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Abstract

A simple congruency model is used to examine the case for shifting research resources from favored to marginal environments, with particular reference to wheat breeding. Preliminary analysis suggests that research resources invested in marginal environments of LDCs have been roughly proportional to the weighted value of wheat production in these environments.

Introduction

Over the past two decades, modern semi-dwarf wheat varieties (MVs) originating in Mexico have revolutionized wheat production in countries such as India, Pakistan, and Turkey (Dalrymple). However, the gains accruing from the so-called Green Revolution in wheat have not been distributed uniformly across environments. Initially at least, the improved seed-fertilizer technologies seemed to have their largest impact in irrigated and high-rainfall areas, while marginal production environments characterized by low and variable rainfall remained relatively unaffected. In view of this uneven diffusion pattern, it has been suggested that the Green Revolution 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 favored environments (Lipton with Longhurst; Scobie).

Although empirical evidence to support these assertions is incomplete, some policy makers have urged that research resources be re-allocated from favored to marginal environments. Four arguments are commonly cited in support of such a shift:

1. Returns to research may now be higher in marginal environments than in favored environments, because the marginal productivity of further investment targeted at favored environments is expected to decline.

2. A large number of people currently depend on marginal environments for their survival, and increasing population pressure is forcing more people into these areas.

3. The people who live in marginal areas are among the poorest groups of the population; therefore, increased research investment in these environments is justified on equity grounds.

4. 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 be sustainable over the longer term.

This paper reviews the record of MVs in marginal areas and evaluates the case for shifting research resources from favored to marginal environments, with particular reference to wheat. Wheat is the second most important crop in the developing world after rice and is currently grown on about 100 million ha. It is also the crop for which MVs have had the greatest impact, spreading to two-thirds of total planted area in developing countries (CIMMYT 1989a). We first briefly identify the extent of marginal

environments for wheat (defined on the basis of the major limiting factor, moisture) and review the impact of MVs in these environments. We then use a simple congruency model to analyze the allocation of research resources between favored and marginal environments for all developing countries and for a major wheat-producing country, India.

The extent of marginal environments for wheat

The International Maize and Wheat Improvement Center (CIMMYT) is an autonomous, international, nonprofit scientific research and training institution headquartered in Mexico, with regional offices throughout the developing world. CIMMYT operates a global program of maize, wheat, and triticale improvement, investigates economic issues related to these crops, and provides various forms of support to about 100 national agricultural research programs responsible for maize and wheat in developing countries.

Wheat scientists at CIMMYT define dryland marginal environments for wheat as those in which drought stress reduces average potential yields to less than 40% of potential yields defined by available solar radiation (CIMMYT 1989b). In an effort to operationalize this conceptual definition, data on the extent and importance of different wheat production environments (distinguished primarily by agroclimatic characteristics) were assembled for the 25 largest wheat-producing countries of the developing world.[1] Based on the amount and distribution of rainfall, combined with subjective judgements of wheat scientists, a subset of these wheat production zones was classified as marginal due to moisture stress. After accounting for differences in rainfall and temperature patterns, seven different types of rainfed marginal environments were distinguished (for additional details, see Morris et al.).

In order to establish whether or not the dryland marginal environments thus identified were consistent with the conceptual definition, a representative site was selected for each type of marginal environment, and the EPIC crop model was used to simulate potential wheat yields under both rainfed and irrigated conditions (Table 1).[2] Across the representative sites, the ratio of potential rainfed to potential irrigated yields varied from 0.13 to 0.48, indicating that the subjective classifications corresponded quite well to the conceptual definition and suggesting that the CIMMYT database represented a reasonable means of estimating the extent and importance of marginal environments.

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1 Data were collected for all developing countries in which over 100,000 ha were sown to wheat in the early 1980s.

2 For documentation of the EPIC model, see Williams et al. 1990, Sharpley and Williams 1990.

Table 1. Simulated potential wheat yields in seven marginal mega-environments (rainfed vs. irrigated)

Repre-sentative site	Moisture regime	Dominant wheat type(s)	Average potential rainfed yield[a] (t/ha) (CV)	Average potential irrigated yield[a] (t/ha) (CV)	Potential rainfed/ potential irrigated yield
Kasba Tadla, Morocco	Rainfall, late drought	Autumn sown, spring habit	1.09 (44)	8.17 (8)	0.13
Marcos Juárez, Argentina	Rainfall, 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	Rainfall (variable)	Autumn sown, spring habit	2.99 (27)	6.07 (8)	0.49
Ankara, Turkey	Rainfall (variable)	Facultative or winter	2.05 (41)	7.82 (4)	0.26
Harbin, China	Rainfall (variable)	Spring sown, spring habit	3.64 (28)	6.95 (12)	0.52

[a] Calculated from EPIC model simulation results (50 year simulation).

Table 2 presents data on the global distribution of rainfed marginal environments for 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 during the growing season. (Because much more bread wheat is produced in the world than durum wheat, these percentages are misleading. Even though a relatively small percentage of bread wheat is produced in marginal environments, the total amount of bread wheat produced in marginal environments is still four times as large as the amount of durum wheat produced in marginal environments.) Although marginal environments are widely distributed, wheat production in these environments is concentrated in West Asia and North Africa and South Asia.

Table 2. Area sown to wheat in low-rainfall zones of selected developing countries, mid-1980s

	Low-rainfall bread wheat area (million ha)	Percent of bread wheat area (%)	Low-rainfall durum wheat area (million ha)	Percent of durum wheat area (%)
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
South America	4.5	50	0.1	16
Developing countries total	28.5	32	7.5	72

Source: CIMMYT mega-environments database.

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 successful in raising yields in marginal environments than in favored environments. If major wheat-producing countries are divided into those in which wheat is grown largely in favored 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 (Morris et al.).

Table 3. Growth rates of area, yield, and production by moisture regime in selected countries (%/year)

	Favorable 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.

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 in favored environments; in a number of countries, area planted to wheat in marginal environments has actually declined as rainfed areas have been put under irrigation. As a result of these trends, wheat production in developing countries has increasingly been concentrated in favored environments, while marginal environments have declined steadily in importance (Byerlee 1991).

Adoption of MVs in marginal environments

During the first decade of the Green Revolution (1965-75), MVs spread mainly into irrigated production zones, although the same varieties targeted for irrigated zones were often adopted as well in neighboring well-watered rainfed areas (Rochin). Since then, MVs have moved slowly but steadily into less favorable areas, including areas characterized by low and variable rainfall (Byerlee 1990; CIMMYT 1989a; Pena et al.). In most cases, the spread of MVs to more marginal rainfed areas has involved varieties developed specifically for those areas, rather than spillover of varieties developed for irrigated areas, as happened in the early years. However, despite evident progress, adoption remains low in the areas of lowest rainfall (Table 4).

Table 4. Adoption of MVs by moisture regime, developing and developed countries, 1980s

	Irrigated zones	>500 mm rainfall	300-500 mm rainfall	<300 mm rainfall	All areas
	(Percent of area harvested sown to MVs)				
Developing countries	91	60	45	21	62
Industrialized countries	96	37	50	na	40
Total	92	42	47	21	49

Source: CIMMYT database.

Yield impacts of MVs

In irrigated zones, adoption of MVs resulted in immediate yield increases of about 40%, assuming farmers were using modest doses of fertilizer (CIMMYT 1989b; Lipton with Longhurst; Nagy; Sidhu). This initial one-time yield boost was followed by a period of slow but steady yield growth during which the first MVs were gradually replaced by second- and third-generation MVs characterized by higher yield potential and increased resistance to insects and especially diseases. Since 1960 wheat breeders have been able to raise yield potential in favored environments by about 2% annually (roughly 50 kg/ha/yr). However, this rate of gain appears to have slowed somewhat in recent years; from 1970 to 1990, yield potential increased at about 1% annually (Byerlee 1990; Waddington et al.).

In marginal environments, yield gains achieved through the adoption of MVs have been much more modest. Where MVs have been released for marginal areas, initial one-time yield gains over traditional varieties have usually been less than 20% and often less than 10% (Brennan; Gafsi; Nagy). In extremely harsh environments, MVs may offer little or no increase in yield potential, although they tend to exhibit other favorable characteristics, such as disease resistance. Over the longer term, breeders have rarely averaged annual gains in yield potential due to the release of new varieties of more than 0.5% per year in marginal environments.[3] Because of the lower base yield in marginal environments, such percentage increments translate into gains 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:

1. Modest yield gains offered by MVs. Wheat breeders made spectacular breakthroughs in overcoming the most limiting factor in favored environments -- poor response to improved fertility. No such breakthroughs have been possible in rainfed marginal environments, where the most limiting factor is insufficient moisture.[4]

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3 Slower progress in breeding for marginal environments does not necessarily reflect a lack of research. Even in industrialized countries such as Australia, strong wheat breeding efforts targeted at marginal environments have made only modest progress.

4 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.

2. Lack of incentives to use complementary inputs. Although it is now well established that MVs usually yield better than traditional varieties even under very low input conditions, MVs fully express their higher yield potential only with assured water supplies and adequate fertility. Given low and uncertain rainfall in marginal environments, use of inorganic fertilizer is risky, and farmers may lose their fertilizer investment in dry years. In addition, marginal environments for wheat production tend to be located in remote areas poorly served by transportation and communication infrastructure, so that many farmers do not have ready access to improved inputs. Under these circumstances, economic incentives to use purchased inputs are reduced, and MVs become less attractive.

3. Grain quality considerations. Traditional wheat varieties grown in rainfed production zones typically command market price premiums of 15-20% over MVs because of special grain qualities desired by consumers (e.g., appearance, taste, aroma, cooking quality). In many marginal environments, relatively modest yield differences between MVs and traditional varieties fail to compensate farmers for differences in market prices, causing them to reject MVs in favor of lower-yielding (but more profitable) traditional varieties.

4. 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 lightly grazed during early growth stages (Belaid and Morris), or it may be intercropped with fodder crops (Hobbs et al.). Where meat-to-grain price ratios are high, the value of straw often is also high, sometimes exceeding the value of grain in dry years. Under favorable production conditions, MVs provide more straw than traditional varieties, but under unfavorable conditions (especially low rainfall and low fertility), MVs may provide less straw. In some cases, the decreased quantity (and sometimes quality) of straw offsets any grain yield advantage, providing farmers with an additional reason to reject MVs in favor of traditional varieties.

Research resource allocation targeted at marginal environments

The empirical evidence would thus appear to support the claim that improved seed-fertilizer technologies have made less of an impact in marginal environments than in favored environments. Differential rates of yield gains 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 and economic factors which make traditional varieties more attractive than MVs. These divergent trends cast doubt on whether current improved technologies are appropriate for marginal environments and raise an obvious question: Has there been consistent underinvestment in research targeted for marginal environments?

Congruency analysis

Although a number of methods have been proposed for analyzing 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 (Anderson and Parton; Barker; McIntire; Ruttan). A modified congruency approach was used to examine the allocation of CIMMYT research resources to wheat breeding for favored and marginal environments. The exercise was then repeated for India, the second largest wheat producer in the developing world (after China) and a country which has a significant portion of wheat area located in marginal environments.

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 simply calculated as:

$$V_i = P_i W_i / (\sum P_i W_i) \qquad (1)$$

where:

P_i = the price of wheat in environment i

W_i = the production of wheat in environment i

One measure of congruency is given by:

$$C = [1 - \sum (R_i - V_i)^2] \qquad (2)$$

In the present study, this standard congruency approach was modified to incorporate elements of the scoring approach described by Anderson and Parton. The index of the value of wheat production in each environment was modified by weighting the value of production according to the following factors:

1. 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 historically has been lower in dryland environments, it was assumed that progress in marginal areas would continue to be slower in the future, but that the gap would narrow since diminishing returns may have been reached in breeding for favorable environments.

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

3. **Strength of the local research effort.** This was estimated subjectively to take into account the capacity of the national breeding programs operating within each environment. CIMMYT's involvement in local wheat research was also considered, because research impacts are a combination of international and national efforts (Horton).

Since data on most of these weighting factors are available only for politically defined divisions (e.g., countries and states), rather than by type of wheat production environment (e.g., favorable vs. marginal), the weighted index I_i of the value of production was calculated as:

$$I_i = g_i \, P_i \, \sum \, (N_j \, R_j \, W_{ij}) \qquad (3)$$

where:

g_i = expected rate of research progress in environment i

P_i = relative price of wheat in environment i

N_j = index of the strength of the national research program operating in country/state j (ranging from 1 for the strongest programs to 4 for the weakest)

R_j = relative incidence of poverty in country/state j (index based on the reciprocal of the rural wage rate expressed in kg wheat/day to convert to real terms)

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

The parameter V_i in equation (1) was then simply defined as $V_i = I_i \, / \, \sum \, I_i$.

Research resource allocation within CIMMYT

Allocation of research resources among CIMMYT's wheat breeding programs was analyzed using the environmental database described earlier. For purposes of this paper, eight wheat production environments were defined based on type of wheat (bread wheat vs. durum wheat), growth habit (spring

vs. winter), and moisture status (irrigated/well-watered vs. low-rainfall). Rates of expected research progress were assigned to each environment based on judgements made by knowledgeable wheat scientists; it was assumed that progress in marginal areas would generally be faster than in past years, although less rapid than in favored areas. Durum wheat was assigned a 15% price premium based on differences in average long-term world market prices. Data on rural wage rates and subjective estimates of the strength of the national breeding program were taken from the CIMMYT database.

Table 5. Allocation of CIMMYT wheat breeding resources by wheat production environments, 1989

	Percent area	Percent production (unweighted)	Percent production (weighted)	Percent resource allocation
Spring bread wheat				
- favored environments	51.1	61.1	59.7	47.4
- marginal environments	16.3	7.8	5.7	16.6
Spring durum wheat				
- favored environments	10.6	17.6	20.6	3.3
- marginal environments	11.5	6.1	6.1	16.6
Winter bread wheat				
- favored environments	2.8	3.2	4.2	9.6
- marginal environments	6.3	3.1	2.3	5.8
Winter durum wheat				
- favored environments	0.2	0.4	0.5	0.3
- marginal environments	1.2	0.9	0.9	0.3
Total				
- favored environments	64.6	82.2	85.1	60.6
- marginal environments	35.4	17.9	14.9	39.4
Congruency index (C)[a]	0.99	0.94	0.93	----

[a] Calculated with respect to actual resource allocation (right-hand column).

Source: Calculated by the authors.

The results summarized in Table 5 indicate that although marginal wheat environments make up 35% of wheat area in developing countries, they account for only 18% of the unweighted value of production (due to low yields) and only 15% of the weighted value of production. The difference between

the unweighted and weighted values of production represents the net effect of the various weighting factors. In particular, marginal areas tend to be less poor than favored areas, reflecting their concentration in West Asia and North Africa, a region of relatively high incomes (and relatively high rural wage rates). In contrast, some of the largest favored environments are characterized by extreme poverty, especially the large wheat tracts of India.

A comparison of the index of the weighted value of production (or the "allocation index") with the actual allocation of resources among CIMMYT wheat breeding programs indicates that CIMMYT may be overinvesting in marginal areas at the expense of favored areas, especially for bread wheat. Overall, CIMMYT invests 39% of its wheat breeding resources in marginal areas, significantly higher than the 15% which would appear to be justified based on the allocation index. Despite this discrepency, the congruency index based on the weighted value of production is still quite high (0.93). Interestingly, the congruency index based on area planted to wheat is close to unity (0.99), suggesting that the overinvestment in marginal areas may be due to the fact that CIMMYT has tended to allocate resources according to area, rather than production.

Research resource allocation in India

The congruency approach was also used to assess the allocation of wheat breeding resources in India. Indian wheat production was divided into three major zones (following approximately the agroclimatic zones used by the All India Coordinated Wheat Improvement Program) and two moisture regimes. Indices of the unweighted and weighted values of wheat production in India appear in Table 6. In unweighted terms, wheat produced in marginal environments comprises 13% of the value of total wheat production in India. Incorporating the weighting factors reduces the figure to 10%. The additional value assigned to wheat in marginal environments due to its higher market value and due to the higher incidence of poverty in states characterized by marginal environments is more than offset by a lower expected rate of research progress in marginal environments.

How do these results compare to the actual pattern of investment in wheat research in India? Data are not available on the allocation of research resources to dryland vs. irrigated wheat breeding, but the number of varietal releases by moisture category is probably a good proxy for research expenditures.[5] The MVs released in India during 1961-86 were used to construct an index of estimated research expenditures. The overall congruency index C is 0.94, which is relatively high compared to other studies

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5 Some wheat scientists disagree, however, arguing that more resources go into producing each variety targeted for marginal environments. If true, this would imply that the present analysis if anything understates the investment in marginal areas.

(e.g., Ryan). The biggest discrepancies occur within irrigated areas (especially the allocation between the Northeast Plains and Central and Southern India), rather than between favored and marginal environments.

Table 6. Congruency of allocation of wheat breeding resources in India

	Percent area	Percent production (unweighted)	Percent production (weighted)	Percent resource allocation
Irrigated				
- Northwest	38.6	51.4	51.8	31.0
- Northeast Plains	25.4	25.5	39.5	22.4
- Central and Southern	9.9	10.0	18.6	36.2
Rainfed				
- North	10.1	6.5	4.5	6.9
- Central and Southern	16.1	6.6	5.6	3.4
Total				
- favored environments	73.9	86.9	89.9	89.6
- marginal environments	26.2	13.1	10.1	10.3
Congruency index (C)[a]	0.91	0.89	0.94	---

[a] Calculated with respect to actual resource allocation (right-hand column).

Source: Calculated by the authors.

These preliminary results suggest that in order to justify increased research targeted at marginal environments, Indian policy makers need to believe that research progress in these environments will be much more rapid than in the past (indeed, more rapid than projected progress in favored environments), *or* they need to attach a very high weight to alleviating poverty. In the latter case, research targeted at irrigated wheat in the northeast would also have to be prioritized.

Conclusions

Although the empirical record is still incomplete, improved seed-fertilizer technologies for wheat appear to have been less widely adopted in marginal environments and to have had less of an impact than in favored environments. These trends hold true both 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 will be similar to those achieved in favored 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 favored 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 favored 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 the CIMMYT wheat breeding program, as well as for wheat breeding research in India. Preliminary analysis suggests that the amount of research resources invested in marginal environments has been roughly proportional to the value of wheat production in these environments, taking into account relative poverty, the strength of local breeding efforts, and expected research progress. If anything, our results suggest modest overinvestment within CIMMYT in breeding for marginal areas. Our findings therefore do not support the claim that research resources should be reallocated to work targeted at marginal environments, at least not for wheat breeding.

These results need to be qualified in two ways. First, it is important to recognize that MVs (grown using adequate levels of fertilizer) represent a land-saving technology. Since as much as half of the land in marginal environments is typically left fallow, 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 efficiency of moisture conservation and

utilization (e.g., conservation tillage, crop rotation, clean fallow, collection of water runoff, improved weed control, irrigation management) may have a much larger payoff in marginal environments. Thus, 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 favored 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 likely allocate more resources to marginal environments, since crops other than wheat are more important in these environments.

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