Science in improved farming systems: Reflections on the organization of crop research in the CGIAR

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Abstract
Increases in crop yield will be the principal path to meeting future world food needs. This paper reviews the history of the search for crop yield increases in the post-Green Revolution period within the CGIAR. The paper sets out a stage theory of increases in crop productivity, against which to understand the determinants of such increases under varying market and institutional conditions. The paper then reviews the experience with organizing crop management and varietal improvement research and in targeting such research to diverse farming systems and institutional settings around the globe. The changes in the organization of agricultural research is framed in regards to advances in the science versus an improved understanding in the conditions under which agricultural technology will be adopted by farmers. The paper concludes with reflections on the needs in organizing research to meet future increases in crop productivity.

Media Summary
The organization of crop research in the CGIAR has been an evolving interaction between new science and success in the adoption of new technologies.

Key Words
Crop productivity, varietal improvement, natural resource management, biotechnology

Introduction
Malthus, in his pessimistic extrapolation of the interaction between growth in population and in food supply, was documenting the history of mankind up to the beginnings of the industrial revolution. The subsequent science and technology development that underpinned the expansion in urban material culture in the latter part of the 19th century provided the institutional base for the application of science to agriculture. Agricultural research allowed the shift from production based on land extensive methods to intensive methods based on raising crop yields. Productivity increases unimaginable by Malthus allowed food production to grow at a rate ahead of population growth, sometimes spectacularly so. Nevertheless, although most parts of the world had at least nascent agricultural research capacity by the early part of the 20th century—in Asia and Africa arising from the importance of agricultural trade in the colonial system--, there were mixed abilities of countries to attain this yield take-off. Is this problem due to inadequacies in the organization and implementation of crop research—resulting in inappropriate design of agricultural technologies for local conditions-- or to ineffective economic, policy, and institutional structures for the application of agricultural technologies? Policy makers often argue the first side of the question and agricultural researchers the latter. The answer, however, is ambiguous because agricultural research and the agricultural economy interact to varying degrees. This interaction forms the thrust of this paper.

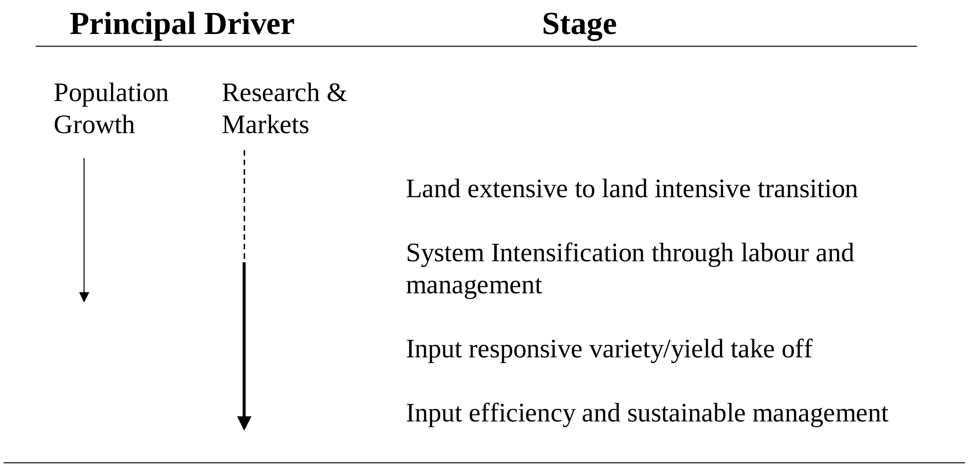
The basis of crop yield increase is at its most fundamental an interaction between a biological system and a socio-economic system. However, agricultural research is organized primarily around enhancements in the efficiency of biological systems, taking the farming systems, the agricultural market systems and the support institutions as a given. The design of these biological technologies draws on advances in the agricultural and biological sciences and in more detailed understanding of the socio-economic environment that conditions the use of these technologies, that is a mix of biological and social sciences. How to apply the advances in biological sciences within very diverse agricultural and farming systems is at the core of the agricultural research enterprise, with a key question of whether advances in biological sciences or advances in understanding of productivity constraints in target farming systems is the principal driver in the design of new technologies. Interestingly, the social scientist is a relatively recent addition to agricultural research, agricultural economists arriving only in the 1960's and social scientists only really establishing themselves after the Green Revolution. This paper draws on that body of work by first relating the adoption of crop technologies to differing market and institutional environments, then reviewing the interplay between science and farm characterization in the organization of research, and finally reviewing how recent advances in molecular biology are conditioning both the organization of research and perceived needs in the design of technology.

Stages in the Improvement of Crop Yield

Crop yield is dependent on the availability of soil nutrients, soil moisture and light, the protection of the plant from pest and disease attack, the partitioning of photosynthate to economic product (the 'harvest index'), and the efficiency by which the plant converts available resources into economic product. Crop research focuses on all four of these avenues to increased crop yield. The research directed to these alternative paths of enhancing crop yield can be divided between genetic and non-genetic approaches, ie between varietal improvement research and crop management research . Plant varietal research works on better adaptation of the plant to the environment, better tolerance to pests and diseases and more efficient plant types. Crop management research encompasses the cultural practices from land preparation to harvest, soil fertility maintenance, pest, disease and weed control, and irrigation, that is modifications of the environment for enhanced plant growth. These two principal research lines are very complementary, with crop management often providing from a half to two-thirds of the yield gain even in a Green Revolution scenario. However, development of breeding breakthroughs is closely associated with the yield takeoff in developed countries. The Green Revolution reinforced this seeming causality between genetic progress through breeding and yield take off in the agricultural sector. A principal point of this paper is that a range of prior investments and institutional innovations condition where varieties themselves will have such impacts. Moreover, while varietal improvement and crop management research positively interact, each has very different implications for how research is organized and technology is transferred, and in essence the conditions under which impact on yields is obtained. A focus just on breeding will under a range of conditions undercut the potential of achieving crop yield increases, especially in many parts of the developing world where agricultural research has yet to achieve significant impacts.

The modern history of crop yield growth is one of sequential stages in the increasing intensification of land use (Byerlee, 1994). As depicted in Figure 1, the initial stage is the transition from land extensive modes of production, for example fallowing and shifting agriculture, to permanent field systems (Ruthenberg, 1980). This transition is primarily driven by rural population growth, is critically dependent on a change in soil fertility management and associated changes in plant population and weeding practices, can require quite long time periods, and often results in degradation of the natural resource base. Such transition processes are still underway in many parts of Africa, the highland areas of Southeast Asia, and the Amazon basin of Latin America. As such they are often associated with deforestation and impacts on hydrological systems. Research directed to facilitating this transition process while preserving the natural resource base are a relatively recent phenomenon, starting with the creation of IITA in the early 1970's and its focus on intensifying shifting agricultural systems.

Figure 1: Stages in the Intensification of Crop Yield



The movement to permanent cropping systems entails significant changes in crop management in the search for higher and stable yields. Such intensification is dependent on increased labor inputs per unit of land, better synchrony with local climatic patterns, control of the increased weed and pest pressures, and increased use of biomass and legumes in soil fertility management. This Boserupian (1981) intensification is driven by increasing rural population densities, changes in land tenure arrangements, and improving access to output markets. This stage of yield improvement is essentially dependent on changes in labor input and crop management systems. These changes are oriented to minimizing the extractive features of agriculture, especially the draw down in soil nutrients. Where agriculture developed on flood plains with associated irrigation and drainage development, such systems were very sustainable. Where soil management systems do not respond quickly enough to such drivers as improvements in markets or population growth, the result again can be degradation of the land resource base, as occurred in the US in the 1930's or is currently occurring in large parts of Africa. Designing technology interventions for such conditions is often problematic because of such factors as insecure rights in land, inefficient markets, high management requirements of the technology, particularly when associated with low levels of education of the farming population, and lack of investment resources by farmers. All of these conditions characterize most of African agriculture today, and it is not therefore surprising that Africa is the only continent where food production fails to keep pace with population growth.

The yield take-off of the type represented by the Green Revolution is associated with the introduction of an input-responsive variety into an economic and institutional environment that facilitates access to and utilization of those inputs. Maize hybrids and short stature rice and wheat varieties have revolutionized world agriculture, partly because these three crops dominate as a share of total cropped area. Adoption of these varietal innovations has resulted in dramatic increases in yields but also dramatic increases in the use of chemical inputs, particularly fertilizer. The Green Revolution in Asia resulted from the introduction of yield enhancing technology in a context of government intervention to provide price support and price stability (dampening the price depression that often comes with rapid technological change), price subsidies to fertilizer, government investment in extension systems, and significant investments in public infrastructure, particularly roads and irrigation. Within this context, the new technology generated large income benefits for farmers, as well as significant growth multipliers in the local rural economies. However, only recently have agricultural economists (Gabre-Madhin, et al, 2003) reinterpreted the Green Revolution experience in light of the policy, market, and institutional investments that provided the preconditions for such rapid agricultural growth.

The Green Revolution also resulted in the substitution of fertilizer for other forms of soil nutrient management, decreasing efficiencies in plant use of the nitrogen, its associated release into the hydrological system, and increasing problems with pest and disease control. These second generation problems led to the last stage of crop yield growth, where the focus was on maintenance research, in breeding to protect yield gains and in crop management to improve efficiency in input use and sustainable management of the natural resource base. Research focused on input efficiency and externalities, which in turn was characterized by significant return to improved crop and resource management research. This latter stage is probably best represented by the rapid expansion in conservation tillage systems and improved soil organic matter management in Brazilian cropping systems over the last decade.

The question that such a stage theory generates is how to make the transition from one stage to another. Particularly, what is the role of research in the transition process and what are the other preconditions necessary to facilitate the adoption of technology that then precipitates the yield gains? As the Green Revolution in Asia suggests this transition can be very rapid indeed, but as the lack of a Green Revolution in Africa suggests, other preconditions are necessary to facilitate such a rapid increase in yields. These preconditions, such as markets, credit, extension, and information systems, are developed outside the research sector itself and together with land/labor ratios and rural population growth define the stage of crop yield development. Agricultural research cannot substitute for these larger systems but rather research must adapt its design strategies to each stage. The important point is that the relative importance of breeding versus crop and natural resource management strategies changes at each of the stages, with breeding generating its huge potential only when crop management systems and larger support systems are relatively well developed. While this would seem a rational argument, the other driver in the organization of agricultural research is advances in the biological sciences. The international agricultural research system, as an example, has responded to the pull of these two forces in the organization of its research. Particularly, a focus on new science often obscures the ability to adapt the technology design process to the conditions that will maximize technological impact, the topic of the next section.

Crop Yield and the Organization of Agricultural Research

The emergence of the international agricultural research system in the 1960's and early 1970's built on the collapse of colonial regional and international structures and their incorporation into emergent national research systems, the early programs of the Rockefeller and Ford Foundations to develop those national research capacities in Asia and Latin America, and uncertainties about global food supplies, particularly after the drought in South Asia in the late 1960's. This international system, complemented by capacities in the North, led to significant changes in how agricultural research was conceptualized and organized. Agricultural research up to that point in time was largely organized around disciplines, reflecting the structuring of agricultural science in universities and the academy. The organizational changes in agricultural research following the creation of the CGIAR in the late 1960's and early 1970's were primarily a product of two factors, the early success of the Green Revolution with the resultant emphasis on impact and the very different organizational requirements of varietal improvement and crop management research.

Crop management and varietal improvement research have very different characteristics (Figure 2), and these differences in turn lead to quite contrasting organizational modes for agricultural research. For varietal improvement there are scale economies in organizing germplasm banks, population improvement, and breeding programs. These activities can be centralized in international research institutes and further adaptation and selection can be done within national research programs. Some controversy surrounds the extent of wide adaptation that may be sought in such breeding programs, but even in crops such as cassava, where genotype-environment interactions are high, there is the basis of a division of labor between centralized, global capacities and germplasm flows to national programs. Research progress is embodied in the seed, and because seed is a relatively high value, low volume product—at least compared to fertilizer--, there is potential for development of seed input markets, particularly where it can be based on hybrids. However, to generate the large yield gains that potentially comes from breeding requires markets to absorb the increased production, increased nutrient availability to the plant, usually from fertilizer, control of other biotic constraints, other adaptations in crop management, the input markets to supply the seed and fertilizer, and a profitable ratio of output to input prices. That is, the Green Revolution depended on matching breeding progress with a sufficient economic and institutional environment to motivate farmer and market response.

Figure 2: Different Characteristics of Varietal Improvement and Crop Management Research

Varietal Improvement	**Crop and Resource Management**
Information embodied in seed	Management and information intensive
Potential for wide adaptation	Location and system specificity
Dependent on input markets	Dependent on extension systems
Scale economies in research	Decentralized research systems
Potential for yield take off	Incremental change
Dependent on market and policy support	Internalized within farming system

Crop management research, on the other hand, has very different properties. The science relies on understanding principles or processes and applying them in very different contexts. The conceptual basis of this research usually takes place in an explicit systems framework. Application of that research is undertaken through an applied and adaptive research process in a decentralized research mode, typical of the early development of the Japanese and US research system. Improved crop and resource management that focuses on yield improvement in the first two stages of crop yield improvement usually entails both improved farmer management capacity and increased labor inputs, which often substitute for inputs such as fertilizer and pesticides. Such intensification is often driven by changes in land labor ratios, increased soil nutrient extraction, and shifts of crops in the farming system. Many of the effects of changed crop or natural resource management are incremental and long term ,compared to the introduction of new varieties. This mitigates against management research in the ongoing competitive struggle in the organization and funding of these two principal research areas within the CGIAR.

The formation of IRRI in 1959 and CIMMYT in 1963 were outgrowths of successes by Rockefeller Foundation’s Mexico program and the Ford Foundation’s programs in Asia. The former focused on increasing crop yield at a plot scale and the latter on increasing productivity at a farm scale. Although initially organized along disciplinary lines, IRRI particularly developed principal research foci around breeding and cropping systems. While the breeding program focused on increasing the responsiveness of rice varieties to increased fertilizer application in irrigated plots, the cropping systems work focused on maximizing resource use through multiple cropping, testing of alternative crops in dry seasons when water was not assured, improved timing of operations through selective mechanization, and weed and disease control. As Harwood (1999) notes, “(Richard Bradfield’s) research took place within the context of a centuries-old evolution of intensive cropping systems by Asian farmers and was influenced along the way by those researching farming systems, particularly in Africa.” Emergent thinking about cropping and farming systems was central in the formation of IITA and CIAT in the late 1960’s, where the research focus would be a diversified, systems-based approach to increasing productivity in the lowland tropics of Latin America and Africa.

The Green Revolution radically changed the debate on the sources of growth in crop yield. It came at a time of global concern about world food supplies and a prospective famine situation in Asia. Instead, this region was able to produce a yield take-off that mirrored that which had started in the Europe and the US in the 1930’s and gathered momentum in the 1950’s. The large income flows generated by the introduction of more input responsive varieties into a positive market and institutional context motivated significant growth linkages in these rural economies, leading to quite broad based agricultural growth.

The Green Revolution also coincided with Robert McNamara's shift of World Bank lending toward poverty reduction objectives. The Green Revolution both created a model of successful agricultural development based on sustained increases in crop productivity and at the same time put investment in agricultural research at the core of development policy at both national level and within international aid agencies. With agricultural research now an instrument of development policy, a significant debate arose on the income distributional consequences of the new technology and the impacts on poverty. The CGIAR put impacts on agricultural growth, poverty reduction, and food security at the core of its objectives. Resource allocation and impact assessment in relation to these objectives became a core function of economics research at the international centers. Both of these in turn resulted in significant changes in how research was organized in the centers. In particular, the Green Revolution put breeding at the center of the international agricultural research system.

The Green Revolution gave rise to the centrality of the multi-disciplinary, crop research program as the organizational basis for much of agricultural research. These programs were organized around principal yield constraints, with breeding being at the core of the program. The yield constraints in turn provided a framework for effective resource allocation. Entomology, pathology, soil science, and physiology to a large extent supported breeding programs through diagnosis of yield constraints, sourcing resistance within germplasm collections, developing screening protocols, and performing some of the specialized screening. Where there was little potential of a breeding solution, research on other management options were undertaken. Such a commodity focus could also be linked to market development, consumer and processing quality characteristics, and policy issues. This was a powerful organizational model and as it was linked to IARC training programs, it spilled over into research organization in national systems. The support to national programs was reinforced by the development of international varietal testing systems, which moved germplasm at various levels of population and varietal development into national breeding programs. A prime example of this change was CIAT's termination of its farming systems program and the organization of its research around four commodity programs. IITA and ICRISAT did not go quite so far in eliminating all of their systems research but resources did shift into a focus on principal mandate crops.

The commodity research program remained an organizational model for only little more than a decade. Commodity programs over time evolved more of a balance between breeding and crop management research, and to a large extent absorbed the continuing evolution of farming systems research, or as CIMMYT would put it, research on maize- and wheat-based systems within a farming systems perspective. However, by the latter part of the 1980's a confluence of forces combined to induce a further change in the evolution of international agricultural research. First, evidence was accumulating that not only was the growth in Asian rice productivity slowing but that there was also significant declines in fertilizer use efficiency in irrigated rice systems (Pingali, 1994). Secondly, the extension of the Green Revolution into rainfed agriculture was facing far more constraints than had been anticipated. An evaluation of the impacts of CIP's research on potatoes (Walker and Crissman, 1995) had to focus on specific case studies, where varietal adoption was much more discrete, depended on significant local adaptation, and was associated with the potential for commercialization. As the impact assessment noted, "changes in yield potential and harvest index are unlikely to be sources of growth in potato production as they have been in cereals. In developing countries, the driving force for varietal change in potatoes is the demand for resistance to diseases and pests and environmental stresses such as drought and frost." Thirdly, systems approaches in areas like agroforestry, integrated pest management, and integrated soil fertility management were given credibility by the success of IITA's biological control program for cassava mealy bug in Africa. And, finally, the Bruntland report of 1987 put resource and production system sustainability onto the international policy agenda with its linkage of environmental concerns to growth in agricultural production. In response the CGIAR was expanded to add centers working explicitly in the natural resource management area and most of the existing centers added individual programs on natural resource management, all at a time when the overall budget reached a plateau.

The reemergence of crop and resource management led to a more decentralized approach to international agricultural research. An attempt was made to formalize this decentralization into ecoregional centers (McCalla, 1994), but such formal restructuring did not occur. Rather there was a more passive decentralization by all the centers, with an inherent lack of coordination. While initially driven by the shift into resource management, decentralization also took place in breeding systems. Large, international testing networks gradually disappeared to be replaced by more regional breeding efforts. Breeding strategies shifted to more regionally adapted populations, with a focus on incorporating resistances to principal biotic and abiotic stresses. Such populations were then fed to national breeding programs for either incorporation into local breeding efforts or direct selection and evaluation. Simultaneously, crop and resource management research shifted to systems approaches. Integrated pest and soil management, agroforestry, and integrated crop-livestock production systems became frameworks around which to organize research programs. Thus, soils management research shifted from a focus on plant nutrition, deficiency symptoms, and selection for soil toxicity or deficiency constraints to understanding the role and management of soil organic matter, the role of micro and macro fauna in the soil, and management of organic and inorganic resources to both supply plant nutrients as well as enhance the quality of the soil resource base.

Decentralization within the CGIAR should have seen a reintegration of breeding and crop and resource management research. In fact, the two became increasingly independent of one another. The systems focus of the latter was one contributing factor, as in the earlier years of IRRI, the two established quite independent research paths. The development of molecular biology and biotechnology during the 1990's reinforced this separation on the breeding side. Connectivity between biotechnology research, which is done in a centralized but distributed manner, and breeding programs became a central organizational challenge for research systems, one that still has not been resolved. The key organizational problem is one of gene or character deployment into suitable genetic backgrounds appropriate for local conditions. Biotechnology reinforces the focus on constraint breeding, allowing searches across genomes for relevant resistances. However, intellectual property rights are a constraint on access and utilization of gene constructs, there is still significant varietal specificity in terms of the ability to transform and regenerate, biosafety systems are still only in an emergent state in most developing countries, and the ability to appropriately phenotype lags well behind the ability to undertake the molecular analysis. All of this has introduced complexity into the organization of applied breeding and biotechnology in international agricultural research, but the result is a search for organizational modes solely within the genetic improvement area of research. This is reinforced by continued expansion in the adoption of genetically engineered crops (James, 2003). Such adoption has occurred almost solely in large countries, ie China, Brazil, Argentina and South Africa, focuses only on maize, soybean, and cotton, and utilizes essentially herbicide tolerance and Bt insect resistance genes. In sum, this reflects the stages of easy gains in crop yield from new research breakthroughs, with the difference that the advances are driven by private rather than public sector investment. The broadening of their application to other crops, countries, and genes will come at increasing costs and principally within the public sector.

The evolution of the international agricultural research system over the past 40 to 50 years has been episodic, and driven more by larger global forces than by the ability to better adapt technology design to the differing needs of agriculture across the developing world. The application of biotechnology in the developing world has recently become a driving force. But, large parts of the developing world as yet do not have the institutional and economic structures needed to support a Green Revolution-type yield increase. This presents major challenges to the international research system in organizing itself to meet the need for continuing productivity increases, especially in areas such as sub-Saharan Africa, North Africa and the middle East, the upland areas of Southeast Asia, the Andean zone and Central America, and the eastern part of the South Asian sub-continent, that is the areas where rural poverty currently resides in the world and where it has remained most intractable.

The Search for Crop Yield Gain into the Next Millennium

Continued growth in crop yield will be essential to feed the world's population going into the first quarter of the new millennium. As McCalla (1998) summarizes the task, "given the widespread agreement on the needs, or demand, side of the (global food) equation, and its magnitude—the greatest increase in human numbers in history and the corresponding increase in food production that will be required—why is there so little agreement on the ease or difficulty of generating the supply to meet that demand?" McCalla goes on to note that "under all scenarios, the biological yield increases accomplished over the last thirty years must be at least maintained, or better yet, increased." Much of this yield increase must come in the developing world, and the questions that this paper raises are (1) what mode of scientific investigation will best generate the next phase of crop yield increases across very variable economic and institutional conditions, (2) how will the technology development process best be linked to other support services and institutions in order to increase productivity in farmers' fields, and (3) how can the synergies between genetic improvement and crop and resource management research be best exploited when organizational dynamics are creating increasing separation?

More than thirty years after the Green Revolution, the impact record would suggest that rather than being a model for future increases in crop yield that it was relatively unique in the modern history of crop yield. The vast irrigated areas of the Punjab or the river deltas of Southeast Asia are in themselves unique in relation to global agriculture, combining controlled production environments, village nucleated settlement for efficient information flow, high production density of either wheat or rice and thus efficient product assembly, processing and marketing, close access to either urban or export markets, input subsidies together with output price supports, and effective extension systems. That is, the Green Revolution took place within a context of very productive agricultural environments, very efficient market systems, highly effective delivery of services and guaranteed profitability—highly input responsive varieties were in effect only the last piece in the puzzle. However, even in Asia there were significant lags in putting all the necessary conditions together, as only in the last decade has Vietnam achieved sharp increases in rice yields in the Red River and Mekong deltas.

Literature of the last decade indicates that the impact of agricultural technologies in the developing world is primarily through adoption of technologies differentiated for very circumscribed conditions. In some cases, initial jumps in productivity not only were not sustained, but yields actually declined, e.g. the adoption of improved maize varieties and fertilizer in Kenya (Hassan, 1998). As Smale and Jayne (2003) note, "the 'maize success stories' (in East and Southern Africa) were largely a phenomenon of the 1970's and 1980's. During the 1990's, (Kenya, Zambia, and Zimbabwe) experienced absolute declines in maize production." Moreover, as noted by Ali and Byerlee (undated) for Pakistan, "continuous and widespread resource degradation (in the irrigated sector) as measured by soil and water quality has had a significant negative effect on productivity with the largest effect in the wheat-rice system, where resource degradation has more than offset the productivity effects of technological change." All of this is suggestive that the "easy" gains in crop yield have been achieved, even maintaining those yield gains will require continued research and investment, and progress in crop yield into the future will be more incremental and location specific.

The evolution of genetic improvement and crop and resource management research (Figure 3) over the last four decades has each responded in different ways to these challenges. Breeding has become more decentralized, works across a wider range of traits, and involves more intricate flows and institutional arrangements between international and national breeding programs. However, only in the last decade or so is varietal uptake apparent in non-cereal crops such as cassava in Uganda and Nigeria, beans in Rwanda, dual purpose cowpeas in the guinea savannas of West Africa, and soybeans in Nigeria. On the other hand, crop and resource management has moved to broader systems frameworks, shifted increasingly into resource management, integrated methodological innovations into the research process, and moved to multiple scales of analysis. Adoption of components coming out of this research are apparent, such as conservation tillage in Brazil and Paraguay, improved agroforestry fallows in Zambia, biocontrol of water hyacinth in Lake Victoria, or zai water harvesting in the Sahel. In neither the genetic improvement or the resource management technologies were the adoption and impact especially predictable. Nor was it clear either what the impacts on crop yields were or what other factors were necessary preconditions for the adoption process. In sum, it is increasingly difficult to assess impacts of new technology due to the restricted conditions under which they occur-- so that they are not reflected in national yields figures--, to the increasing complexity of the technologies, and to differences in farmer management of the technology.

Figure 3: Evolution of Breeding and Crop Management Research

Genetic Improvement	**Crop and Resource Management**
Hybrid breeding	Disciplinary crop management/agronomy, soil science
High harvest index/input responsive varieties	Crop and farming systems research
Agroecological adaptation/stress breeding	Integrated crop management research
Biotechnology	Integrated natural resource management

Systems research over the last several decades has embedded crop yield within larger farming, economic and social systems. The impact literature is suggestive that these higher order systems can constrain adoption and impact of new technologies more than multiple biotic or edaphic constraints. The stage theory of crop intensification in the first section is a further reflection of how farmers respond to progressive organization of labor, capital, input and output markets. The logic inherent in the evolution of crop and resource management research has led progressively to working at higher scales and incorporating markets, credit systems, and farmer organization into the research process, a framework known as integrated natural resource management (INRM) or research for development (R4D) (Harwood and Kassam, 2003). It is as yet unclear how such a research framework is best organized, other than it will involve pluralistic institutional arrangements. As might be expected, significant uncertainty surrounds the potential success of this approach and the cost implications for implementing it at a sufficient scale.

The emergence of biotechnology has created a completely different dynamic in the area of genetic improvement. The dramatic increase in private sector investment, the shift to patenting of research and the transaction costs inherent in securing intellectual property rights, the ability to work across species, and the perception that this new science may lead to the next generation of yield breakthroughs have sparked suggestions for the reorganization of research in the international system to better capture the potential benefits of this technology. As a recent evaluation of the CGIAR system by the World Bank (2003) suggests, "the System is being pulled in two opposite directions. On the one hand, the CGIAR Centers are not conducting sufficiently coordinated research on the highly decentralized nature of NRM research, which calls for effective partnerships with NARS to produce regional and national public goods in NRM. On the other hand, the System is not sufficiently centralized to deal with advances in the biological sciences and IPRs, which call for a more unified approach to research strategies and policies."

It is important to stress that the explosion in literature on the potential of biotechnology in world agriculture and particularly within agriculture in the developing world rests on the perception of the transformative potential of seed technologies. As the World Bank study stresses, "impact studies provide convincing evidence that the (mostly conventional) crop breeding research of the CGIAR Centers, together with the follow-up work with developing country NARS, continues to generate extraordinary high returns to investment. Those returns, ranging from 40 to 78%, are well above the returns attainable from many alternative uses of public funds." The study goes on to conclude that, " while improved NRM is crucial, there are no major scientific breakthroughs in the management of tropical soils or water." This represents a return to science as the major driver of the organization of international agricultural research, rather than a considered analysis of where different regions are in terms of the systems constraints on crop yield and where they are at in the stages of land intensification. Moreover, it represents a return to the Green Revolution focus purely on genetic improvement as the source of crop yield increase, a course that has had little impact in large parts of the developing world.

International agricultural research is now reorganizing around two very different views on the source of future yield growth, divided along the very traditional boundaries of genetics versus crop and resource management. It might be asked if a wedge of perceived economic efficiency, of which the Bank study is the best example, is reinforcing the traditional problematic split of agricultural research into two very different research communities. The varietal improvement component is centralizing in response to the needs of biotechnology, with some question of whether this will augment or undercut the decentralization that has actually taken place in breeding capacities. This vision is built around the promise of harnessing new science, of tapping historically high increases in private sector investment in agricultural research, and at its most rhetorical, of generating a new green revolution in areas not impacted by the last green revolution.As the expansion in NRM research in the 1990's undercut the funding for commodity research programs, the expansion of biotechnology will raise increasing questions about an appropriate allocation of resources within international agricultural research. The resource allocation decisions made now will determine the capacities to raise crop yields in the next two decades.

Conclusions

This paper has argued that our understanding of the causes of crop yield increase are imprecise at best and offer only speculative guidance to future needs. Those needs are especially daunting, as yield increases will be the principal basis for the provision of future food supplies and the prospects are that future yield increments will come at increasing costs. The task is even more daunting for large parts of the world still mired in rural poverty, especially but not exclusively Africa. This author's very summary reading of the impact record over the last three decades suggests that crop management research has been significantly undervalued because it is not viewed as science, the contribution of varietal improvement research has been over emphasized—partly because of the natural appeal of the link between new science and impact and partly because the other investments necessary to achieve impact are de-emphasized—and that natural resource management research has not had enough history to establish its potential. The way forward will require all three as well as significant investments at higher systems levels in extension, market development, rural credit, and infrastructure; the critical issue will be in what proportion and how they will be organized. The last thirty years in international agricultural research has seen an evolution from the integration of genetic improvement and crop management research in crop research programs to two separate and different paradigms of achieving increases in crop yield. The current organizational logic of each is very different and they compete significantly at the margin for resources, especially during a period of flat or declining public investments in agricultural research. Nevertheless, it is still true that at the farm level there are very important synergies in the combination of improved germplasm with innovative crop, soil and resource management strategies. Where in the research process these synergies can now be exploited is a question; that is, are such synergies only exploited, if even then, at the adaptive research phase by national systems?

This author's view is that systems research offers critical insights into these challenges but that it has not found a consistent home in international research, from its early organizational problems at IITA, CIAT, ICRISAT, and ICARDA—centers whose mandate focused on agro-climatic regions--, the short history of farming systems research, and the sub-system work in soils, pest management and agroforestry. The CGIAR missed an opportunity in the early 1990's in not reorganizing around ecoregional centers, which then would have provided a capacity to connect to more global germplasm and biotechnology capacities. It did in fact decentralize but in a completely uncoordinated manner. Ecoregional centers would have consolidated more regional diagnosis of multi-level constraints, provided capacity to deal with the very different research agendas in each region, and would have provided a platform for the systems research that would have arisen from it. How to build the appropriate research capacities at national, regional, and global levels will remain the central challenge in meeting future world food needs. An improved ability to understand the basis for increased crop yields continues to be critical to planning and investing for the future.

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