January 6, 1994

Systems approaches for crop improvement and natural resources management research in CIMMYT: past and future[1]

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[1] Prepared for the workshop "Opportunities for use of systems research methods in agriculture in developing countries" organized by ISNAR and the International Consortium for Application of Systems Approaches to Agriculture (ICASA), The Hague, Netherlands, November 22-24, 1993. Opinions expressed are not necessarily those of CIMMYT. The authors would like to acknowledge helpful comments from R. A. Fischer and Roger Rowe.

INTRODUCTION

Since CIMMYT was established in 1966, the world has undergone considerable change. Since that date, population in developing countries increased from 2.4 to 4.2 billion people, while maize production in those countries rose from 91 to 217 million tons (m t) and wheat production increased from 74 to 244 m t. To a considerable degree, the fear of global famine has receded. However, widespread and unrelenting poverty remains a cause for concern, particularly in South Asia and sub-Saharan Africa.

In the next 20 years, maize and wheat farmers in developing countries will have to double current harvests to meet growing demand. It is important that they do so without threatening the well-being of future generations through the degradation of agricultural resources. New technologies are needed that are both productivity-enhancing and resource-conserving. In the past, CIMMYT's contributions to a more productive and more sustainable agriculture principally have come through crop improvement. Some of these contributions have been *direct*: maize and wheat varieties that resist insects and diseases without requiring pesticides, or that use water and nutrients more efficiently. More of these contributions, however, have been *indirect* or *preventive*.

New agricultural technology can avert or forestall resource degradation by helping ameliorate poverty, generate employment and stimulate broad-based economic development, thereby reducing pressure on fragile agricultural lands (Harrington 1993). There is a tendency to dismiss these preventive contributions as esoteric or unimportant. Note, then, some of the preventive contributions of Green Revolution technologies.

"Without modern varieties, production of rice and wheat in the 90 countries with humid tropical lands may have been 20-30 million tons less than it is. To have made up this shortfall from non irrigated lands with traditional varieties and management practices would have required an additional area under cultivation on the order of 20-40 million ha, probably an underestimate given the rapid degradation of newly cleared land." (CGIAR 1985, Chapter 14).

In the future, CIMMYT aims to: continue to produce maize and wheat varieties that perform well with minimal use of pesticides; use biotechnology to accelerate breeding research; continue efforts to rescue, store, utilize and share maize and wheat genetic resources; augment social science research to ensure that environmentally friendly technologies remain profitable and in other ways "farmer friendly"; and add to research on natural resource management and conservation, focusing on large ecosystems where maize or wheat is a major crop (CIMMYT 1992).

CIMMYT is increasingly interested in expanding its use of systems research methods to improve the efficiency of conventional field research, and to conduct kinds of experimentation (especially in natural resources management research) that are difficult or impossible to carry out in the field.

The remainder of this paper is divided into two sections. First, CIMMYT's past and current investments in the use of systems research methods are discussed. These investments primarily have been in the use of geographic information systems (GISs) and crop models to target germplasm improvement to well-defined production zones or "megaenvironments". Then, CIMMYT's current and future investment in natural resources management research (NRMR) is described and possible roles for systems research are introduced.

USING SYSTEMS RESEARCH TO INCREASE THE EFFICIENCY OF CROP IMPROVEMENT

Introduction

CIMMYT's global mandate for maize and wheat improvement compels it to deal with an extensive range of production environments. Farmers' germplasm requirements vary notably over these environments with regard to adaptation, maturity, and tolerance to biotic and abiotic stresses. Efficient management of research resources in global crop improvement requires an understanding of production and testing environments and of the types of germplasm being improved.

Identification and characterization of production environments[1]

Within CIMMYT, the concept of the "megaenvironment" (ME) has been developed as a means of organizing and focusing crop improvement programs. A ME is defined as a large geographic area (not necessarily contiguous and frequently transcontinental) characterized by similar biotic and abiotic stresses, cropping system requirements and consumer preferences. Each ME represents a minimum of 1 million ha, resulting in zones large enough to be of interest to an international center. MEs are most useful when they help target breeding efforts.

The use of GIS has enhanced CIMMYT's capacity to identify and characterize the diverse maize and wheat MEs throughout the world. Compared to earlier cartographically-based approaches to agroecological zoning (e.g., FAO 1981) a dynamic approach allows more accurate environmental characterization, integration with data on production systems, and assessment of changing production frontiers (e.g., genotypes) and constraints (ranging from diseases to resource access). Work to date at CIMMYT has featured the development of robust, reproducible monthly climate surfaces based on a dataset of climate normals (station or point data), a global digital elevation model and robust algorithms for spatial interpolation of the climate data. These climate surfaces provide data for grid cells in a GIS and can then be used as input for grouping of these cells based on selected variables, e.g. temperatures and rainfall for the months of April to September.

In a prototype study, a cluster analysis was performed on seven months of monthly climate data (matching the maize growing season) in Mexico. The summary characteristics of the resulting clusters (environments) were then interpreted into maize adaptation zones. The

[1] This section and the following one are adapted from Corbett (1993).

criteria used to form the zones from one or more clusters were derived from maize breeders' perceptions of the suitability of different maize germplasm to different environments. The results illustrate two advantages of this approach: 1) with the climate surface database in place, researchers can select only those elements of climate that best differentiate germplasm-specific zones, and 2) different environments are no longer combined on the basis of arbitrary, discrete boundaries.

These methods are being used in a collaborative project with the Kenya Agricultural Research Institute (KARI). Clustering techniques have been applied in combination with ground truth and production data to define germplasm-specific maize environments. Preliminary results indicate that the incidence and relative size of various maize production environments in Kenya are substantially different from what had been assumed (Table 1). This information will be used to reassess priorities for maize improvement and agronomic research in Kenya.

Identification and characterization of testing environments

Maize. The usefulness of the climate surface database expands as reliable mechanisms are identified that relate monthly data to an array of agricultural issues. CIMMYT's International Maize Testing Program annually distributes seed for evaluation trials all over the world. Climate surfaces can contribute to the interpretation of the results of international trials through environmental characterization of test sites to identify their suitability as representative sites of either ME's or for particular stresses.

Analysis of international trial results can identify those stations situated in "hot spots" for biotic stresses. CIMMYT pathologists can include susceptible genotypes in trials planted at various locations to empirically test disease pressure. Descriptive models can then be constructed using actual weather data from the sites. These models, when combined with climate surfaces, can be used to extrapolate the relationships and estimate the potential frequency and intensity of disease pressure in different areas. The resulting expert diagnosis of a cluster analysis of climate variables, specific to a disease, can identify the spatial extent of areas where the disease is expected to be severe. This serves two purposes: 1) resistant maize varieties can be better targeted and priority can be given to improvement for resistance based on potential demand, and 2) suitable test sites can be identified. Abiotic stresses are also considered a serious challenge to CIMMYT germplasm. Drought, for example, is thought to be responsible for about 15% of all maize yield losses in the lowland tropics. A proposed project aims to use climate surfaces to characterize the frequency and severity of drought in selected areas (e.g., southern Africa) so that we may better estimate the potential returns to continued investment in drought-tolerant germplasm.

Wheat. CIMMYT's Wheat Program, in an analysis of the results of 26 years of multi-location field trials with 50 cultivars per year, identified key characteristics of wheat production environments (DeLacy et al. 1993). In this study, wheat production environments were differentiated on the basis of the performance of wheat germplasm itself. Future research can build on these results by assessing the extent to which environmental information can explain observed patterns in wheat germplasm performance. In addition, the location of trial sites can be rationalized in terms of identified wheat environments and their underlying characteristics. Finally, the spatial extent of climatically similar areas (from the point of view of wheat germplasm) can then be assessed, allowing more accurate targeting of wheat germplasm and its improvement. In general, analysis of environmental and trial data using a GIS can help to identify two types of testing sites: those that best represent a particular ME and those that represent "hot spots" for specific stresses. This information increases the efficiency of testing and improves the accuracy of the weighting given to the data obtained.

Characterization of genotype responses and interactions with environments

Maize. An improved understanding of the characteristics of the range of CIMMYT germplasm can be used to fine-tune environment definitions as well as to efficiently interpret trial performance data where genotype by environment (GxE) interactions across locations are complex. Data from international testing trials and CIMMYT trials have been used to estimate parameters for simulation models to describe different CIMMYT maize germplasm. In the classification example described for Mexico (above), a simulation model was linked to the GIS (Chapman 1992). The crop simulation model used monthly temperature data to estimate flowering date, using the parameters of a tropical intermediate genotype for each of the cells in the GIS. The results were then grouped to produce a map of the extent of adaptation for this genotype. Where flowering dates exceeded 70 days after sowing, the genotype was considered to be not adapted. Repeating the simulation with other genotype parameters or for other planting provides a series of GIS databases that can be combined to refine estimates of the extent of areas suitable for such a genotype. Modeling of phenology is only a starting point, as other genotype characteristics can be simulated. Further, the use of historical weather data would enable climatic risk to be considered in the selection and definition of genotypes (Muchow et al. 1991).

Wheat.[2] Experimental evaluation of GxE interactions in wheat trials is laborious and time-consuming because it requires experimentation under a wide range of environmental conditions that typically are impossible to control. Application of explanatory crop growth simulation models, in which the relations between crop and/or cultivar characteristics and environmental conditions are quantitatively described, could improve the efficiency of research. These models allow a systematic analysis of the relative contribution of the various factors to yield level and stability (de Wit and Penning de Vries 1985). Moreover, they facilitate extrapolation of results in time and space through combination with GIS-based information on spatial and temporal variability in environmental conditions.

[2] The work described here is being executed as a Ph.D. project in collaboration between CIMMYT, Wageningen Agricultural University (Department of Theoretical Production Ecology) and the Centre for Agrobiological Research (CABO).

A well-validated crop growth simulation model for the wheat crop is being used to analyze crop-environment interactions in ME 1 (irrigated, low-rainfall temperate areas) where a substantial proportion of wheat in developing countries is produced. The primary purpose of the model is to understand management (especially planting date) by genotype interactions.

NATURAL RESOURCES MANAGEMENT RESEARCH: PROJECTS, CHALLENGES AND OPPORTUNITIES FOR THE USE OF SYSTEMS METHODS

Projects

The contribution of crop improvement research to the development of a sustainable agriculture is primarily an *indirect* one: *averting* the degradation of resources by helping ameliorate poverty and slow population growth. Systems methods can help improve the efficiency of crop improvement and thereby accelerate the speed with which these desirable results are attained. CIMMYT also feels, however, that there are opportunities for the Center to make *direct* contributions through NRMR, defined as research that aims to develop farm- or community-level interventions to slow or reverse resource degradation processes while increasing system productivity. NRMR at CIMMYT understandably emphasizes farming systems where maize or wheat are important. CIMMYT has been involved for several years in a number of NRMR endeavors. Most prominent among these are:

- Collaborative research on productivity and sustainability issues (soil fertility decline, groundwater depletion, water-induced land degradation, build-up of pests and diseases) associated with the rice-wheat cropping pattern in South Asia. Much of this research is conducted in collaboration with IRRI and national programs from Bangladesh, India, Nepal and Pakistan. CIMMYT's contribution has featured participation with NARS and IRRI colleagues in diagnostic surveys to elicit a users' perspective on rice-wheat issues, and in on-farm experiments.

- Research on conservation tillage and maize-legume combinations to improve maize-based system productivity and reduce land degradation (particularly erosion) in Mexico and Central America. Much of this research is conducted in collaboration with a CIAT-led consortium that includes other IARCs, national programs and NGOs. CIMMYT's role has featured participation with NGOs in farmer-participatory research and extension as well as strategic agronomic research implemented under the supervision of a NARS-led research network.

Apart from these two projects, research is also being conducted on conservation tillage for wheat-soybean systems in the Southern Cone of Latin America and for highland maize-wheat systems in Mexico. In addition, a proposal is being developed for ecoregional research on long-term soil fertility issues in maize-based systems in Eastern and Southern Africa.

Opportunities for collaboration in the application of systems methods

In pursuing NRMR, CIMMYT recognizes that systems methods, combined with GISs, can be exceedingly valuable to:

- understand the processes that underlie land and water degradation problems,
- assess the extent and incidence of these problems, to allow better targeting of research, including crop improvement as well as NRMR,
- explore interactions between possible solutions to these problems and environmental characteristics, including weather variability,
- identify the specific environments in which certain interventions are likely to be most attractive to farmers, and
- explore implications for the future of ongoing degradation processes, in terms of trends in crop yields and production, system productivity and resource quality, given different assumptions on farmer adoption of alternative resource-conserving practices.

CIMMYT welcomes collaboration with other institutions to apply systems methods for the kinds of purposes described above, in the context of our on-going and proposed NRMR endeavors.

A caution . . .

Systems approaches can help assess the attractiveness of alternative technologies that aim to improve farm productivity while contributing to the conservation of agricultural resources. However, recommendations developed with the help of these approaches must take account of the broad range of factors that affect farmer adoption. Many of these factors are subtle and frequently ignored (Tripp et al. 1993).

- Models that compare the attractiveness of technical alternatives are partly based on information on costs and returns. Many productivity-enhancing resource-conserving techniques, however, are new to farmers. *In these cases, accurate cost and return information simply may not be available* -- especially given that farmers are known to make *major adaptations to technologies* in order to tailor them to their own agroclimatic and socioeconomic circumstances.
- Farming systems are tremendously variable -- much more so than germplasm adaptation zones -- and the ability of farmers to adapt resource-conserving practices to their own circumstances is a key to the adoption of these practices. In addition, technologies developed through NRMR are complex and require a great deal of site-specific adaptation. In some cases this will require formal training for farmers in new techniques.
- Economic assessment of alternative practices for a crop may fail to take account of the broader farming system. System-based analysis often gives a different picture of the profitability of alternative practices than one based on one or two commodities (or one cropping sequence) within that system. This is particularly true when crop-livestock interactions are strong.

- Finally, farmers often are not willing to invest in a resource-conserving technology with downstream benefits without assured access to the improved land resource. Land tenure is consequently an important factor influencing adoption of these technologies.

Table 1. Estimates of the proportion of maize area found in Kenya in different maize environments: a comparison of two approaches.

Maize environment	Estimate from 1988 maize megaenvironment database, based on subjective judgment[a]	Estimate from 1993 collaborative project with KARI featuring GIS and cluster analysis[b]
Lowland tropics	7%	3%
Mid-altitude tropics	56%	18%
Tropical transition zone	35%	43%
Highland tropics	1%	28%
Other	1%	8%
Total maize area (000 ha)	1,425	1,075[c]

[a] CIMMYT Maize Program 1988.

[b] Preliminary results, KARI-CIMMYT collaborative maize GIS database project.

[c] National maize area under the GIS project was estimated from five years' data from aerial photography, hence is thought to be more reliable than the earlier estimate.

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