# Research for marginal environments

## Are we underinvested?

**Derek Byerlee and Michael Morris**

**Evidence is presented to show that adoption of modern wheat varieties in rainfed marginal environments of the developing world has lagged substantially compared to adoption in favoured well-watered areas. Possible reasons for this lag are discussed, and a simple congruency model is used to examine the case for shifting research resources from favoured to marginal environments, with particular reference to wheat breeding. Application of the model to resource allocation in wheat research at the international level and for India, a major wheat-producing country, suggests that the proportion of research resources invested in marginal environments has been adequate or even a bit high relative to the share of the value of wheat produced in these environments, taking into account both efficiency and equity criteria.**

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[1]Michael Lipton with Richard Longhurst, *continued on page 382*

Over the past two decades, modern cereal varieties have revolutionized food production in many countries, especially in Asia, where the bulk of the rice and wheat area is now planted to improved high-yielding varieties associated with the so-called Green Revolution. However, the gains accruing from the Green Revolution have not been distributed uniformly across environments. Initially at least, improved seed-fertilizer technologies had their largest impact in irrigated and more favourable rainfed areas, while marginal environments characterized by low and variable rainfall (or poor water control in the case of rice) remained relatively unaffected. In view of this uneven diffusion pattern, it has been suggested that the Green Revolution may have widened inter-regional income disparities, because farmers in marginal environments were largely bypassed by the new technologies and in some cases may have been adversely affected through lower producer prices resulting from increased productivity in favoured environments.[1]

Although empirical evidence to support these assertions is still incomplete, some research policy makers have suggested that what they characterize as a historical bias in technology development efforts can be mitigated by reallocating research resources from favoured to marginal environments. This view is held even by some of those who were most actively involved in generating the original Green Revolution technologies. For example, a recent strategic planning document produced by the Technical Advisory Committee (TAC) of the Consultative Group for International Agricultural Research (CGIAR) states:

> Many of the technologies needed for intensification of agriculture in the less-favoured environments are not currently available. Past research has concentrated on areas of potentially high impact and short-term payoff, such as irrigated areas and favourable rainfed zones.
>
> The TAC believes that if a significant technological breakthrough in [less favoured environments] is to be achieved, strong and focused research efforts must begin now and be sustained at substantially increased levels of investment over the long term.[2]

Four arguments are commonly cited in support of a shift in research resources from favoured to marginal environments:

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- Returns to research may now be higher in marginal environments than in favoured environments, because the incremental productivity of further investment targeted at favoured environments is declining.
- A large number of people currently depend on marginal environments for their survival, and increasing population pressure is forcing more people into these areas.
- The people who live in marginal environments are among the poorest groups of the population; therefore increased research investment in these areas is justified on equity grounds.
- Many marginal environments are characterized by a fragile resource base, so for these areas special efforts will be needed to develop appropriate production technologies that will sustain or improve the quality of the resource base over the longer term.

This paper reviews the record of modern varieties in marginal environments and evaluates the case for shifting research resources for crop improvement from favoured to marginal environments, with particular reference to wheat. Wheat is the second most important food crop in the developing world after rice and is currently grown on about 100 million ha. It is also the crop for which modern varieties have had the greatest impact, spreading to over 70% of total wheat area in developing countries.[3]

We first briefly identify the extent of wheat cultivation in marginal environments (defined on the basis of the major limiting factor, moisture) and review the evidence on adoption of modern wheat varieties (MVs) in these environments. We then use a simple congruency model to examine the allocation of research resources at the international level between favoured and marginal environments, as well as the allocation of wheat research resources between favoured and marginal environments in India, a major wheat producing country.

## The extent of wheat cultivation in marginal environments

Marginal environments can be defined in terms of many different agroclimatic stresses. However, by far the most important type of marginal environment for wheat and most other food crops is one in which drought stress is the major factor limiting yields. For the purposes of this paper, we adopt the conceptual definition of marginal environments as those in which drought stress reduces yields (averaged over the longer term) to less than 40% of potential yields defined by available solar radiation.[4]

In an effort to operationalize this definition, data on the extent and importance of different environments in which wheat is grown (distinguished primarily by agroclimatic characteristics) were assembled for the 25 largest wheat-producing countries of the developing world.[5] Based on the amount and distribution of rainfall, combined with subjective judgements of wheat scientists, a subset of these environments was classified as marginal due to moisture stress. After accounting for differences in rainfall and temperature patterns, seven marginal wheat production environments, defined in terms of moisture stress, were distinguished.[6]

To establish whether the marginal environments thus identified were consistent with the conceptual definition, a representative site was selected for each, and the EPIC crop model was used to simulate potential wheat yields under both rainfed and irrigated conditions

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*New Seeds and Poor People*, Johns Hopkins University Press, Baltimore, MD, 1989; Grant M. Scobie, *Investment in Agricultural Research: Some Economic Principles*, Working Paper, CIMMYT, Mexico, DF, 1984.
[2]Technical Advisory Committee of the Consultative Group on International Agricultural Research Secretariat, *CGIAR Priorities and Future Strategies*, FAO, Rome, 1987.
[3]International Maize and Wheat Improvement Center (CIMMYT), *1987–88 CIMMYT World Wheat Facts and Trends, The Wheat Revolution Revisited: Recent Trends and Future Challenges*, CIMMYT, Mexico, DF, 1989.
[4]International Maize and Wheat Improvement Center (CIMMYT), *Toward the 21st Century: CIMMYT's Strategy*, CIMMYT, Mexico, DF, 1989.
[5]Data were collected for all developing countries in which over 100 000 ha were sown to wheat in the early 1980s.
[6]For additional details, see Michael Morris, Abderrezak Belaid and Derek Byerlee, 'Wheat and barley production in rainfed marginal environments of the developing world', Part I in CIMMYT, *1990–91 CIMMYT World Wheat Facts and Trends, Wheat and Barley Production in Rainfed Marginal Environments of the Developing World*, Mexico, DF, CIMMYT, 1991.

**Table 1. Simulated potential wheat yields in seven marginal environments (rainfed *v* irrigated).**

| Representative site | Moisture regime | Dominant wheat types(s)[a] | Average potential rainfed yield[b] (t/ha) (CV) | Average potential irrigated yield[b] (t/ha) (CV) | Potential rainfed/ potential irrigated yield |
|---|---|---|---|---|---|
| Kasba Tadla, Morocco | Rainfed, late drought | Autumn sown, spring habit | 1.09 (44) | 8.17 (8) | 0.13 |
| Marcos Juárez, Argentina | Rainfed, early drought | Autumn sown, spring habit | 2.21 (52) | 10.38 (7) | 0.21 |
| Mirzapur, India | Residual moisture | Autumn sown, spring habit | 1.11 (14) | 6.05 (3) | 0.18 |
| Sagar, India | Residual moisture | Autumn sown, spring habit | 2.29 (25) | 6.72 (6) | 0.34 |
| Diyarbakir, Turkey | Rainfed (variable stress) | Autumn sown, spring habit | 2.99 (27) | 6.07 (8) | 0.49 |
| Ankara, Turkey | Rainfed (variable stress) | Autumn sown, facultative or winter habit | 2.05 (41) | 7.82 (4) | 0.26 |
| Harbin, China | Rainfed (variable stress) | Spring sown, spring habit | 3.64 (28) | 6.95 (12) | 0.52 |

[a]Spring habit wheat can be grown without vernalization (exposure to cold) in the seedling stage.
[b]Calculated from EPIC model simulation results (50-year simulation).

(Table 1).[7] Across the representative sites, the ratio of potential rainfed to potential irrigated yields varied from 0.13 to 0.52, indicating that, except for one site, the subjective classifications corresponded quite well to the conceptual definition.

Table 2 presents data on the global distribution of area planted in developing countries to the two major commercial species of wheat, bread wheat and durum wheat. Nearly one-third of the area planted to bread wheat in developing countries and nearly three-quarters of the area planted to durum wheat is located in marginal environments characterized by frequent drought stress during the growing season. (In interpreting these figures, it should be noted that all irrigated wheat production was classified as taking place in favoured environments.) However, because the total area planted to bread wheat is much larger than that planted to durum wheat, in absolute terms the area planted to bread wheat in marginal environments is much larger than the area planted to durum wheat in such environments. Although marginal environments are widely distributed across the developing world, they tend to be concentrated in West Asia and North Africa, and in South Asia. In West Asia and North Africa, wheat production depends largely on growing season rainfall, while in South Asia wheat is grown on residual moisture after the monsoon has abated.

## Impacts of MVs: the empirical record

### *Trends in yield, area and production*

There now seems little doubt that the improved seed-fertilizer technologies associated with the Green Revolution in wheat have been less

[7]For documentation of the EPIC model, see A.N. Sharpley and J.R. Williams, *EPIC – Erosion/Productivity Impact Calculator*, Technical Bulletin No 1768, USDA, Washington, DC, September 1990.

**Table 2. Area sown to wheat in low-rainfall zones in the developing world, by region, mid-1980s.**

| Region | Low-rainfall bread wheat area (million ha) | Per cent of total bread wheat area in region | Low-rainfall durum wheat area (million ha) | Per cent of total durum wheat area in region |
|---|---|---|---|---|
| West Asia and North Africa | 12.5 | 63 | 5.9 | 74 |
| South Asia | 6.8 | 23 | 1.5 | 94 |
| East Asia | 4.7 | 16 | 0.0 | 0 |
| South America | 4.5 | 50 | 0.1 | 16 |
| Developing countries total | 28.5 | 32 | 7.5 | 72 |

*Source*: CIMMYT mega-environments database.

**Table 3. Growth rates of area, yield and production in selected developing countries (% per year).**

| | Favourable environments | | | Marginal environments | | |
|---|---|---|---|---|---|---|
| **Country (period)** | **Area** | **Yield** | **Production** | **Area** | **Yield** | **Production** |
| India[a] (1970–86) | 3.5 | 2.8 | 6.3 | −2.9 | 1.4 | −1.5 |
| Syria[b] (1968–87) | 6.8 | 6.1 | 13.3 | −0.7 | 3.6 | 2.9 |
| Tunisia[c] (1963–89) | −0.5 | 1.7 | 1.2 | −1.3 | −0.2 | −1.5 |

[a]Bread wheat and durum wheat.
[b]Bread wheat only.
[c]Wheat and barley.

*Source*: Calculated using data from the Indian, Syrian and Tunisian Ministries of Agriculture.

successful in raising yields in marginal environments than in favoured environments. If major wheat-producing countries are divided into those in which wheat is grown largely in favoured environments and those in which wheat is grown largely in marginal environments, wheat yields in the first group of countries grew at 4% annually from 1961 to 1989, as compared to only 2% annually in the second group.[8]

Similar trends are evident within individual countries where disaggregated data are available (Table 3). Yield growth rates in low-rainfall zones have generally averaged less than half of yield growth rates in well-watered zones. Meanwhile, area planted to wheat in marginal environments has grown more slowly than area planted to wheat in favoured environments. In a number of countries, area planted to wheat in marginal environments has actually declined as rainfed land has been put under irrigation and/or as farmers have shifted out of wheat into more profitable alternative crop or livestock enterprises. Conversion of rainfed land to irrigated land has been particularly dramatic in India, where irrigation has spread rapidly in the past three decades, induced in part by the availability of MVs associated with the Green Revolution (Figure 1). As a result of these trends, wheat production in developing countries has increasingly been concentrated in favoured environments, while marginal environments have declined steadily in importance.

The slow growth of production in marginal environments, coupled with rapidly increasing consumption, means that marginal environments have become increasingly food deficit.[9] For example, wheat imports into West Asia and North Africa, where most of the area planted to wheat receives less than 500 mm annual rainfall, now account for nearly 35% of consumption in that region. Over one-third of the wheat

[8]Morris *et al*, *op cit*, Ref 6.
[9]Peter Beaumont, 'Wheat production and the growing food crisis in the Middle East', *Food Policy*, Vol 14, No 1, November 1989, pp 378–384.

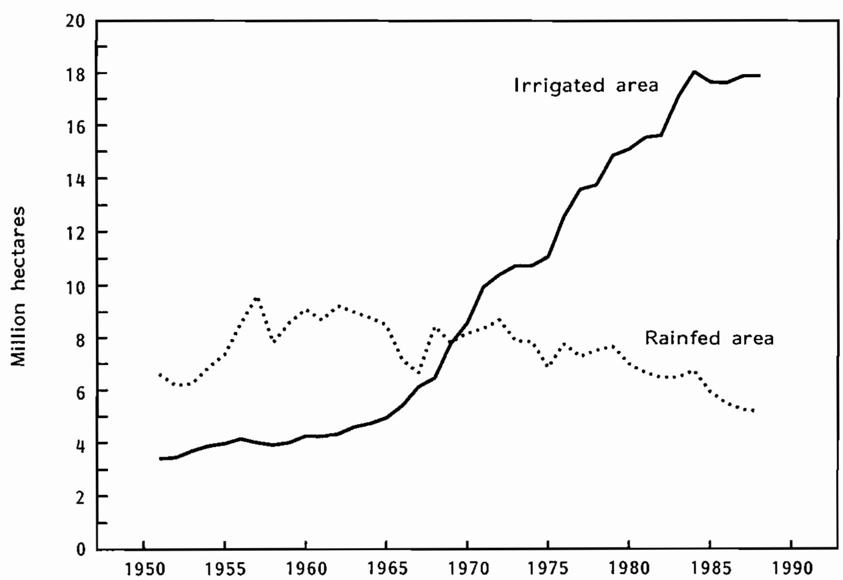


**Figure 1.** Trends in irrigated and rainfed wheat area in India, 1951–88.

*Source*: Derek Byerlee, *Dryland Wheat in India: The Impact of Technical Change and Future Research Challenges*, Economics Working Paper 92-05, CIMMYT, Mexico, DF, 1992.

**Table 4. Adoption of semi-dwarf wheat varieties by moisture regime, developing and industrialized countries, 1980s (% of area harvested sown to semi-dwarf varieties).**

| | Irrigated zones | Rainfed zones: >500 mm rainfall | Rainfed zones: 300–500 mm rainfall | Rainfed zones: <300 mm rainfall | All areas |
|---|---|---|---|---|---|
| Developing countries | 91 | 60 | 45 | 21 | 62 |
| Industrialized countries | 96 | 37 | 50 | na | 40 |
| Total | 92 | 42 | 47 | 21 | 49 |

na = not applicable.

*Source*: CIMMYT database.

imported by developing countries goes to West Asia and North Africa.

*Adoption of MVs in marginal environments*

The different rates of yield growth achieved in favoured versus marginal environments partly reflect differential adoption of improved technology.[10] During the first decade of the Green Revolution (mid-1960s to mid-1970s), MVs spread rapidly in irrigated production zones; the same MVs were often adopted as well in neighbouring well-watered rainfed areas.[11] Since then, MVs have moved into less favourable environments, including areas characterized by low and variable rainfall.[12] The slow but steady expansion of MVs into marginal production zones reflects the development of newer generations of broadly adapted MVs targeted for favourable environments but also suitable for marginal environments, as well as the development of increasing numbers of MVs specifically targeted for marginal production conditions. However, despite evident progress in rainfed zones, adoption of MVs remains modest in the areas of lowest rainfall (Table 4).

*Yield impacts of MVs in marginal environments*

In irrigated zones, adoption of MVs frequently resulted in immediate yield increases of 35–40%, assuming farmers also applied a modest dose of fertilizer.[13] This initial one-time yield boost was usually followed by a period of less dramatic but nonetheless steady yield growth during which the original MVs were gradually replaced by second- and third-generation MVs characterized by higher yield potential and increased resistance to diseases.[14] Since the initial Green Revolution varieties were released, wheat breeders have been able to raise yield potential in favoured environments by about 1% annually, roughly 50 kg/ha/yr.[15]

In marginal environments, yield gains achieved through the adoption of MVs have been much more modest. Where MVs have been released for low-rainfall zones, initial one-time yield gains over traditional varieties (TVs) have usually been less than 20% and often less than 10%.[16] In extremely harsh environments, MVs may offer little or no increase in yield potential, although they tend to exhibit other favourable characteristics such as disease resistance. Over the longer term, annual gains in yield potential attributable to the release of new varieties have rarely averaged more than 0.5% per year in marginal environments.[17] Because of the lower absolute yield levels achieved in marginal environments, such percentage gains often translate into increments of less than 10 kg/ha/yr.

*Factors explaining low adoption of MVs in marginal environments*

At least four factors help explain the slow and incomplete adoption of MVs in marginal environments:

[10]Additional factors such as public investment in infrastructure, availability of production credit and preferential market access also may have contributed to faster rates of yield growth in favoured environments compared to marginal environments.
[11]Dana Dalrymple, *Development and Spread of High-yielding Wheat Varieties in Developing Countries*, USAID Bureau for Science and Technology, Washington, DC, 1986; R.I. Rochin, 'A micro-economic analysis of small-holder response to high-yielding varieties of wheat in West Pakistan', unpublished PhD thesis, Michigan State University, East Lansing, MI, 1971.
[12]Derek Byerlee, *Technical Change and Returns to Wheat Breeding Research in Pakistan's Punjab in the Post-Green Revolution Period*, PARC/CIMMYT Paper 90/7, Pakistan Agricultural Research Council, Islamabad, 1990; CIMMYT, *op cit*, Ref 3; J.A. Peña, L.F. Macagno and G.M. Navarro, *Difusión de las Variedades de Trigo con Germoplasma Méxicana y su Impacto en la Producción Nacional: Un Análisis Económico*, Documento de Trabajo No 3, Instituto Nacional de Tecnología Agropecuaria, Buenos Aires, 1983.
[13]CIMMYT, *op cit*, Ref 4; Lipton with Longhurst, *op cit*, Ref 1; Joseph G. Nagy, 'The Pakistan agricultural development model: an economic evaluation of research and extension expenditures', unpublished PhD thesis, University of Minnesota, St Paul, MN, 1984; S. Sidhu, 'Relative efficiency in wheat production in the Indian Punjab', *American Economic Review*, Vol 64, 1974, pp 743–754.
[14]Increases in *yield potential* (ie genetic gains due to breeding) are measured by growing varieties under strictly controlled experimental conditions in which inputs and management are held constant. Increases in *yields* actually achieved by farmers may reflect changes in yield potential of the varieties being planted, as well as changes in inputs and management.
[15]Steven R. Waddington, Joel R. Ransom, Mahmoud Osmanzai and David A. Saunders, 'Improvement in the yield potential of bread wheats adapted to Northwest Mexico', *Crop Science*, Vol 26, 1986, pp 698–703; Derek Byerlee and Piedad Moya, 'Impacts of international wheat breeding research in the developing world, 1966–1990', draft paper, CIMMYT, Mexico, DF, 1993.
[16]John P. Brennan, 'Spillover effects
*continued on page 386*

*Modest yield gains offered by MVs.* In favoured environments, wheat breeders made spectacular breakthroughs in overcoming the most limiting factor – poor response of TVs to improved fertility. No such breakthroughs have been possible in marginal environments, where the most limiting factor is insufficient moisture.[18]

*Low use of complementary inputs.* Although it is now well established that MVs usually yield better than TVs even under very low input conditions, MVs fully express their high yield potential only with assured water supplies and adequate fertility. Given low and uncertain rainfall in marginal environments, use of fertilizer is risky.[19] In addition, marginal environments are often poorly served by transportation and communication infrastructure, so that many farmers do not have ready access to improved inputs. Under these circumstances use of purchased inputs is low or negligible, and MVs become less attractive.

*Grain quality considerations.* Typically TVs command market price premiums of 15–20% over MVs because of special grain qualities desired by consumers (eg appearance, taste, aroma, cooking quality). In many marginal environments, relatively modest yield differences between MVs and TVs fail to compensate farmers for differences in market prices based on quality. Indeed in some countries (eg India), this quality premium has tended to widen as the supply of TVs is reduced by the expansion of MVs in favourable environments, and farmers in marginal environments have developed speciality markets for high-quality grain.[20]

*Importance of livestock in the farming system.* In most marginal environments, livestock are a major component of the farming system, and wheat is often a dual-purpose grain and fodder crop. In livestock-dominated systems the wheat crop may be grazed lightly during early growth stages[21] or intercropped with fodder crops.[22] The value of straw as a fodder is also high, sometimes exceeding the value of grain in dry years. Under favourable production conditions MVs provide more straw than TVs, but under unfavourable conditions (especially low rainfall and low fertility) MVs may provide less straw, and this may offset any grain yield advantage of MVs.[23]

## Has there been consistent underinvestment in marginal environments?

The empirical evidence summarized above supports the claim that improved seed-fertilizer technologies have had less impact in marginal environments than in favoured environments. Differential rates of yield gain can be explained partly in terms of differential rates of adoption of MVs (and associated management practices), which in turn can be attributed to a combination of technical, economic and institutional factors. This raises an obvious question: Has there been consistent underinvestment in research targeted for marginal environments? The question has important policy implications, because if there has been underinvestment in research targeted for marginal environments, this may explain the relative lack of success achieved in developing MVs for these environments and justify a reallocation of research resources.

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of international agricultural research: CIMMYT-based semi-dwarf wheats in Australia', *Agricultural Economics*, Vol 3, 1989, pp 255–398; Salem Gafsi, *Green Revolution: The Tunisian Experience*, CIMMYT, Mexico, DF, 1976; Nagy, *op cit*, Ref 13; Z. Ahmad, M. Ahmed, D. Byerlee and H. Azeem, *Factors Affecting Adoption of Semi-Dwarf Wheats in Marginal Areas: Evidence from the Rainfed Northern Punjab*, PARC/CIMMYT Paper 91-2, Pakistan Agricultural Research Council, Islamabad, 1991.

[17]K.B.L. Jain and Derek Byerlee, 'Wheat breeding in India: trends and impacts', draft paper, ICAR/CIMMYT, 1993; Byerlee and Moya, *op cit*, Ref 15. Slower progress in breeding for marginal environments does not necessarily reflect a lack of research effort, as we show later. Even in industrialized countries such as Australia, strong wheat breeding programmes targeted at marginal environments have made only modest progress.

[18]In the case of marginal environments defined in terms of limiting factors other than moisture, much faster progress may be possible. For example, wheat breeders in Brazil have made rapid progress in selecting for tolerance to acid soils.

[19]Kutlu Somel, *Effect of Fertilizer Use on the Variability of Barley Yield in Dry Areas*, Discussion Paper No 17, ICARDA, Aleppo, Syria, 1986.

[20]Derek Byerlee, *Dryland Wheat in India: The Impact of Technical Change and Future Research Challenges*, Economics Program Working Paper 92-05, CIMMYT, Mexico, DF, 1992.

[21]Abderrezak Belaid and Michael Morris, *Wheat and Barley Production in Rainfed Marginal Environments of WANA Region: Problems and Prospects*, Economics Working Paper 91-02, CIMMYT, Mexico, DF, 1991.

[22]P. Hobbs, A. Razzaq, N.I. Hashmi, M. Munir and B.R. Khan, 'The effect of mustard grown as a mixed intercrop on the yield of wheat', *Pakistan Journal of Agricultural Research*, Vol 6, No 4, 1985, pp 241–247.

[23]Gregory Traxler and Derek Byerlee, 'A joint product perspective on the evolution and adoption of modern cereal varieties in developing countries', *American Journal of Agricultural Economics* (forthcoming).

## Congruency analysis

Although a number of methods have been proposed for analysing research resource allocation in agriculture, the simplest and by far the most commonly used is congruency analysis, under which the actual prevailing pattern of research resource allocation is compared to an index based on the value of production.[24]

In the standard congruency approach, the share of research resources $R_i$ allocated to environment $i$ is compared to the share of the value of production $V_i$ in environment $i$. $V_i$ is calculated as:

$$V_i = P_i W_i / (\Sigma P_i W_i) \quad (1)$$

where:

$P_i$ = the price of wheat in environment $i$
$W_i$ = the production of wheat in environment $i$.

One commonly used measure of congruency is given by:

$$C = [1 - \Sigma(R_i - V_i)^2] \quad (2)$$

where $0 \leq C \leq 1$, with $C = 0$ indicating no congruency between the allocation of research resources and the value of wheat production, and $C = 1$ indicating perfect congruency.

In the present study, this standard congruency approach was modified to incorporate elements of the scoring approach described by Anderson and Parton.[25] The index of the value of wheat production in each environment was adjusted by weighting the value of production according to three factors. Two of these factors consisted of efficiency criteria relating to the expected payoffs to wheat research expenditures, while the third consisted of an equity criterion relating to the expected distributional effects of technical change:

*Rate of expected research progress.* Standard congruency analysis assumes that the rate of future research progress will be equal in all environments. Since the rate of progress in wheat breeding has historically differed between environments, differences in expected future rates of progress were explicitly considered.

*Strength of the local research effort.* Since the effectiveness of research depends on both national and international efforts,[26] the strength of national wheat breeding programmes was subjectively estimated to take into account possible substitution of local breeding programmes operating within each environment for research by international centres on a given environment.

*Incidence of poverty.* One of the major justifications for investing in research targeted at marginal environments is the alleged higher incidence of poverty in these environments. Consequently, the incidence of poverty across environments was explicitly considered.

Because data on these three weighting factors are available only for politically defined divisions (eg countries and states), rather than for types of wheat production environment (eg favourable *v* marginal), the weighted index $I_i$ of the value of production was calculated as:

$$I_i = \phi_i P_i \Sigma (N_j R_j W_{ij}) \quad (3)$$

[24]Jock R. Anderson and K.A. Parton, 'Techniques for guiding the allocation of resources among rural research projects: state of the art', *Prometheus*, Vol 1, 1983, pp 180–201; Randy Barker, *Methods for Setting Agricultural Research Priorities: Report of a Bellagio Conference*, Working Paper No 88-3, Department of Agricultural Economics, Cornell University, Ithaca, NY, 1988; John McIntire, *Allocation of Livestock Research Resources in Sub-Saharan Africa*, Bulletin 22, ILCA, Addis Ababa, 1985; Vernon W. Ruttan, *Agricultural Research Policy*, University of Minnesota Press, Minneapolis, MN, 1982.
[25]Anderson and Parton, *op cit*, Ref 24.
[26]Douglas Horton, 'Assessing the impact of international agricultural research and development programs', *World Development*, Vol 14, 1986, pp 453–468.

where:

$\phi_i$ = expected rate of research progress in environment $i$. (The expected rate of research progress was based on subjective judgements made by knowledgeable wheat scientists. Given that explicit research attention is now being directed to marginal environments, it was assumed that future progress in these environments will be slightly faster than in the past, although still less rapid than in favoured environments.)[27]

$P_i$ = relative price of wheat in environment $i$. (Durum wheat was assigned a 15% price premium relative to bread wheat based on differences in average long-term world market prices.)

$N_j$ = index of the strength of the national research programme operating in country/state $j$. (This index, based on a survey of wheat breeders with considerable experience in developing countries, ranged from 1 for the strongest programmes to 4 for the weakest.)

$R_j$ = relative incidence of poverty in country/state $j$. (After considering several measures, we selected the reciprocal of the rural wage rate in wheat production because poor people depend largely on wage earnings for income and because lower wage economies use fewer mechanical practices in crop production and hence generate more employment per unit of wheat produced. By dividing through by the domestic price of wheat, we converted this wage rate to real terms in order to avoid problems inherent in comparing incomes across countries with distorted exchange rate regimes.[28] In countries where wage rates were not available for each type of environment, we used the simplifying assumption that within-country wage rate differentials between favoured and marginal environments are the same as for India, a 2:1 ratio.)

$W_{ij}$ = production of wheat in environment $i$ and country/state $j$.

The parameter $V_i$ in Equation (1) was then defined as $V_i = I_i/\Sigma I_i$.

## Two empirical applications of the modified congruency approach

As part of the planning process of the International Maize and Wheat Improvement Center (CIMMYT), the modified congruency approach was used to examine the allocation of CIMMYT's wheat breeding resources among favoured and marginal environments. Headquartered in Mexico, CIMMYT has the global mandate for international research in wheat improvement for developing countries.[29] The exercise was then repeated for India, the second largest wheat producer in the developing world and a country which has a significant portion of its wheat area located in marginal environments.

### *Research resource allocation within CIMMYT*

*Distribution of wheat production in the developing world.* For purposes of this analysis, eight wheat production environments were defined based on type of wheat (bread wheat *v* durum wheat), growth habit (spring *v* winter), and moisture status (irrigated/well watered *v* low rainfall). These eight production environments, which reflect the organization of many wheat breeding programmes, were used to facilitate

[27] In earlier years, little effort was made explicitly to target wheat research at marginal areas. Rather, breeders tended to develop varieties under optimal production conditions, assuming that these varieties would also perform well under marginal conditions (see for example S. Ceccarelli, 'Wide adaptation: how wide?', *Euphytica*, Vol 40, 1989, pp 197–205). Since 1980 many wheat breeding institutes (including CIMMYT) have established programmes specifically targeted at marginal areas, such as the collaborative programme initiated in 1979 involving CIMMYT and ICARDA (the International Center for Agricultural Research for Dry Areas).

[28] Phil Pardey, Johannes Roseboom and Jock R. Anderson, eds, *Agricultural Research Policy: International Quantitative Perspectives*, Cambridge University Press, Cambridge, UK, 1991.

[29] In West Asia and North Africa, CIMMYT pursues its wheat breeding objectives in collaboration with ICARDA. In this paper all references to CIMMYT wheat breeding activities include the work of CIMMYT staff posted to ICARDA headquarters in Aleppo, Syria.

**Table 5. Allocation of CIMMYT wheat breeding resources by wheat production environments, 1989.[a]**

| | Per cent area | Per cent production | Per cent production (weighted)[b] | Per cent resource allocation |
|---|---|---|---|---|
| Spring bread wheat | | | | |
| Favoured environments | 53.0 | 66.2 | 65.7 | 50.7 |
| Marginal environments | 17.8 | 10.6 | 10.6 | 13.3 |
| Spring durum wheat | | | | |
| Favoured environments | 3.9 | 4.8 | 5.1 | 9.6 |
| Marginal environments | 8.9 | 4.8 | 6.6 | 5.8 |
| Winter bread wheat | | | | |
| Favoured environments | 4.1 | 4.9 | 3.4 | 3.3 |
| Marginal environments | 10.3 | 6.6 | 6.4 | 16.6 |
| Winter durum wheat | | | | |
| Favoured environments | 0.2 | 0.6 | 0.5 | 0.3 |
| Marginal environments | 1.7 | 1.4 | 1.7 | 0.3 |
| Total | | | | |
| Favoured environments | 61.2 | 76.5 | 74.7 | 64.0 |
| Marginal environments | 38.7 | 23.4 | 25.3 | 36.0 |
| Congruency index (C)[c] | 0.99 | 0.96 | 0.96 | – |

[a]Excludes China (see text).
[b]Weighted by rate of expected research progress, strength of local research effort and incidence of poverty (see text, Equation 3).
[c]Calculated with respect to actual resource allocation.

classification of research resource allocation data. Production data from the seven types of rainfed marginal environments originally defined on the basis of agroclimatic data were easily regrouped to correspond to these eight environments. An index was then constructed based on the unweighted value of wheat production in each of these eight environments (Equation 1). After application of the three weighting factors in Equation (3), a second index was derived based on the weighted value of wheat production in each of the eight environments.[30]

The indices (unweighted and weighted) used to analyse CIMMYT's resource allocation pattern were constructed including and excluding wheat area in China, the largest wheat producer in the developing world. The results reported below were obtained using the pair of indices in which wheat area in China was excluded, since this case more fairly reflects the decision criteria used by CIMMYT in establishing wheat breeding priorities. Historically, CIMMYT has targeted very few resources to Chinese environments because (a) China has a very strong national wheat research programme, and (b) many wheat production environments in China have highly unusual requirements (for example, a large area is planted to irrigated winter bread wheat and requires varieties that mature extremely early).

*Allocation of wheat research resources within CIMMYT.* Allocation of research resources among CIMMYT's various wheat breeding programmes was determined from data supplied by the CIMMYT Wheat Program on the time allocation in 1989 of CIMMYT Wheat Program staff, breeders as well scientists from other disciplines who directly support wheat varietal development (eg crop physiologists and pathologists).[31] On aggregate, 36% of CIMMYT's wheat breeding effort of 1989 was targeted to the marginal environments delineated above.

*Results of the congruency analysis.* The data on research resource allocation within CIMMYT were then compared to the two indices of the distribution of the value of wheat production (unweighted and weighted). The results summarized in Table 5 indicate that although

[30]The weighting procedure is described in detail in *Toward the 21st Century: CIMMYT's Strategy*, CIMMYT, Mexico, DF, 1989, and *CIMMYT's Five-Year Budget: 1990–1994*, CIMMYT, Mexico, DF, 1989.
[31]Most of the varietal development work performed by CIMMYT wheat staff posted to West Asia was considered targeted at marginal environments, as well as a portion of the varietal development work of CIMMYT wheat scientists posted to South America. Some of the work carried out at CIMMYT headquarters in Mexico was also considered targeted at marginal environments, especially the screening of wheat germplasm for drought tolerance. Implicit in this approach to estimating research resource allocations is the reasonable assumption that each scientist-year devoted to breeding for marginal environments represents the same expenditure of resources as each scientist year devoted to breeding for favoured environments.

39% of the wheat area in developing countries is located in marginal environments, this area accounts for only 23% of the unweighted value of wheat production (due to low yields) and for only 25% of the weighted value of wheat production. The relatively small difference between the unweighted and weighted values of production represents the net effect of the various weighting factors, which tend to offset one another. In particular, marginal environments for most wheat types tend to be characterized by less poverty than favoured environments, reflecting their concentration in West Asia and North Africa, a region of relatively high income (and relatively high rural wage rates). In contrast, some of the largest favoured environments are characterized by extreme poverty, especially the large wheat tracts of South Asia.

Comparison of the weighted value of production with the actual allocation of resources among CIMMYT wheat breeding programmes reveals that in 1989 CIMMYT was probably overinvesting in marginal environments at the expense of favoured environments. Despite the discrepancy, the congruency index based on the weighted value of wheat production is very high (0.96). Most of the difference between the index of the weighted value of wheat production and the actual resource allocation pattern can be attributed to winter bread wheat. CIMMYT only recently established a winter bread wheat programme and has sought to develop a critical mass of research resources to redress the past neglect of this environment.

*Research resource allocation in India*

*Distribution of wheat production in India.* The modified congruency approach was also used to examine the allocation of wheat breeding resources in India. Indian wheat production was divided into three major zones (based on aggregation of agroclimatic zones used by the All India Coordinated Wheat Improvement Programme) and two moisture regimes. Two rainfed moisture regimes were distinguished, both of which may be defined as marginal. In the central and southern regions of the country, wheat is grown under very severe moisture stress, and adoption of MVs is negligible.[32] In the north of the country, rainfed wheat is grown under somewhat better moisture conditions, and MVs are now widely used. In the north, MVs developed for the irrigated areas have often been successful in adjacent rainfed areas. However, in the central and southern regions a separate breeding effort is required for the rainfed areas.

Data on unweighted values of wheat production in India appear in Table 6.[33] Marginal environments constitute 26% of the total national wheat area, but because yields are low in these environments, they account for only 13% of the unweighted value of India's wheat production. Incorporating the weighting factors reduced the value of production in marginal environments to 10%. Although weighting increases the valued assigned to wheat produced in marginal environments because this wheat commands higher market prices (the proportion of durum wheat is greater) and because states characterized by marginal environments feature higher incidence of poverty (although poverty levels are also high in irrigated areas in north-eastern India), this effect is more than offset by a lower expected rate of research progress in marginal environments.

*Allocation of wheat research resources in India.* Data on the number of

[32]Byerlee, *op cit*, Ref 20.

[33]In this analysis, $R_j$ and $W_{ij}$ were defined at the level of the individual state $j$, and $N_j$ (the strength of the local research programme) was dropped from the analysis, since the Indian research programme can be regarded as a nationally coordinated and funded research effort.

**Table 6. Allocation of Indian wheat breeding resources by wheat production environments.**

| | Per cent area | Per cent production | Per cent production (weighted)[a] (1973–90) | Per cent resource allocation | Per cent varieties released (1966–91) |
|---|---|---|---|---|---|
| Irrigated | | | | | |
| North-west Plains | 38.6 | 51.4 | 31.8 | 32.6 | 37.1 |
| North-east Plains | 25.4 | 25.5 | 39.5 | 15.6 | 16.4 |
| Central and Southern | 9.9 | 10.0 | 18.6 | 26.0 | 23.6 |
| Rainfed | | | | | |
| North | 10.1 | 6.5 | 4.5 | 13.5 | 12.9 |
| Central and Southern | 16.1 | 6.6 | 5.6 | 12.3 | 10.0 |
| Total | | | | | |
| Favoured environments | 73.9 | 86.9 | 89.9 | 74.2 | 77.1 |
| Marginal environments | 26.2 | 13.1 | 10.1 | 25.8 | 22.9 |
| Congruency index (C)[b] | 0.96 | 0.92 | 0.92 | – | – |

[a]Weighted by rate of expected research progress and incidence of poverty (see text, Equation 3).
[b]Calculated with respect to actual resource allocation.

wheat varietal trials sown in each environment from 1973 to 1990 were used as an indicator of the allocation of wheat breeding resources across environments in India. During this period, an average of about 500 experiments was sown annually as part of the varietal evaluation and release procedure. Although periodic shifts in emphasis can be detected in India's agricultural research priorities as stated in the Five Year Plans implemented between 1973 and 1990, over the entire 17-year period research funding patterns as revealed by the trial data seem to have been quite stable. Funding patterns show no significant changes except for a small decline in the share of resources allocated to the dryland wheat areas of central and southern India – a trend consistent with the steady conversion of dryland wheat area to irrigated area in this part of the country.

*Results of the congruency analysis.* Based on the distribution of wheat production in India, the data on the actual pattern of investment in wheat research give an overall congruency index (C) of 0.92, which is relatively high compared to other studies.[34] Interestingly, as in the case of CIMMYT, the actual resource allocation pattern in India is more highly congruent with area sown (0.96).

Once again, there is no evidence of underinvestment in research targeted at marginal environments. Overall, some 26% of the research resources in wheat breeding have been allocated to low-rainfall production zones, which account for only 10% of the weighted value of wheat production. The discrepancy exists not only at the aggregate national level; significant discrepancies between actual resource allocation and the weighted value of wheat production also occur within irrigated zones (especially the allocation between the North-east Plains and central and southern India).

An indicator of the productivity of the research effort is provided by the share of the number of varieties released for each environment (Table 6). In India the pattern of varietal releases closely follows the pattern of resource allocation (with a somewhat higher rate of varietal releases in the traditional irrigated wheat areas of north-western India). However, the *adoption* of released varieties in the rainfed areas has been much less complete than in the irrigated areas, for reasons similar to those outlined above.[35]

These results suggest that to justify allocating additional resources to wheat breeding targeted at marginal environments, Indian policy mak-

[34]See Jim G. Ryan, 'Efficiency and equity considerations in the design of agricultural technology in developing countries', *Australian Journal of Agricultural Economics*, Vol 28, 1984, pp 109–135.
[35]Byerlee, *op cit*, Ref 20; Jain and Byerlee, *op cit*, Ref 17.

ers need to believe that breeding gains in these environments will be much more rapid than in the past (indeed, more rapid than projected progress in favoured environments), or they need to attach a very high weight to alleviating poverty. In the latter case, research targeted at irrigated wheat in the north-east would also be a high priority.

## Conclusions

The evidence summarized in this paper confirms that improved seed-fertilizer technologies for wheat have been less widely adopted in marginal environments and have had less of an impact than in favoured environments. These trends hold true at the global level as well as within individual countries.

However, lower rates of adoption and less dramatic yield gains do not necessarily mean that there has been systematic underinvestment in research targeted for marginal environments. Agroclimatic and socioeconomic constraints severely limit potential yields in marginal environments, so it would be unrealistic to assume that yield increases achieved in marginal environments from adoption of seed-fertilizer technology will be similar to those achieved in favoured environments. Therefore impact *per se* (as measured by varietal adoption patterns and relative rates of yield growth) should probably not be used to guide research resource allocation between favoured and marginal environments. From a policy perspective, it is more important that the level of research investment targeted at marginal environments be consistent with the value of wheat produced in those environments, with the number and poverty level of the people who live there, and with the prospects for achieving technological progress. In these respects, while marginal environments certainly merit the attention of wheat researchers, their importance must be kept in perspective in view of the far greater importance of favoured environments. The common practice, probably unintentional, of evaluating the importance of marginal environments in terms of crop area located in those environments considerably overstates their significance because of their lower land productivity (actual and potential).

These conclusions are corroborated by congruency analysis carried out for CIMMYT's wheat breeding programmes, as well as for wheat breeding research in India. Our analysis suggests that marginal environments have received at least their share of research resources as measured by the proportional value of wheat production in these environments, once appropriate adjustments are made for relative poverty levels, the strength of local breeding efforts and expected rate of research progress. If anything, our results suggest that, for CIMMYT at least, there may have been modest overinvestment in breeding for marginal environments in 1989 (although on the basis of the resource allocation model developed here, research priorities are now being adjusted to conform more closely to the pattern suggested by the weighted index). On the whole, our findings therefore do not support the claim that *more* research resources should be allocated to marginal environments, at least not for wheat breeding.

Undoubtedly, CIMMYT's modest overinvestment in marginal environments was influenced by the need to demonstrate that marginal environments were being explicitly targeted, since many of CIMMYT's donors and client countries were under the impression (perhaps mistaken) that goals of equity and poverty alleviation could best be achieved by focusing additional attention on marginal environments. However, the importance of continuing to give greatest weight to favoured environments is supported by evidence that there are significant positive spillovers from technical change in favoured environments which benefit poor people in marginal environments through lower food prices, increased employment and higher wages.[36] These spillovers may actually exceed the positive benefits generated through research targeted specifically at marginal environments.[37]

These results need to be qualified in two ways. First, it is important to recognize that MVs represent a land-saving technology. Since as much as half of the land in marginal environments is typically left fallow, production technologies in most marginal environments are relatively land extensive; thus MVs do not help relieve the key constraint of marginal environments, which is lack of moisture. Research focused on technologies that enhance moisture conservation and efficiency of moisture utilization (eg conservation tillage, crop rotation, clean fallow, collection of water runoff, improved weed control) may have a much larger payoff in marginal environments. Therefore repeating the analysis with a focus on research related to crop and soil management, rather than on breeding, might give quite different results.

Second, it should be noted that, compared to most other crops, wheat is grown disproportionately in favoured environments. For example, whereas only 20% of all arable land in developing countries is irrigated, approximately 40% of the area planted to wheat is irrigated. Hence a multicommodity analysis would probably allocate more resources to marginal environments, since crops other than wheat are more important in these environments. The analysis in this paper for one important crop, wheat, should be extended to other crops and research problems.

[36]Christina David and K. Otsuka, 'The Green Revolution and income distribution across production environments in Asia', paper presented at the Rice Research Seminar, IRRI, Los Baños, Philippines, 1992.

[37]Mitch Renkow, *Modeling the Aggregate Effects of Technological Change on Income Distribution in Pakistan's Favored and Marginal Production Environments*, Economics Paper No 4, CIMMYT, Mexico, DF, 1991.