they indicate. Traditional systems were public systems, using government supported investment and information exchange and decentralized farmer-based R&D. Modern hybrid systems are proprietary systems with in-built enforcement mechanisms, but applying only to a few of the important modern-day crop varieties (maize and sorghum). Future genetic use restrictions will extend the proprietary systems to all varieties of crops. In order to examine the future, we look at modern day experience with the hybrid systems. The finding is that a private sector-based R&D system results in enhanced rates of growth due to innovation, but combined with reduced rates of diffusion. For some reason the private sector system both fails to invest in diffusion and also disarms the effectiveness of the existing public R&D system. The extension of this system to all crop varieties is likely to crowd out the public system of investment in diffusion while encouraging a higher rate of private sector-based R&D focused on the technological frontier.

1. Introduction

This paper describes the nature of the R&D system in agriculture: past, present and future. The R&D system in agriculture was a basic one at the outset, when most technological change occurred by means of users operating through basic methods of observation and selection. This was enhanced by means of government investments into the collection, storage and exchange of important plant varieties, but the basic method and approach remained the same. Agricultural development was a very diffuse and diverse enterprise, in which the vast majority of the globe both participated and benefit. The basic framework for information and innovation exchange was "openness", and the public sector was actively involved in both innovation but especially diffusion.

The next phase in agricultural development commenced only seventy-five years ago when the private sector first entered into R&D activities. A major structural shift in agricultural development occurred over the next half century in those sectors where private entry occurred. These private entrants operated primarily on those varieties where their innovations were well protected via hybrid crossing methods. In this phase of agricultural R&D, the private sector had a major impact on both the overall make-up of the R&D sector and also the distribution of the benefits resulting from innovation. Private sector R&D accelerated the rate of growth in the affected sectors, but at the cost of a reduced rate of diffusion away from the technological frontier. It displaced public sector investment in diffusion while failing to invest sufficiently in diffusion itself. The result was a widening gap between those countries on the technological frontier and those within. A regime that focused on restricting the flow of information, and hence innovation, was displacing the one that emphasized openness.

The final phase of technological change in agriculture will be much more carefully protected, primarily through technology but partly through the extension of patent systems. Genetic based use restriction methods exist which will enable the extension of the hybrid experience to all other crop varieties at some point in the near future. Without adequate investment in the diffusion of innovation, this would indicate that the private sector would continue to expand and displace the public sector in this arena. If this is the case, then we can expect the future of agriculture development to be one in which technological change becomes increasingly focused on the frontier.

Proprietary rights in agriculture have become increasingly well-defined and readily enforced, and will become perfectly so with the advent of biotechnological enforcement methods. The experience with proprietary rights in agriculture is an odd one, in which they function as crude mechanisms for appropriation rather than dynamic instruments for innovation and diffusion. This means that increased innovation has resulted from increasingly well-defined proprietary rights, but only in a very narrow sense. The innovations that have occurred have been focused narrowly on the technological frontier, and then adapted and diffused only gradually. The result is a distribution of benefits that increasingly focuses on the frontier states, and with a greater dispersion over time. Increased proprietary rights here have increased the gap between the "haves" and the "have nots". In this chapter we attempt to explain the process that generated this outcome, and the reasons for its occurrence.

2. The Beginnings of Technological Change in Agriculture: Collections and Plant Breeding

The first phase of agricultural research and development (R&D) runs nearly ten thousand years. It commences with the first plant cultivators, and their intervention into natural selection. Their recognition of the range of genetic characteristics inherent within a single plant variety extends back much further than the understanding of the underlying processes. Through a process of observation (of the plant varieties that withstood inclement conditions) and selection (through selective cultivation and inter-breeding), these farmers nurtured a broad set of genetic resources across the ages.

As western cultures transported their selected crops far from their centres of origin, their governments came to recognize the threats inherent in being disassociated from the centres of diversity. In the nineteenth century this recognition led to the development of various forms of agricultural collections, in order to supply distant farmers with the genetic resources required for their ongoing breeding programmes. Governments then took the next step to establishing public research stations that both collected genetic resources and experimented with them. The culmination of this era of R&D was the establishment of such public research stations at both the national and international level across the globe, providing collections and information to encourage traditional R&D in most countries across the world.

2.1 Farmer Breeding of Crops and Livestock

Prior to 1843, most crop and livestock improvement was produced by farmers. Some seedsmen were engaged in plant breeding in the late 1700s and early 1800s, but it was not until after 1885 that plant breeding became a formal professional activity[1]. Crop farmers improved crops through seed selection. In some communities (e.g., in the Philippines) "seed selectors" were designated in rural communities. In the process of seed selection farmers created "landraces" or specific sub-types of the cultivated species. These landraces and related mutations and wild species have become the "raw materials" that "conventional" plant breeders use for crop improvement today.

These landraces and related materials are usually classified as follows:

1. Landraces from the "Center of Origin" of cultivation.
2. Landraces from the "Centers of Diversity" of cultivation.
3. Landraces from New World cultivation.

Landraces from the Center of Origin of cultivation date back many centuries. The dating and location of earliest cultivation of crop species remains subject to some uncertainty, but earliest cultivation for most crop species is dated from 2000 B.C. to 12,000 B.C. Earliest cultivation was often achieved in what today are developing country locations. Maize originated in Central America, wheat in West Asia, rice in South Asia, Southeast Asia and Africa[2], sorghum in Africa, etc. Approximately 7000 crop species are edible and cultivated in different countries. Of these, 120 have national importance. The leading 30 crop species, however, account for 90 percent of the world's caloric intake.

Some crop species are "self-pollinating" (e.g. rice, where both male and female organs are contained in the same pod). Others are cross pollinating (e.g. maize). But most seeds are the result of "sexual" reproduction[3]. Modern plant breeders typically seek to achieve a cross between two parents. In some cases this is a single parent, in most cases, two parents. This means that a female parent must

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[1] It is often thought that the "rediscovery" in 1900 of Gregor Mendel's 1856 work on quantitative genetics was the basis for renewed interest in plant breeding. But many plant breeding programs were in place in many countries by 1880

[2] Two species of rice, *Oryza sativa* and *Oryza glabarrima* are cultivated. *O. glabarrima* originated in Africa.

[3] Some crops are reproduced asexually. Sugarcane, potatoes and similar crops can be reproduced asexually.

sometimes be physically created through “detasselling” in the case of maize or emasculation of male organs in the case of rice.

Centers of Origin were favorable to early cultivation. They were also favorable to pest and pathogen development for a cultivated species. Centers of Diversity, on the other hand, were in locations where population movement created new conditions. As populations moved into Centers of Diversity and later to New World locations, more landraces were created. For example, as rice cultivation was expanded to deeper water conditions, the cultivars selected became taller. As soil conditions changed (e.g., higher pH), rice cultivars became more tolerant of alkaline soils. And as rice cultivation was moved to temperate climate zones, insect and disease conditions changed[4].

For many decades technological innovation in agriculture simply made use of the diversity deriving from these centres, and combined it in important and useful ways. Modern day breeders have essentially operated by combining landraces in complex fashions to achieve broad insect and disease resistance traits. For this reason numerous *ex situ* gene banks were developed with collections of landraces, mutations of landraces (and of “wild” or uncultivated species in the same genus). These have been the source of the basic building blocks of information, on which R&D in agriculture has been undertaken.

2.2 Early Agricultural R&D: Collection, Classification and Storage

Collections of plants for breeding have been around for much longer even than known breeders. C. Linnaes developed the modern systems for classifying plants and animals into species, genus, and higher units in 1696. This system of classification remains relevant today[5]. As the classifications efforts proceeded, the interest in preserving species in collection grew. This let to the development of the Botanical Garden. These Botanical Gardens preceded the Agricultural Experiment Stations (see below) as research centers for plants. Today 1500 Botanical Gardens are maintained in many countries. 698 Botanical Gardens maintain collections of ornamental plants and other species, 119 of these maintain collections of cultivated species. The research programs of Botanical Gardens have been focused on collection, classification and preservation of species of higher plants. Botanical Gardens generally have few research programs to improve the performance of crop species. As a consequence they have never been effective research organizations.

The 19th Century agricultural innovators were primarily curious and observant farmers. In the west they were usually supplied by their governments and agricultural departments. These governments usually had to acquire the genetic resources from elsewhere. For this reason expeditions to other countries to collect seeds to be evaluated in new conditions have been an important activity in many countries for many years. In the United States, even the Patent office commissioned seed collection missions. In 1819 the Secretary of the Treasury sent requests to U.S. Counsels and naval offices asking them to collect seeds in foreign locations. In 1827 a second request was sent including complete details on procedures for preservation and shipment of seeds. The navy proved to be particularly cooperative in these missions. Seed distribution was a major activity of the US Department of Agriculture (USDA) from its inception in 1819. For example, in 1849, 60,000 packets

[4] Most crop species perform best in temperate zone conditions.

[5] It is estimated by some that many species remain unknown and that there are as many as 10 to 20 million species (1.46 million have been classified). This estimate, however, is almost surely wrong because few new species are being discovered.

of seeds were distributed to farmers in the United States for use and breeding. These searches and the resultant relocation of varieties to western agriculturalists were infrequently successful but some important successes did occur. A number of early varieties including Purplestian wheat and Lancaster wheat were the result of these informal breeding operations. (Huffman and Evenson, 2005).

2.3 Extension of Early Ag R&D: The Development of the Agricultural Experiment Station

The major event in the early development of agricultural R&D was the development of the Agricultural Experiment Station (AES) model. The Rothamsted Experiment Station established in 1843[6] is generally regarded to be the first modern agricultural experiment station. Other stations established in Saxony at roughly the same time can also lay claim to being among the first experiment stations.The AES model brought the concept of formal experimental science to agricultural research programs. Experimental designs were developed with specific "treatments" and "controls". Thus, a fertilizer experiment might entail a randomized planting system where different levels of fertilizer (including zero fertilizer) application rates were applied on different plots. As the AES model matured, formal statistical tests were applied to the data generated. This experimental design system and the associated statistical methods were inherently "scientific", even though the biological sciences were not well developed at the time[7].

In the U.S. the Hatch Act of 1887 provided funding for a State Agricultural Experiment Station (SAES) in every State. However, the United States Department of Agriculture and a number of States had adopted the AES model before the Hatch Act was passed. The combination of USDA research and SAES research served the U. S. well[8].

The same model was then extended to many if not most other countries, where agricultural stations have been supported by government services and development agencies. These agricultural experiment stations became centers of both plant breeding and seed collections, and they were the sources of much of the seed that was used in breeding experimentation throughout the world. For many years it was common practice of these stations to share stored seed with other scientists at other stations, in the interests of a common advancement of agriculture. This public sector based plant breeding existed for many years, resulting in large collections of plant genetic resources and many new and advanced forms of plant varieties. As time passed, and private sector investment in plant breeding burgeoned, the public and private sectors jointly combined to enhance collections and increase breeding.

In support of the Green Revolution, several International Agricultural Research Centres (IARCs) were established in the postwar era to act as central storage and informational exchanges: examples include the International Rice Research Institute in Manila; CIMMYT for maize in Mexico City; International Food Policy Research Institute in Washington, D.C.. These IARCs at the international level are counterparts to the AES at the domestic level. They continue to serve as conduits for the movement of genetic resources and technological changes throughout the latter part of the twentieth century and into the present day. This sharing of information and genetic material at the global level culminated in a golden era of collection-based agricultural development. Gains in both frontier yields and in yields in most other user countries were achieved through transportation of

[6] The Station was privately supported by Sir Bennet Lawes.

[7] R. A. Fisher was the statistician on the Rothamsted Station from 1919 to 1933. He is credited with numerous statistical developments including some relevant to modern day econometrics.

[8] It is often thought that Congress showed exceptional insight in passing the Hatch Act in 1887and before that the Land Grant College Act in 1862. But in both cases considerable experience with Land Grant Colleges and Experiment Stations was available to Congress.

innovations and germplasm throughout the global agricultural research system, both international and domestic .

The outcome of this era of resource and technology-sharing was a diffuse and diverse system of research and development, built initially upon a foundation of public sector collections and farmer-based breeding and then later on agricultural experiment stations. The story of agricultural R&D in the nineteenth and early twentieth centuries is one of widespread collections of historically useful germplasm, exchanged relatively freely and incorporated into innovative plant varieties. The commitment to public R&D took the initial form of collection and transport of genetic resources, and then to the broader undertaking of all aspects of agricultural R&D. Initially, the gains were achieved at the technological frontier (Europe and North America). Later the system became globalised, and the benefits of agricultural R&D were diffused more generally in the course of the green revolution.

2.4 Example: Early Plant Breeding in Agricultural Experiment Stations – sugarcane

Formal plant breeding programs were established shortly after AES programs were initiated in many countries. The case of sugarcane breeding program is instructive in this regard[9]. It will be useful to characterize the development of cane varieties as occurring in four major stages:

2.4.1 Stage I – Selection of Native Varieties

Prior to 1887 relatively few cane varieties were in commercial production. The cane plant reproduces itself asexually, and planters were unable to alter the genetic structure of the existing varieties. From the sixth century to the eighteenth century a single variety, the "Creole" (a hybrid with sterile flowers, thus incapable of sexual reproduction) was produced throughout the world. During the eighteenth century a second variety, the "Bourbon" or "Otaheite" cane was discovered on the island of Tahiti in the Pacific and later introduced to all cane-growing areas of the world. It proved to be superior to the Creole variety and eventually replaced it as the dominant cane in most producing countries. It is of interest to note that it was not introduced to the British West Indies, a major cane-producing area, until 1785, more than a hundred years after it was first known to have been commercially produced in Madagascar and on Bourbon (or Reunion) Island. Produced under a variety of names (Lahania, Vellai, Louiser) it dominated world production until it became subject to disease in 1840 in Mauritius, in 1860 in Puerto Rico, in the 1890s in the British West Indies, and in the early twentieth century in Hawaii.

A third major set of wild canes, the "Batavian," were discovered in Java around 1782. These canes were eventually produced in many countries (including Cystalina in Cuba, Rose Bamboo in Hawaii, and the Transparent canes in the British West Indies), but were not always superior to the Bourbon cane. After the disease epidemics in the Bourbon cane, the Batavian varieties became dominant. However, they were later subject to the Sereh disease in many parts of the world. Other wild varieties were discovered in the late 1800s, including the Tanas from New Hebrides, Badila from New Guinea, and Uba, probably from India. Badila and Uba became important varieties because of their resistance to the cane diseases increasingly prevalent from 1890 to 1925.

2.4.2 Stage 2 – Sexual Reproduction: The Noble Canes

The original sugarcane varieties undoubtedly arose as seedlings from rare cases of natural sexual reproduction. It was not until 1858 that any record of the existence of cane seedlings was

[9] This section draws on Evenson and Kislev (1975).

reported. J. W. Parris, a sugar planter in Barbados, British West Indies, reported that an employee had noticed cane seedlings growing in a field of ratoon cane (a cane crop obtained from the regrowth after harvesting the original crop). He was satisfied that these seedlings had grown from cane “arrows.” Parris managed to save seven of the seedlings and eventually raised four-and-a-half acres of cane from them. Finding that these new canes were not superior to the Transparent variety in his fields, he abandoned his project.

Other reports of seedling growth were made later, but it was not until the 1887-88 cane-growing season, when the fertility of the cane plant was rediscovered, that a basis for the deliberate use of seedlings for producing new varieties existed. In the early part of that crop year, Soltwedel, in the Proefstatien Oost Java (POJ),[10] demonstrated that the sugarcane plant could produce seedlings. Later that same year Harrison and Bovell, in the newly established experiment station in Barbados, British West Indies, independently made the same discovery. The researchers at both stations recognized that each individual seedling could be grown and allowed to reproduce asexually, thus creating an entirely new variety having the same genetic characteristics as the seedling.

The inducement of flowering in the cane plant depends on temperature and light control, thus the production of seedlings was difficult. Only a few experiment stations, including the two pioneer stations in Barbados and Java, were able to establish breeding programs before 1900. The stations in Barbados, Java and British Guiana had produced new, commercially important varieties by that date. The stations in Hawaii, Mauritius, and Reunion produced commercial varieties shortly thereafter. The Indian station at Coimbatore did not release its first variety until 1912.

The earliest breeding programs were not systematic in the sense that seedlings were produced from random fertilization of parent varieties grown in proximity to one another. Parentage was not identified. Procedures were later developed to identify parentage and to pursue more systematic cross-breeding procedures as experiment stations gained experience with breeding programs.[11]

2.4.3 Stage 3 –Interspecific Hybridization

Cane-breeding achieved a major advance with the introduction of additional cane species to the breeding program. The term “nobilization” was used to describe the breeding work in Java, which sought to improve the wild species of cane (hardy and disease-resistant but otherwise inferior) by successive crossing and back-crossing with the noble canes. The breeders in Java introduced the species *Saccharum spontaneum* (a wild species) to their breeding program, obtaining important results by 1920. In 1921 the variety POJ 2878 was produced by this program. It proved to be both disease-resistant and high-yielding. More than 50,000 acres were in production, with an estimated 30 percent yield increase due to this variety. Ultimately POJ 2878 was planted in every cane producing country in the world.

The Coimbatore Experiment Station in India developed a series of tri-hybrid canes (the Co. varieties) by using the noble *Saccharum officinarum* and the vigorous *Saccharum spontaneum* species and introducing a third species, *Saccharum barberi*. The *Saccharum barberi* canes were local varieties adaptable to local climate, soil and disease conditions. The Co. and POJ varieties were eventually transferred to almost every producing country. Hawaii also produced several major nobilized varieties, which were planted in other countries. The Barbados and British Guiana stations lagged in their introduction of the nobilization breeding technique.

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[10] The experiment station in Java, was later to become the world’s leading producer of important varieties.

[11] Bovell, in 1900, pursued a breeding program of “selfing,” i.e. inbreeding to identify the characteristics of progeny of specific varieties to determine their value as breeding stock. It was shortly after this that Shull and East in the United States used the same principle to develop the “hybridization” of corn.

2.4.4 Stage 4 – Breeding for Specific Soil and Climatic Conditions

The introduction of local species into the breeding program in the Coimbatore station in India set the stage for modern breeding activity. More than a hundred sugarcane experiment stations are now in existence. In almost every case these stations are pursuing a breeding program that involves the systematic crossing and selfing of parent species to develop new varieties suited to the specific soil, climate, and disease conditions, as well as the cultivating and harvesting techniques of relatively small producing regions.

Modern cane-breeding of the stage 4 type is considerably more sophisticated that earlier work. As a result of worldwide searches for new cane species, new genetic materials have been made available for breeding programs. The level of investment in scientific education and the intellectual investment required of the modern researcher have increased. Overall, the proportion of the effort of the sugarcane experiment station's staff directly devoted to cane-breeding has decreased as more resources have been devoted to research in the fundamental physiological and biological properties of the cane plant and its environment.

Economic considerations enter into modern cane-breeding programs. Factor price changes in cane production, for example, alter the breeding strategy. A relative decline in the price of fertilizer increases the economic value of fertilizer responsiveness in the cane plant. A relative increase in the price of labor increases the economic value of improvements in machine-harvesting technology. It also increases the economic value of uniformity and non-lodging characteristics of the cane plant, which are complementary to machine-harvesting technology. The development of machine-harvesting techniques was in part dependant on the cane-breeding efforts to develop varieties suitable to these techniques.

The sugarcane example showed the importance of interspecific hybridization. This was achieved earliest in sugarcane, but interspecific hybridization techniques chiefly embryo reserve" techniques have now been developed for virtually all crop species. In rice, for example, a search of *Oryza sativa* landraces found little or no resistance to the Grassy Stunt virus disease. But using interspecific hybridization techniques, *Oryza nivara*, an uncultivated rice species was combined with *Oryza sativa* to achieve resistance to grassy stunt.

3. The Entry of the Private Sector into Agricultural R&D: hybrids, PBRs and diffusion

In the course of the twentieth century, a burgeoning private agricultural R&D sector began to interact with the public sector, using the genetic resources of the public sector and providing its own information and innovations to the increasingly joint enterprise of agricultural development. For this reason the outcome of the twentieth century was a very "mixed economy" of agricultural R&D. Table 1 reports investments in both developing and developed countries in both the public sector (including the International Agricultural Research Centers) and in the private sector. In addition Table 2 reports public and private sector expenditures as a share of agricultural GDP and expenditures per capita. Figure 1 reports the state of existing genetic resource collections. While data are incomplete for many crops, it may be noted that for many crops, genetic resource collections are quite complete. Figure 1 also reports the storage status of collection and the types of genetic resources in collection.

This mixed outcome required the development of specific forms of rights to enable private operators to "hive off" the benefits of their innovations. These rights were initially biologically-based, in that innovations in certain plant forms (hybrids) were more readily appropriated than others. Then a legislative movement to extend rights in plant breeders' innovations to other (non-hybrid) plant varieties was initiated. These systems of rights (biological and non-biological) encouraged the development of a private R&D sector, but kept it focused more on the plant varieties where biology worked in the private sectors' favor (primarily maize).

This era provided an interesting experiment in the inter-relations between the private and public sectors in agricultural development. We are able to observe the impact of private sector R&D on both innovation-based gains at the frontier, and also on the diffusion of those innovations within the technological frontier. Surprisingly, the most important impacts of the entry of the private sector into R&D were primarily in regard to the effectiveness of the public sector.

3.1 Private Sector Investment in Plant Breeding: hybrid varieties, plant breeders rights and IPR

Formal plant breeding requires a sexual cross involving one or two parent cultivars. For some purposes the breeding process entails "selfing" or inbreeding followed by out crossing i.e. achieving a cross between two parents. Most plant breeders in most crops utilize two parents to produce an F1 generation of progeny. The progeny generations are then subjected to selection procedures. These are usually "selection under pressure" procedures. For example, a rice breeder selecting for resistance to a disease may inoculate the progeny with the disease. After several generations of selection, the resultant variety is submitted to a Variety Release Board. This Board decides whether to name and release the variety. The release of a variety is carefully guarded. Very few of the products of a cross actually become released varieties. These techniques have been further developed in recent decades. It is now possible to breach the species breeding barrier allowing sexual crosses to be made between cultivated species and "wild" uncultivated species in the same genus. The interspecific hybridization techniques, first developed in sugarcane, have now been used to cross species boundaries in most cultivated species[12].

The second major advance in plant breeding entails another form of "hybridization" to achieve a "heterosis" effect. This advance was also achieved by 1920. It entails first inbreeding or "selfing" and then a single or double cross between inbred lines. The cross exhibits heterosis or hybrid vigor for one generation only.[13] Hybrid seed from a single cross was costly because inbred lines were poor seed producers. But when two single cross hybrids were crossed, seed production was increased and this

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[12] The definition of a species is that a "breeding barrier" exists between species. Interspecific hybridization techniques, particularly embryo rescue techniques now allow most cultivated species to overcome breeding barriers between species in the same genus.

[13] The pioneers in the field were Edward East and George Shull. East was trained as a chemist, but worked at the Illinois Experiment Station as a corn breeder. His work convinced him that inbreeding concentrated genetic characteristic into pure lines. A conflict with the director of the Illinois project led East to move to the Connecticut Agricultural Experiment Station in New Haven, Connecticut in 1907. George Schull was one of the first scientists employed at the Carnegie Institute for Experimental Evaluation in Cold Springs Harbor, Long Island, New York. He began working on hybrids in 1904 and started inbreeding experiments in 1905. He noted that open-pollinated varieties were chance-born complex hybrids. Inbreeding concentrated genetic traits and enabled the rejection of traits associated with recessive genes. Inbred lines did experience a loss of plant vigor, but when inbred lines were crossed this produced hybrid vigor. Schull named this a "heterosis" effect. Donald Jones, also at the Connecticut Agricultural Experiment Station developed the "double cross" method for hybrid seed production over the period 1916-19.

enabled low cost hybrid seed production[14]. The first commercial producer of hybrid corn seed was George Cater a Connecticut farmer. The Connecticut Agricultural Experiment Station was at that time the intellectual center for hybrid corn research, in part because of its affiliation with the Yale Sheffield Scientific School, and it helped to develop this innovation.

The prospects for commercial hybrid seed production attracted a number of investors. The earliest was Funk Brothers where a corn inbreeding program was started in 1916. Henry Wallace (later to become the Vice President of the United States) began inbreeding work in 1913 and had produced a double cross hybrid by 1920. In 1926 Wallace organized the Pioneer Hi-Bred Corn Company. Other private sectors firms commencing at the time were the DeKalb Agricultural Association and Pfister. Out of a farmer-based innovation, and a public sector development, a private sector arose to exploit and transport the innovation.

Until 1930, there were few incentives available to private seed companies to engage in plant breeding. After 1930 private sector companies producing hybrid varieties (primarily maize) came into existence and began to develop substantial R&D programmes. All of the other early plant breeding programs were located in Agricultural experiment stations supported by governments. Early private sector R&D was a relatively minor part of the overall R&D system, and it was highly focused upon one or two hybrid varieties.

The incentives for private sector seed companies changed once again with the introduction of a Plant Breeders Rights (PBR) system first in Europe in 1966 and then in the U. S. in 1970. These rights systems allowed plant breeders to take rights in biologically occurring resources, so long as they could demonstrate the manner in which they were produced as well as the uniform and useful traits which they exhibited. This was the first attempt at generating a rights system in biologically produced innovation, and they were widely used in the US and Europe. The problem for breeders under these systems lies in their reliance upon domestic enforcement mechanisms, should the innovations travel across national boundaries. If a state refused to enforce the PBR, then the farmers acquiring the innovative plant variety would be able to reproduce the innovations from acquired seed and enter into competition with the innovator. These Breeders Rights systems are expected to be implemented in many countries under the WTO – TRIPS agreement but little enforcement action has been undertaken to date.

Thus the incentive systems for private sector plant breeding programs have changed drastically in recent decades. From the 1930 to the 1960s, the incentives were for private investment to be undertaken in only one or two plant forms (maize and soybeans). In these plant varieties, innovations were increasingly initiated within the private sector, as the sector was biologically ensured of its ability to capture the returns from its innovations. From the 1960s to the 1980s, the private sector was endowed with a new system of legally-protected rights – so-called Plant Breeders Rights – which theoretically allowed the taking of rights in all other forms of plants; in practice, PBRs depended upon enforcement mechanisms for their implementation and had little impact outside of their states of origin. We are thus able to see two very distinct eras and management systems for private sector engagement: one in which the private sector was assured of the protection of its innovations (but in a limited number of plant varieties) and the other in which the private sector had very limited assurance of protection (across all forms of plant varieties).

[14] Ironically after 1970 or so, hybrid corn seed producers have reintroduced the single cross hybrid as seed production costs have been reduced.

3.2 Diffusion of Technological Change: hybrid varieties and diffusion

As mentioned above, the major innovations in hybrid varieties occurred in the northeast US in the early part of the twentieth century, but the major markets for hybrid corn were in the Midwest, not in New England where the innovation originated. The experiment stations in Iowa and Illinois began to develop hybrid corn varieties in the early 1920s. The USDA's program was revised in 1922. Then the commercial hybrid companies (described above) came into existence. Together these R&D investments worked to move the innovation out of Connecticut and across the USA. The manner in which this diffusion occurred is important for purposes of understanding how the benefits of technological change are realized, and distributed.

Zvi Griliches, in a University of Chicago dissertation, undertook the first study of the economics of technological diffusion. He studied the hybrid corn industry. Figure 2 from the Griliches study illustrates several points relevant to the diffusion of hybrid corn varieties. The first obvious question is why farmers in Alabama adopted hybrid corn 20 years later than farmers in Iowa? Was this because farmers in Alabama did not exhaustively evaluate hybrid corn varieties developed for Iowa farmers?

[Insert Figure 2]

Clearly there were more fundamental reasons. Corn is highly photoperiod sensitive. The length of day is longer in Iowa than in Alabama by 30 minutes or so during the peak growing season. Hybrid varieties for Alabama have longer growing seasons. Thus, Alabama farmers did not have viable hybrid corn varieties until public and private sector firms went through the time-consuming process of developing hybrid varieties for production conditions extant in Alabama. Agricultural technologies developed for one location must be not merely adopted in other parts of the country, but they must be adapted first to the new conditions present at the locality.

The lessons of Figure 2 apply to the Green Revolution as well as to U.S. farmers. Argentina and Brazil had hybrid maize varieties sometime after Alabama farmers had them. In East Africa (Kenya) hybrids were introduced in the 1960s. Asia did not have hybrid maize until 1980 or so. West Africa got hybrid varieties in 1990. And Central Africa still does not have hybrid maize varieties. The diffusion of frontier technologies in agriculture requires investment by those states within the frontier, in order to adapt and adopt the technological change to local conditions. Innovation (in agricultural R&D) does not transport readily absent investment.

3.3 Explaining the Distribution of Benefits from Agricultural R&D: Diffusion and Distribution

The relationship between the distribution of benefits and the diffusion of technological change is addressed within the Hayami and Ruttan (1985) framework on induced technological change. This approach states that institutional differences may result in substantial and differential time lags in the responsiveness of distinct societies to changed conditions. Thus the ability of individual countries to respond to changes in fundamental conditions depends on their institutional make-up. Some countries are able to absorb change rapidly (receiving benefits early on) while others are much slower to adapt and adopt. For our purposes, this indicates that the differential ability to absorb technological change will be dependent on different national investment positions, and that the distribution of benefits will result from lagged adoption of technological change.

There is an unevenness to be anticipated from the impact of technological change flowing across countries with different characteristics. These differences may be cultural, physical or institutional, but the more different countries happen to be, the more uneven will be the impacts of the technological change. One of the implications of this theory is that countries that fall off the technological frontier may have a difficult time in "catching up". Once these countries are significantly different from those on the frontier, these differences may slow the capacity for (and thus rate of) absorption of technological change, resulting in these countries becoming even further from the frontier.

The impact of technological change may be seen in the context of Table 3, below. Here it is possible to see that the rate of yield growth over the past half-century has averaged from 0.84% to 2.45% per annum, depending on the global crop concerned. There is a high variance in yield growth across countries, demonstrating that the frictions to adoption exist. Given that this part of the century gave rise to the first evidence of a "mixed economy" in agricultural R&D, it is interesting to look more generally at the manner in which gains have occurred within the private and the public sectors during this period. Table 3 shows the rates of advance at the technological frontier for each of the main global crop categories, as well as the change in the differential yield between "frontier economies" and "within-frontier economies" between 1960 and 2000. The crops marked "hybrid" varieties were those dominated by the private R&D sector, while the others remained largely within the public sphere over this time period.

[Insert Table 3]

There are three important points to take away from this survey of yield impacts across the latter half of the twentieth century. First, there were only two of the eight crops that were hybrid-based technologies, and so dominated by private sector R&D: maize and sorghum. Second, these two private sector dominated crops were two of the top three in terms of the rate of yield growth at the technological frontier (cotton being the one exception to the rule). Third, the difference in average yields (between those states at the technological frontier and those within) was widest for the two private sector-based crops.

Together these three points paint a picture of differential rates of yield and diffusion between the public and private sector dominated crops. Private sector-based R&D enhanced yield levels at the frontier, but also reduced the rate of absorption within the frontier. This is the reason that the evidence is consistent with a reduced rate of "catching up" within the private sector-dominated crops (compared to those within the public sector). Countries that start out behind in crop yield are falling further behind. This is evident in a plot of initial yields on growth in yields. There is no convergence evident in the case of the private R&D sectors (maize and sorghum) while there is some evidence to support convergence of yields in the other crops. (see Figure 3)

[Insert Figure 3]

This is all evidence of a relatively reduced rate of diffusion in the private R&D sector that causes the distribution of benefits from technological change to be concentrated along the frontier. Of course the higher rates of yield in the private sector will at some point result in higher yields everywhere, so long as there is some sort of process of diffusion. The question is whether the countries of the frontier benefit sufficiently from the higher yields to make up for the reduced rate of diffusion. Our estimations indicate that the present value of the relative “loss” is approximately doubled to a country off the frontier, depending on whether technological change has occurred within the private (maize) sector or the public (soybean) sector. In both cases there is some lag resulting from its situation off the frontier *a la* Hayami and Ruttan, but in the case of the private sector that loss is effectively twice the size that of the innovations sourced in the public sector. Benefit diffusion and hence distribution is being reduced for those innovations sourced within the private sector.

3.4 Institutions and Diffusion: Public and Private Sector Roles Explained

Technological change has differential impacts, when things are not equal. One of those things is the institutional background against which technological change in agriculture is occurring. Agricultural research and development is a system that makes use of factors - from many if not most parts of the world - in producing its outputs. Plant breeding (as described above) has been a joint enterprise and not a "stand alone" entity. These outputs are then widely-used in modern agriculture, as part of a comprehensive system of agriculture, and the benefits are distributed in accordance with various arrangements and negotiations. A change must be assessed against the background of this institutional structure.

It is important to emphasise that the R&D industry in plant breeding, although centred in the developed world, relies heavily on inputs from the developing. The production of a new plant variety involves, at a minimum, human inputs (scientists), capital inputs (land, laboratories) and natural inputs (diverse genetic resources). While the former are primarily generated in the developed world, the latter are often sourced in the developing. Production function studies have estimated that diverse genetic resources provide nearly a third of the contribution required for the production of new plant varieties. (Evenson and Gollin 1998) It is in this sense that the production of R&D has been a joint enterprise, relying upon inputs from across the world to generate final outputs, both collections of resources and their selective breeding.

To some extent the entire matter has been confused because of an identity between certain suppliers and certain consumers within the industry. Farmers both supply the R&D process (with genetic resources), and then also purchase its ultimate outputs. It is important that the benefits from the R&D process be appropriable (at the end of the pipeline, i.e. by the plant breeder) but it is equally important that the contributions of the various factors of production be compensated. These two separate problems were confounded, and farmers came to expect to receive their share of modern agriculture's benefits through the process of diffusion within the production process.

In the past the public sector has acted to diffuse innovations as a means of encouraging agricultural development and compensating contributions to it. Wherever an innovation originated, the public sector often acted as the catalyst for adopting and adapting it to local conditions worldwide. If public sector acts to diffuse innovation rapidly enough, then any inequities in the initial distribution of rents is ameliorated.

This public investment in technology transfer between developed and developing worlds has previously taken the concrete form of international investment in the Consultative Group on International Agriculture Research and its various research stations around the world (CIMMYT for maize research, IRRI for rice research). It has also taken the form of various bilateral and multilateral investments in "national agricultural research" stations across the world. One of the most important functions of such investments has been to enhance the rate of diffusion of new technologies from the frontier states (in the developed world) to the needs and uses of the developing countries.

This brings us back to the point about distribution and diffusion. Technological change plays an important role in distributional considerations, only to the extent that institutional or other differences influence the rate at which new technologies diffuse across countries. For some reason, private sector R&D has created substantial distributional differences, and this must indicate that there has been a failure of diffusion in both the private and the public R&D sectors.

The basic explanation for the pattern of growth is that private sector investment in R&D has been focused on the technological frontier and less-so on the countries within the frontier. This may be for historical or climatic conditions, but in any event it is apparent in the data. This may be obvious in the first instance, since enhanced property rights systems must necessarily be given effect by disabling free diffusion; however, this simply indicates that some sort of contract or transaction is required before diffusion is allowed. For some reason these contracts or transactions have not occurred readily across the developing world, meaning that the enhanced property right system has also translated into reduced diffusion. The first point to take away from this experience is that private sector R&D has reduced diffusion rates while enhancing frontier growth, on account of a private sector failure to invest in diffusion.

This failure of private investment might have been counteracted by public investments, as was often the case in the past. The public sector investments in technology transfer could be used as an alternative mechanism for aiding diffusion where the private sector failed to act. Even if innovators were able to capture a greater share of their innovation's benefits, the public sector investment could then provide other countries with the capacity to observe and to understand the information embodied within the innovation. Then the other countries would be able to reproduce that information in an innovative form that most suited the situation of that country. Hence public investments in "technology transfer" can act as a means for encouraging the rate of diffusion from the technological frontier.

Clearly there has been a change in private sector R&D that has both caused reduced rates of diffusion and also reduced the effectiveness of public transfer of innovation from the private sector. The private sector has not only failed to invest in diffusion where it entered, but it has effectively braked the effectiveness of the public sector in these fields as well.

Therefore, the introduction of the private sector into agricultural R&D in the twentieth century has resulted in three distinct phenomena: 1) increased yield-generating innovation in the private R&D sector (relative to the public); 2) reduced rates of diffusion of those innovations by the private sector to the countries within the technological frontier; and 3) reduced rates of diffusion of the innovation within the private sector by the public sector. Agricultural development has increasingly become a bifurcated system, between a public sector focused on its varieties and a private R&D sector focused on its own - with much less capacity for complementarity or interaction. Those countries reliant upon the public sector fall further from the technological frontier in those crops within the private sector, while those countries on the technological frontier advance more rapidly. Given this, there is a widening gap between the "haves" and the "have nots" under the private sector regime. It has effectively disabled the ability of the public sector to act to enhance diffusion in these fields. There has been effective "crowding out" of the public sector, without the private sector taking on the role.

4. The Future of Proprietary Rights in Agricultural Development: BioTechnology and Industry

Two developments in 1980s and 1990s changed the future of agricultural development significantly. The first was the Chakarbarty decision opening the door to the patenting of multicellular plants and animals in the U. S. Traditional (original) patent protection has been provided to inventors in the chemical, electrical and mechanical fields of invention for many years, but this was expanded to biological innovation in 1980 by a US court decision. In the case of Diamond vs. Chakarbarty (447US 303[1980]), the court ruled that multicellular living plants and animals were not excluded from patent protection.[15] Further, court rulings in *ex parte Hibbard* for plants (227 USPQ 443(1985) and for animals, *ex parte Allen* (2 USPQ 2d 1425) reaffirmed this. This opened the door to patenting of plants, animals and of genes and gene constructs.[16] The second and more important development was the advent of bio-technologies which enabled the extension of use restriction strategies biologically. Patents were taken out on forms of genetic alterations that would enable plant breeders to "switch off" any characteristic of a given organism, including its reproductive capacity. This capability would effectively enable the translation of the use restriction strategy inherent within hybrid varieties to all other plant forms. To some extent this technologically based use restriction made the legal form of protection irrelevant from the outset. The future most likely belongs to genetic use restriction technologies, not legal system-based use restrictions.

Technologically enforced use restriction brings with it an entirely distinct form of R&D system. In effect the future would appear to be one of forecasted "regime change", in which world agricultural R&D shifts from being primarily public sector-based to being primarily private sector-based. The advent of enforceable proprietary rights in agricultural innovation means that it will now be possible to extend the experience with private R&D in hybrid crops to all other varieties. If the experience is in fact replicated, this does not bode well for those countries furthest off the technological frontier. The hybrid crop case study discussed previously was one in which the private sector failed to invest heavily in diffusion, and also made it more difficult for the public sector to perform that function in its place. If this "crowding out" is witnessed across agriculture, a relatively higher rate of innovation-based growth will be complemented by a reduced rate of diffusion. The gap between the "haves" and "have nots" will become broader and more generalized.

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[15] Other IPR systems have not fully adapted US practice in this regard, but the WIPO-TRIPs agreement puts pressure on many countries to follow the US lead on this.

[16] The Board of Patent Appeals and Interferences of the US Patent and Trademark Office has interpreted Diamond v. Chakarbaty to mean that any plant can be patented provided that it satisifes the basic standards for patentability. The US Supreme Court in JEM. Ag Supply vs. Pioneer Hybred Int. Inc. (534US124 (2001)) agreed with this interpretation and ruled that the availability of plant variety protection was not in conflict with patent regulations for plants.

4.1 Proprietary Rights in Plant Varieties and the Future of Use Restriction

The marketing of hybrid varieties enables the sale of innovative characteristics without the bundled sale of the technology for reproducing these characteristics. Thus innovative hybrid crop varieties are marketable by their breeders without the threat of reproduction and re-sale by the consuming public. Hybridisation was the first technology used as a method for 'use-restriction' in plant breeding. It would be a very short-sighted industry indeed that did not appreciate the commercial importance of this difference, and did not consider the possibility of extending this characteristic to other crop varieties. The advent of new biotechnologies reduced the barriers between various species (including plant varieties). The possibilities for transferring desirable traits between species were expanded as never before. An obvious "next step" within the plant breeding industry was to investigate the translocation of these use restriction technologies through genetic transference.

The area of biotechnological research and development focused on the problem of appropriability is referred to as "genetic use restriction technologies" or GURTs. GURTs come in two distinct forms, at least theoretically. (Goeschl and Swanson 1991; Swanson 2003b) Variety-based GURTs (V-GURTs or "Terminators") are plant varieties that are not reproducible in any way by the purchaser. The basic idea is to create a seed that will generate the desired plant variety that itself generates sterile seed. (Crouch 1998) Thus, with V-GURTs the purchaser acquires the innovative plant variety without acquiring the technology for reproducing any part of the plant. Trait-based GURTs (or T-GURTs) are plant varieties with the potential for innovative traits, but requiring the application of a complementary product (an initiator) that causes the trait to come to fruition. With T-GURTs the purchaser acquires the reproductive technology for the standard plant variety, but must purchase the complementary product to acquire the benefits of the innovation. It should be noted that neither technology is yet in commercial use, but both are feasible.

GURTs is the area of research concerned with the technological resolution of the problem of appropriability that so severely afflicts the plant breeding industry. Agriculture has evolved into an enterprise heavily dependent on research and development, represented by the cycling of widely-planted varieties subjected to increasing pest and pathogen problems. The international legal system has struggled to create an incentive system capable of rewarding such research and development investments, on account of the asymmetry between the nationalities of investors and users. Technology has stepped up to fill this gap by evolving the means by which use restrictions might be built into most crop varieties.

Thus a very important part of the biotechnology revolution in agriculture concerns this fundamental change in the industrial structure of agriculture. Biotechnologies are pursued for profits by the private sector, and the solution of the appropriability problem in plant breeding is an important potential source of increased profitability. Much early effort has gone into developing the technologies for enhancing the appropriability of returns from innovation, rather into innovation itself. Thus the pursuit of GURTs in biotechnology is predictable, and probably unavoidable. It is the future of proprietary rights in agricultural development and will, in practical effect, result in the translation of the experience with the hybrid varieties to agricultural R&D more generally.

4.2 Impacts of Technological Enforcement – Static and Dynamic Dimensions

The move to technological enforcement has relatively straightforward static implications, but more complex dynamic ones. Statically, the shift to universal and uniform enforcement of property rights will enable producers to capture a much more significant share of the rents from production. That is, the first implication is a shift of consumer surplus toward producers. In addition, it may be possible for producers to engage in more refined forms of price discrimination, and thus to both shift consumer surplus toward producers while simultaneously avoiding deadweight loss.[17] In static terms, the advent of technological enforceability is a straightforward redistribution of surplus from consumers to producers.

What are the dynamic impacts of GURTs – their general impacts on diffusion? We saw in the previous section that the experience with the hybrid crops indicated that diffusion was delayed, but here we wish to investigate why this might be the case. The GURT technology enables the producer to sell its innovative product without selling the reproductive technology bundled along with it. This allows the price of the seed to be set at the "single use price", while allowing the purchasers individually to elect the number of years in which to purchase the product. This means that some purchasers may choose to purchase the innovation for use in a single year, while others may choose to use it each year for a number of years. Others may disdain the innovative feature, and elect not to purchase the variety at all. In the abstract such a change in marketing technology can only be to the benefit of both producers and consumers. This is because it enables the finer segregation of the market, and allows for the specific targeting of individual user's needs. Users may decide on an annual basis whether they are willing to pay the price for the innovative feature.

The problem with this approach is that it elides the issue of the available alternatives. In the first years of use of GURTs, the consumer has a clearly welfare-enhancing choice. It makes use of the freely-available standard plant variety, or it makes use of the standard plant variety with the innovative trait imbedded within it. The user makes the decision whether, given individual conditions, it is willing to pay the market price for the innovative trait or not. If the user is willing to purchase the use of the trait for that year, then it clearly must be welfare-enhancing for it to do so. In this regard, GURTs may be analogised to the sale of an annual license for the use of new software (the innovative trait), and the consumer is allowed the individual choice on whether to acquire the license or not.

The problem is that in the case of plant varieties the software and the hardware become commingled over time. If the plant breeding industry introduces traits only within the context of GURT varieties, then over time the freely-available standard variety may come to be something very unlike the variety into which the innovative traits are imbedded. That is, the proprietary traits may be allowed to accumulate within the commercial sector, without allowing their diffusion into the public arena. Then the commercial breeders would be able to work with the commercial "hardware" (by paying for licenses for one another's innovations) while the public sector breeders (individual farmers, universities, government researchers) may be left with antiquated varieties as their alternatives. Within five or ten years, there may be no real alternative to the use of the GURT varieties, because the

[17] This would occur by reason of enabling producers to sell multiple year licenses to those users who desired further use of the variety, and single year licenses to those who desire only a single use. (Fisher 2002)

hardware within the public sector would be without a decade's worth of developments. Then users would become wholly dependent on the plant breeding sector for their seed.[18]

GURTs provide even more substantial protection than would perfectly enforced intellectual property rights. Unlike intellectual property rights, there are no time limitations on GURTs. Unless the state concerned has the biotechnological capability to reverse engineer the GURT variety, the trait is not reproducible through conventional breeding technologies. This means that a GURT-protected innovation remains protected indefinitely. Individuals and nations without biotechnology capabilities have only two very stark choices: purchase the technology or live without it. And this choice becomes even more stark over time, as other traits and technologies become available that are dependent on the purchase of the first.

Therefore, in addition to technological enforceability, GURTs are unlike IPRs in that they have the capacity to accumulate and they do not erode over time. These two aspects of GURTs contribute to their tendency to inhibit diffusion. New innovations become bundled together within a single plant line, and the requirement to purchase them on an "all or nothing" basis means that innovations are not available to diffuse individually. It also means that there is no period after which the innovation becomes part of the basic capital stock for general R&D; it forever remains a purchasable innovation. In some respects, GURTs does not merely inhibit diffusion, it would actually prevent it altogether.

4.3 Forecasting the Impacts of Use Restriction in Agricultural Development

How then will genetic use restriction affect the average country? We can extrapolate from the hybrid experience to find out. This approach indicates that the impact of enhance proprietary rights all depends on the circumstances affecting that country. Figures 4 to 7 report the expected impacts graphically over a 20 year time horizon for four different countries (based on their experiences with hybrid crops).[19] The forecasts show that the individual country experiences vary quite considerably. In developed countries (fig.1), the adoption of user restriction results in higher growth rates in yield and a more favourable yield development over the 20 year time horizon. This is because the developed countries exist on the technological frontier where all technological change occurs. Enhanced appropriability involves no trade-offs for these states.

Figure 4

There are developing countries where the experience is very similar to developed countries, but arises in a slightly delayed fashion: In China (fig. 5) for instance, yields in the first ten years are expected to be very similar under both scenarios. Then the impact of use restriction on the yield frontier begins to push yields in China above the baseline. China is an example of a developing country that is very near the technological frontier in terms of agricultural production of maize, and so the delayed diffusion has little impact. The case of Ethiopia (Figure 6) illustrates a country that in the short run would be better off under the current regime, as the flow of innovations would diffuse more rapidly. However, towards the end of the 20 year horizon, the more rapid expansion at the technological frontier has compensated for the slower diffusion inherent in this regime. Ethiopia is an

[18] Unlike the situation at present where 80% of farmers in developing countries use retained seed.
[19] The study from which these simulations derive is reported in Goeschl and Swanson (2002a).

example of a mid-tier developing country in terms of agricultural development. It tends to benefit from the advent of enhanced use restriction only in the medium term.

Insert Figures 5 and 6

Lastly, the case of Tanzania (Figure 7) illustrates a case where for the foreseeable future, the country would be worse off under a use restriction scenario than under a perpetuation of the current regime. Tanzania is an example of a developing country that falls furthest from the technological frontier. Due to lack of investment and institutional frictions, innovations diffuse very slowly to these states under existing institutions. The advent of additional use restrictions renders a bad situation worse for these states.

Insert Figure 7

These four cases illustrate the range of outcomes that can be expected as a result of the potential adoption of genetic use restriction technologies, and the shift away from IPR regimes as the means of enforcing intellectual property. This diversity implies that over a policy-relevant time horizon, countries will not be indifferent as to the regime adopted, depending on the initial conditions of the country concerned. The figures above demonstrate that the most advanced countries stand to benefit most from use restriction while the least advanced stand to lose most.

As stressed before, when projected sufficiently far into the future, the productivity gains that the stimulation of private R&D through use restriction delivers result in the baseline scenario being overtaken in every state. However, the value of these future gains may be perceived to be insufficient for developing countries to outweigh the mid-term losses. It is interesting to note that even if GURTs led to a doubling of the rate of innovation seen in hybrids at the same rate of diffusion, it would take more than 10 years in the case of Tanzania for yields under use restriction to outperform the baseline yields.

In conclusion, the history of the maize hybrid experience indicates that the shift in the growth trajectory from technological enforceability must lead in the very long run to higher yields everywhere. However, most countries, and particularly the least developed ones, will first have to pass through a phase of losses relative to the present regime. These relative losses are the consequence of a reduced rate of diffusion from the technological frontier to those states within. Depressingly, if history repeats itself, this means that the poorest countries will benefit least from this regime change while the developed countries benefit most. For the very poorest of the poor, it is unlikely that the net present value of this regime change would be positive.

This outcome need not necessarily result from the advent of technological enforceability, but it has resulted once (in the case of hybrid maize). The aggregate outcome from regime change is determined not just by increased appropriability, but also by the investment patterns that result from it. The historical experience with hybrid maize indicates that the developed world did not respond adequately to enable all states to benefit equitably from the enhanced rate of innovation. If the same outcome results from GURTs, the inequalities within the global distribution of benefits from agricultural innovation will be accentuated.

4.4 Assessing the Full Meaning of Regime Change

In the agricultural sector, at least, it is possible to foresee the implementation of a proprietary rights system of near-perfect enforceability as the means for channelling returns from innovations to innovators. The advent of genetic use restriction technologies (GURTs) foretells of a future in which seed patents and plant variety legislation is a "thing of the past". Future biological innovations will be protected biologically, and enforced perfectly. This means that the current system of domestically enforced IPRs will be displaced by a globally uniform system of property right enforcement. Innovators will no longer be dependent upon domestic regimes for the protection of their rights. This also means that individual states will no longer have the discretion to select where their state will lie on the innovation-diffusion trade-off. Every state will exist within a "one size fits all" system that has perfectly enforceable innovation appropriation.

The analysis of the hybrid experience indicates that the impact of such a regime change will depend a lot on the initial situation of the state concerned. Perfectly enforceable intellectual property rights make perfect sense for those countries existing at the frontier, but they will have very different implications for those countries that innovate very little but benefit greatly from the diffusion of innovation. The impact of perfectly enforceable rights for these (less developed) countries is to restrict the free flow of innovations.

It is not necessarily the case that the restriction of the "free flow" of information need be a bad thing, even for the poorest of countries. If firms and states at the technological frontier would make the effort to diffuse the information (once it no longer flows freely) then it would be possible for the poorest countries to benefit as well. However, public sector and private sector investment in the poorest countries would be required for this to be the case.

Is it likely that the shift in regimes will be accompanied by this shift in investment? We have experience to indicate that it is in fact highly unlikely to be the case. The 40 year long history of experience with hybrid (use restriction) technologies is one of enhanced rent appropriation but little change in investment patterns. This implies that implications of the technologies for poorer countries are not good. Developing countries have seen the benefits from these new technologies, in terms of the diffusion of innovation, diffuse even more slowly than those of non-hybrids. This means that enhanced rent appropriation is not changing the diffusion of innovation, but mainly the distribution of rents.

In short, the advent of technological enforceability within biotechnology appears to have some seriously negative implications for developing countries, and especially the poorest of the lot. The IPR system at least has the in-built the capacity for individual countries to take into consideration their individual circumstances when determining the extent of implementation and enforcement. The shift to genetic use restriction technologies removes the option to tailor the system to individual circumstances, and (without other changes that do so) this causes problems for those countries that are far off the technological frontier.

The movement toward a globally uniform system of innovation protection requires that global investment patterns change to reflect that movement. At present the differences between countries are taken into account, in part, by reason of the manner in which different countries approach the IPR implementation and enforcement problem. Some countries focus most on rent appropriation and innovation, while others focus more on diffusion of existing innovations. The fact that IPR regimes require a component of national enforcement to be made effective enables different countries to elect where they stand on this spectrum. The other part of the equation that deals with national differences is the role of public sector investment in diffusion, where the private sector is lacking. This distinctly second-best world of un-enforced IPR and public diffusion of innovation is the mechanism by which diffusion is aided for those furthest from the frontier.

A globally uniform system of use restrictions and enforcement will disable this heterogeneous system, and it will impose a standardised system on a heterogeneous world. This can be beneficial if the industry and the public sector were to respond to the changed system in the appropriate fashion, in order to encourage diffusion where it is restricted. This can be disastrous if the uniform system is imposed without other changes (in investment and diffusion) also occurring at the same time.

5. Conclusion

In this chapter we have attempted to outline the process by which proprietary rights have evolved in regard to agricultural R&D. Although R&D in this sector has always been important, it has only in the past few decades had any significant private sector component. Prior to that time, the mere fact of reproducibility in biological organisms made every user a practitioner of R&D and hence rendered prospects for entry into the industry forbidding. In the 1930s, the discovery of hybrid breeding techniques made reproducibility difficult, and made entry into the R&D plausible.

The introduction of proprietary rights systems into agricultural R&D has generated a puzzling outcome. On the one hand, it produced the anticipated growth effects resulting from enhanced investment in innovation, but on the other hand it also reduced the rate of diffusion of these innovations away from the frontier. The private sector seemed to have the effect of disarming the capacities of the public sector to engage in diffusion without replacing it with its own investment in that activity. This is a puzzle, since there should be incentives to invest in diffusion rather than simply to invest in innovation on the frontier. It would seem to be another example of “orphan R&D”, in which obviously profitable R&D transactions are not pursued.

For this reason it is not possible to be sanguine concerning the prospects for future agricultural R&D activities. As the proprietary rights in agricultural innovations are extended to other crops, it would be disastrous if the same experience was replicated. Then the poorest countries in the world could find that they have less access to technology and to innovation than before, falling further and further behind the frontier. The inability of the public sector to access or to diffuse innovations, on account of technological use restrictions, would leave both the poorest countries and the public sectors helpless to respond.

It could be that this means that the public sectors and poor countries must continue to operate in the traditional R&D sector, rather than to become wholly reliant upon the private bio-tech one of the future. However, it is to be anticipated that the gap between the two technologies will only widen more over time, leaving the poor countries independent but equally far behind. This is not a solution to the problem of diffusion-based inequality.

The case of agricultural development demonstrates that IPR can carry a sting in its tale. The shifting of public and open information based exchange and innovation toward a restrictive and proprietary private sector can generate an unhealthy dependence. Once the technology becomes a "closed" one, society is dependent upon the industry to act in accordance with incentives and societal interests. When, as in the case of orphan R&D, the industry refuses to act, the problems remain unsolved and (to some extent) unsolvable.

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Figure 1 Genetic Resource Collection

Crop	Accessions (000)	Percent in Collection	Storage %				Types %			
Cereals			LT	MT	ST	Other	WS	LR	BL	Other
Wheat (Triticum)	789	95	13	48	4	35	3	18	19	60
Wheat (Aegilops)	21	95	10	40	0	44	51	0	0	44
Wheat (Triticale)	40	40	0	56	0	44	0	0	54	46
Rice (*Oryza*)	420	90	34	22	13	31	1	25	9	65
Maize (Zea)	262	90	25	38	10	26	0	17	11	65
Sorghum (Sorghum)	169	80	25	31	17	27	0	18	21	61
Millet (Elousins)	15	88	12	35	31	22	0	28	2	70
Millet (Evagrastis)	4		0	80	0	20	0	80	0	20
Millet (Setoria)	90		22	58	10	10	0	8	0	92
Pearl Millet (Pennisitum)	39		12	69	6	14	5	53	12	81
Barley (Horderm)	487		10	42	2	46	1	10	11	82
Oat (Avena)	233		19	38	7	72	5	2	6	88
Rye (Secalo)	27		12	36	4	47	6	1	8	90
Food Legumes										
Bean (Phaseola)	268	50	14	29	5	53	1	21	3	76
Bean (Psophocarpus)	5	60	0	0	21	79	0	21	0	79
Soybean (Glysine)	176		24	25	8	42	1	2	7	91
Chickpea (Cicer)	70		11	53	1	31	1	38	7	51
Lentil (Lens)	27		13	31	0	51	3	28	4	59
Faba Beans (Vicia)	32		19	38	3	32	0	39	11	42
Pea (Pisum)	75		10	19	2	66	0	4	7	84
Groundnut (Avachigs)	81		16	17	14	53	1	15	11	72
Bamb Groundnut (Vigna)	4		59	0	0	41	0	100	0	0
Cow Pea (Vigna)	86		23	44	1	32	2	19	1	78
Pigeon Pea (Cajanum)	25		10	46	0	44	2	50	7	41
Lupin (Lupinus)	31		3	31	4	53	14	11	9	38
Cotton (Gossypium)	49		6	0	0	94	1	6	8	85
Flax (Linum)	25		0	34	18	49	0	2	6	92
Jute (Cochorus)	3		62	0	0	38	0	50	9	41
Beverages Crops										
Cocoa (Theobroma)	9		0	0	0	100	2	0	0	98
Coffee (Coffea)	21		0	0	0	100	29	0	22	49
Opium (Popauer)	7		0	47	0	53	0	0	0	100
Miscellaneous										
Arabidopsis (Arabidopsis)	27		30	0	0	70	3	0	27	70
Oil Crops										
Sunflower (Helianthus)	29		0	1	24	75	3	9	54	39
Palm (Elaeis)	21		0	0	0	100	8	0	82	10
Sesame (Sesamun)	18		19	17	7	56	0	0	0	100
Safflower (Corthamus)	8		0	37	0	63	0	0	0	100
Castor Seed (Ricinus)	3		0	0	0	100	0	0	0	100
Sugar Crops										
Beet (Beta)	24		1	48	0	51	23	6	23	49
Sugarcane (Saccaharum)	22	70	0	0	0	100	0	0	0	100
Forage Crops										
Legumes (varlius)	67		20	32	0	48	42	12	0	4
Clover (Trijolium)	78		15	33	3	46	33	1	13	50
Medicago (Medicgo)	53		6	12	0	40	19	0	0	39
Vicia (Vicia)	26		15	24	0	61	27	0	0	73

Pea (Lathyrus)	13		5	95	0	0	74	1	0	25
Trefoil (Lotus)	4		0	50	0	50	0	0	0	100
Grasses (Various)	39		0	10	0	23	16	0	1	17
Grasses (Dactylia)	38		0	60	0	40	3	7	46	44
Fescue (Festuca)	24		0	29	0	71	5	18	1	76
Millet (Panicum)	21		1	5	5	89	0	3	0	97
Grasses (Pao)	8		0	29	0	71	5	18	1	76
Grasses (Bromus)	4		0	52	0	48	0	0	0	100
Grasses (Cenchrus)	2		50	0	0	48	52	0	0	48
Grasses (Andropogan)	2		0	0	0	100	0	0	0	100
Phleum (Phleum)	9		0	55	0	45	0	53	2	45
Rye (Elymus)	3		0	0	0	100	0	0	0	100
Roots & Tubers										
Potatos (Solanum)	30	95	12	8	12	67	5	12	20	61
Sweet Potato (Ipomoea)	32	50	8	12	0	79	6	16	13	65
Cassava (Manihot)	30	35	0	8	0	92	1	21	12	66
Yam (Discorea)	12		0	25	0	75	0	24	1	75
Vegetables										
Mustard (Brassica)	82		13	7	13	67	0	15	6	79
Rape (Brassica)	22		0	23	17	60	0	19	17	65
Tomato (Lycoporsicum)	78		10	15	7	61	51	1	20	22
Capsicum (Capsicum)	54		4	31	17	48	0	6	15	79
Allium (Allium)	25		7	21	8	63	0	13	6	82
Cucurbita (Cucurbita)	17		7	43	0	50	0	18	0	82
Egg Plant (Solanum)	92		0	0	0	99	0	0	0	98
Melon (Citrullus)	4		0	89	0	11	0	0	0	100
Radish (Raphanus)	5		0	22	0	78	0	22	0	78
Carrot (Dacus)	6		24	29	0	47	8	0	16	76
Fruits										
Apple (Malus)	98		0	1	0	99	0	5	49	46
Prunes (Prunus)	64		0	0	0	100	2	2	27	68
Grape (Vitus)	47		5	0	0	95	0	7	20	72
Cantiloupe (Lucumis)	14		18	68	0	14	0	4	8	87
Lemon (Citrus)	6		0	0	0	100	0	0	0	100
Nut (Pnarcardium)	6		0	0	0	100	0	0	0	100
Peach Palm (Bactris)	3		0	0	0	100	0	0	0	100
Ribes (Ribos)	13		0	0	0	100	1	1	3	96
Rose (Rosa)	10		0	0	0	100	6	1	15	79
Sorbus (Sorbus)	2		0	0	0	100	3	1	31	66
Strawberry (Fragaria)	14		0	0	0	100	12	0	17	71

Storage %
LT Long Term
MT Medium Term
ST Short Term

Types %
WS Wild Species
LR Land Races
BL Breeding Lines

Figure 2. Percentage of all Corn Acreage Planted to Hybrid Seed

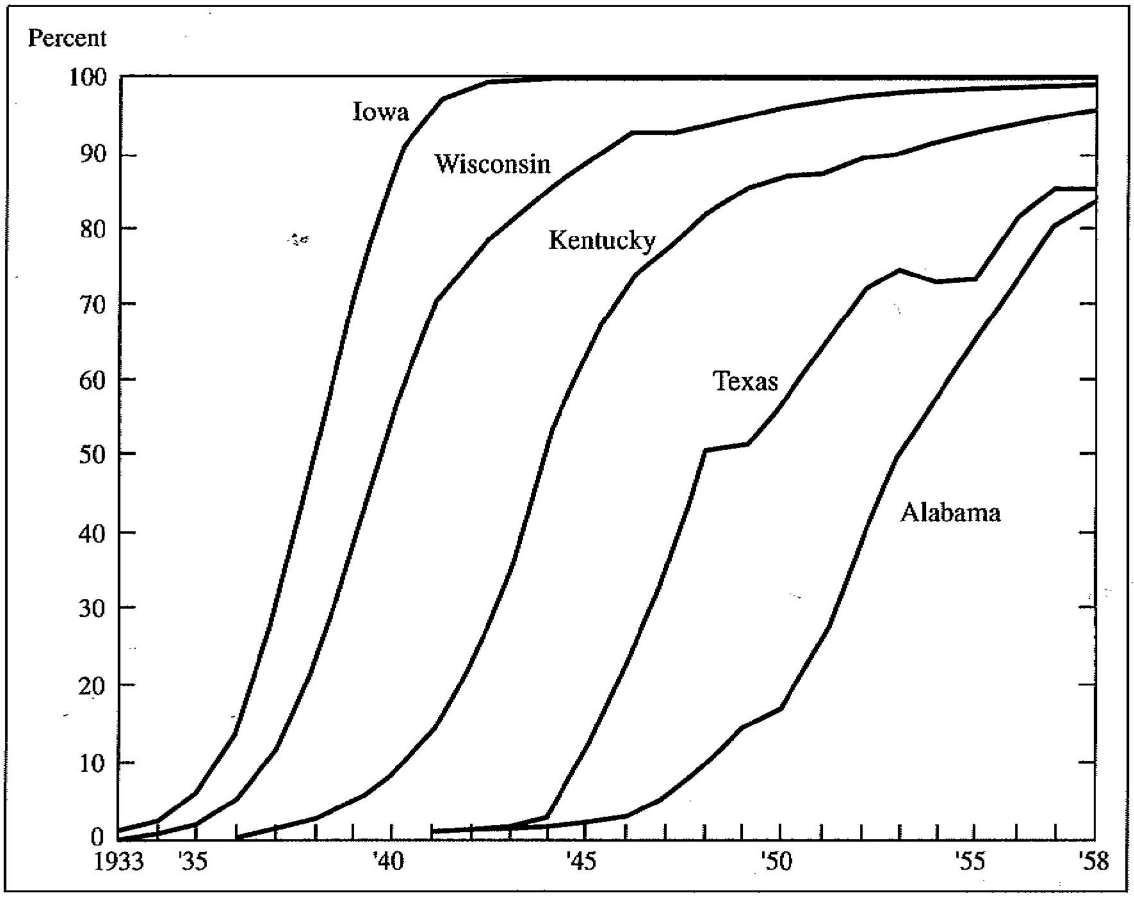


Figure 3: (see end of paper)

Figure 4: Impact of Technological Enforcement in Developed Countries

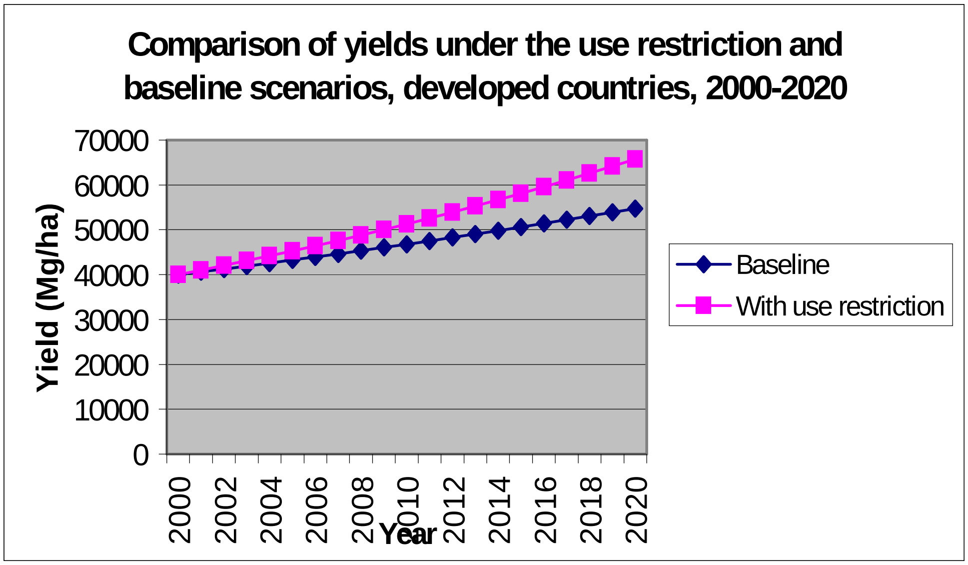


Figure 5: Impact of Technological Enforcement in Developing Countries (China)

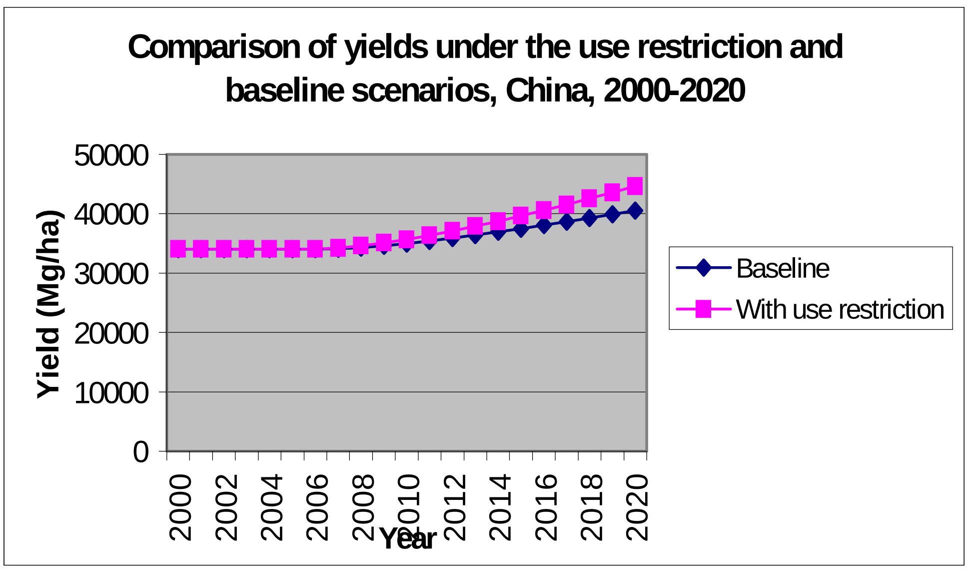


Figure 6: Impact of Technological Enforcement in Developing Countries (Ethiopia)

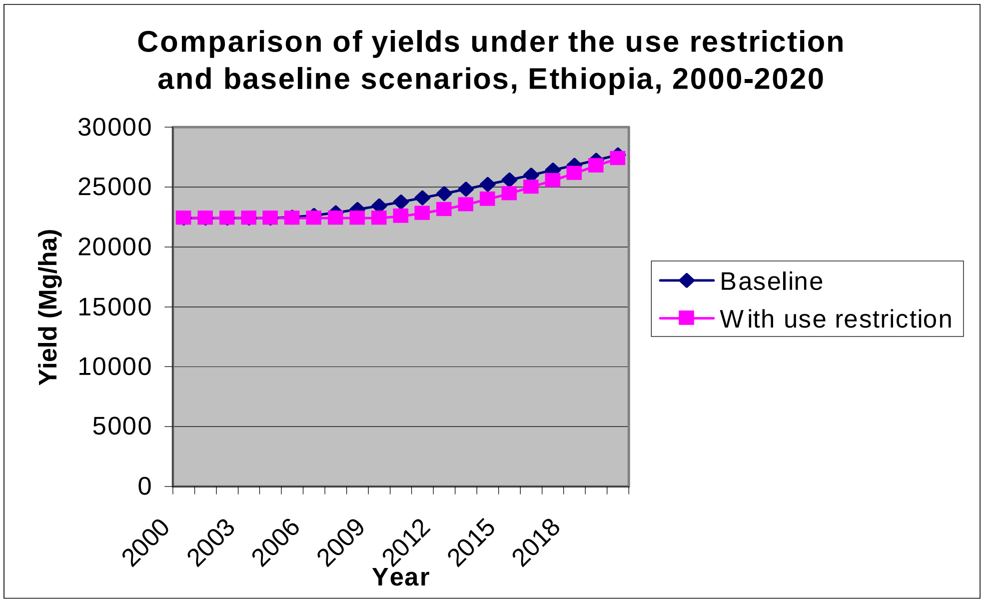


Figure 7: Impact of Technological Enforcement in Developing Countries (Tanzania)

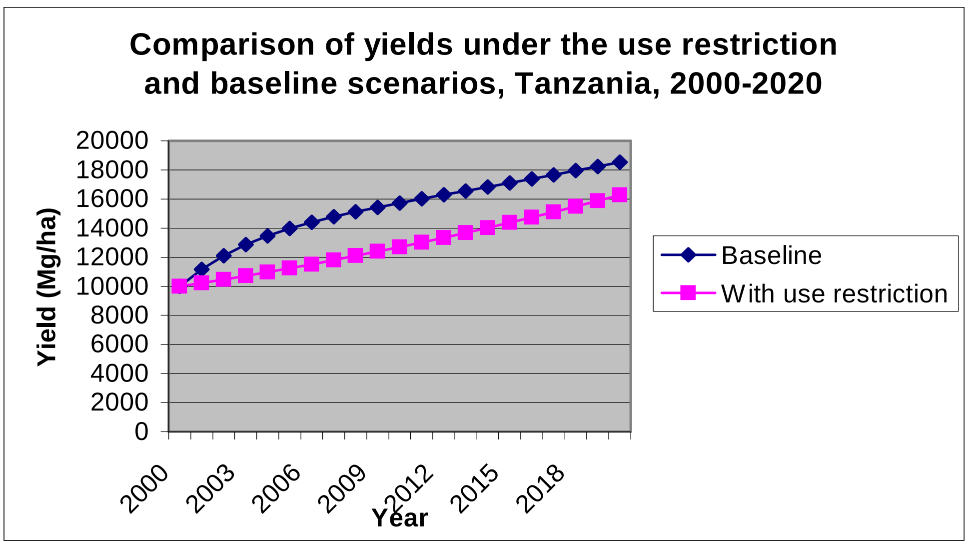


Table 1: Global Expenditures on Agricultural Research in 1995 (millions 2001 US Dollars)

	1965	1976	1985	1995
Public Sector Agricultural Research				
Developed Countries	**6532**	**8270**	**10192**	**11900**
Developing Countries				
China	**377**	**709**	**1396**	**2036**
Other Asia	**441**	**1321**	**2453**	**4619**
Middle East-North Africa	**360**	**582**	**981**	**1521**
Latin America & Caribbean	**562**	**1087**	**1583**	**1947**
Sub-Saharan Africa	**472**	**993**	**1181**	**1270**
International Agricultural Research Centers	**12**	**163**	**315**	**400**
Private Sector R&D in Agriculture				
Developed Countries				10829
Developing Countries				672

Source: Pardey and Beintema (2001) and Boyce and Evenson (1975)

Table 2: Public Agricultural Research Intensities

	Expenditures as a Share of Agricultural GDP			Expenditures Per Capita		
	1976	1985	1995	1976	1985	1995
Developed Countries	**1.53**	**2.13**	**2.64**	**9.6**	**11.0**	**12.0**
Developing Countries	**0.44**	**0.53**	**0.62**	**1.5**	**2.0**	**2.5**
China	0.41	0.42	0.43	0.7	1.3	1.7
Other Asia	0.31	0.44	0.63	1.1	1.7	2.6
Latin America and Caribbean	0.55	0.72	0.98	3.4	4.0	4.6
Sub-Saharan Africa	0.91	0.95	0.85	3.5	3.0	2.0

Source: Pardey and Beintema (2001), Evenson Estimates for Sub-Saharan Africa

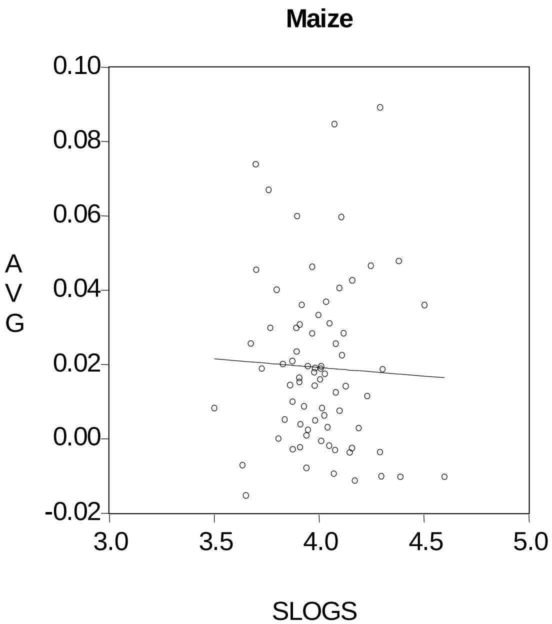
Table 3: Acreage, global distribution, growth and relative yield gap in 8 major crops

(Goeschl and Swanson 2001)

Crop	**Global Acreage in million ha in 1999**	**Share of developing countries[20] in 1999**	**Share of developed countries[4] in 1999**	**Growth Rate at the Frontier, 1961-1999**	**Relative Yield Gap in 1999**
Barley	**58.6**	**28%**	**72%**	**1.53%**	**-59.9%**
Cotton	**34.3**	**72%**	**28%**	**2.45%**	**-47.4%**
Maize (Hybrid)	**139.2**	**67%**	**33%**	**2.27%**	**-72.4%**
Millet	**37.2**	**96%**	**4%**	**0.93%**	**-57.4%**
Rice	**153.1**	**97%**	**3%**	**0.85%**	**-57.9%**
Sorghum (Hybrid)	**44.8**	**90%**	**10%**	**2.08%**	**-67.2%**
Soybean s	**72.1**	**55%**	**45%**	**1.24%**	**-40.0%**
Wheat	**214.2**	**48%**	**52%**	**1.75%**	**-54.5%**

[20] The definition adopted in this table is based on the FAO. This differs slightly from the established definition used in the wider literature. For the rest of this paper, we adopt the customary definition from (Pardey et al 1991).

Figure 3: Catching Up? - Growth in Yields versus Initial Yields in four crops (1960-1999)


Maize
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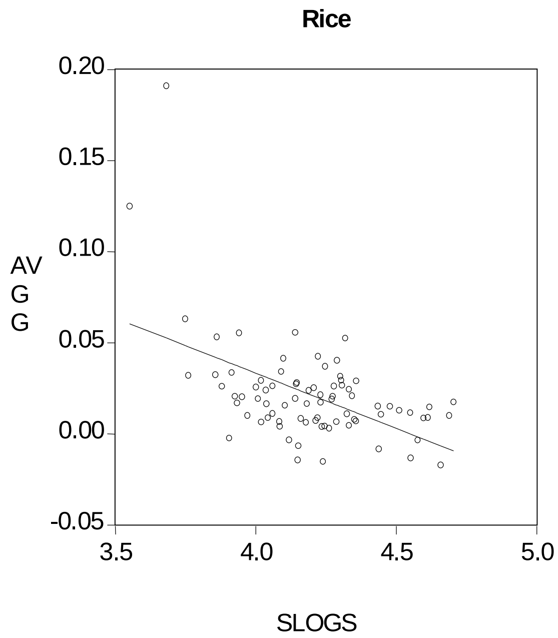
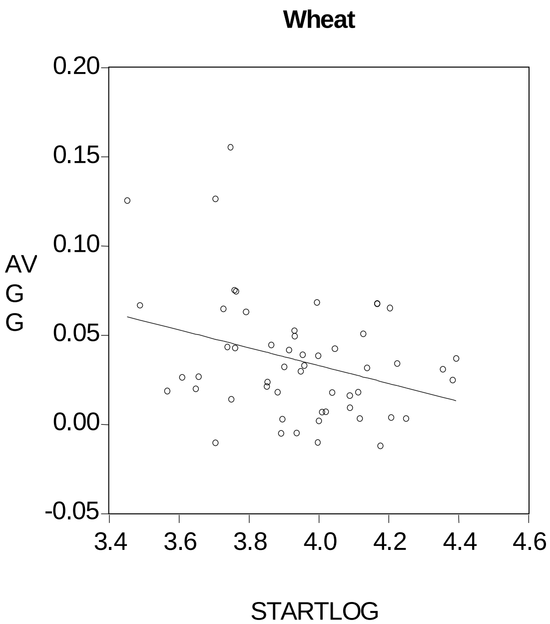
0.08
0.06
0.04
0.02
0.00
-0.02
A V G
3.0
3.5
4.0
4.5
5.0
SLOGS


Rice
0.20
0.15
0.10
0.05
0.00
-0.05
AV G G
3.5
4.0
4.5
5.0
SLOGS


Wheat
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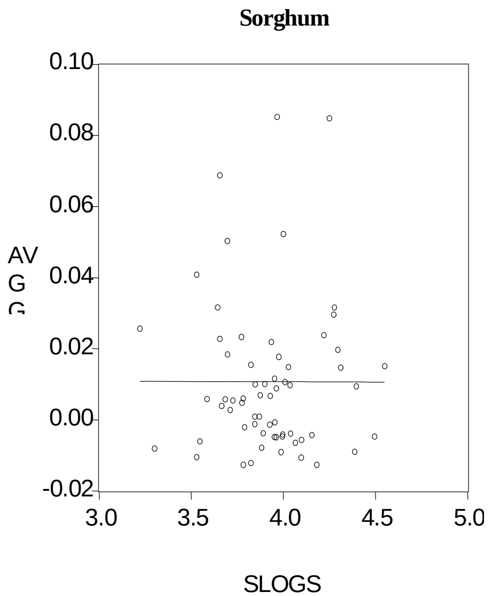
0.15
0.10
0.05
0.00
-0.05
AV
G
G
3.4
3.6
3.8
4.0
4.2
4.4
4.6
STARTLOG


Sorghum
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
AV
G
3.0
3.5
4.0
4.5
5.0
SLOGS