Adoption Ceilings and Modern Coarse Cereal Cultivars in India

Hans G. P. Jansen, Thomas S. Walker, and Randolph Barker

The concept of, and evidence for, regional adoption ceilings is assessed for modern coarse cereal cultivars in India. Adoption is defined as the proportion of total area of a given coarse cereal planted to modern cultivars. Agroclimatic and soil differences are more important than disparities in infrastructure in explaining the variation across regions in estimated adoption ceilings. Qualitatively different modern cultivars from those now released are necessary to change regional adoption behavior. The results support an agricultural research strategy that gives higher priority to more regionally oriented breeding and testing programs in preference to the past emphasis on wide adaptation.

Key words: adoption ceilings, coarse cereals, modern cultivars.

Modern cereal cultivars were released throughout India in the 1960s.[1] Across the major cereals of wheat, rice, sorghum, pearl millet, and maize, the modern cultivars (MCs) represented a substantial change from local varietal types. MCs were photoperiod-insensitive, fertilizer-responsive, and short statured. Grown with good management on fertile soil with access to reliable rainfall, they gave markedly heavier grain yields than local varieties.

By the mid-1980s, the pattern of diffusion of MCs varied sharply among cereals and across space. The wheat MCs had largely completed their diffusion process (Dalrymple 1986b). Rice MCs had also been adopted on most of the area planted to paddy (Dalrymple 1986a). Coarse cereal MCs had penetrated into many major producing regions, but their uptake by farmers has been less uniform than for wheat and rice MCs (table 1).

In India, coarse cereals are mainly produced in the harsh production environment of rainfed agriculture which is often beset by considerable location specificity in the incidence of physical and biotic stress. Rural infrastructure in the major coarse cereal-growing regions is also often poor relative to the better endowed, more heavily irrigated areas (Wanmali).

A notable characteristic about the adoption performance of coarse cereal MCs in India is the persistence of "ceiling" levels of adoption during the 1980s. For many producing regions, adoption has oscillated around a plateau significantly less than 100%. This research seeks to (*a*) assess the relative importance of climatic, edaphic, and infrastructural factors in constraining regional adoption, and (*b*) to draw implications for agricultural investment and research strategy to increase the hypothesized ceiling levels of MC adoption.

The research represents a departure from the previous literature (Griliches 1957, Martinez, Wattleworth) in two important ways. First, the emphasis is not on explaining interregional variation in the speed of diffusion but on understanding spatial differences in endogenously estimated ceiling rates of adoption (Griliches 1980). This emphasis addresses enduring regional imbalances in MC adoption and reflects the view that welfare levels are usually determined by who ultimately adopts rather than by who first adopts (Gerhart). Second, the focus is on whether aggregate diffusion analysis of secondary data can generate insight on the desirability of investing research resources in specific-trait improvement.

Hans G. P. Jansen is an agricultural economist with the International Livestock Centre for Africa Sub-Humid Research Site, Kaduna, Nigeria. Thomas S. Walker is principal economist with the International Crop Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh India. Randolph Barker is a professor of agricultural economics, Cornell University.

The authors thank Tim Mount for his advice on the econometrics, Rolf Mueller for his comments on an earlier version of the paper, and three *Journal* reviewers for their constructive comments and suggestions.

[1] The word cultivar includes both open-pollinated varieties and hybrids.

Table 1. Progress of Area Under Modern Cultivars in India, 1966–67 to 1984–85

	Year						
Crop	66–67	71–72	75–76	80–81	82–83	83–84	84–85
Rice[a]	0.88	7.41	12.44	18.23	18.84	21.74	23.44
	(2.5)	(19.6)	(32.8)	(45.4)	(49.9)	(53.0)	(60.4)
Wheat	0.54	7.86	13.46	16.10	17.84	19.39	19.58
	(4.1)	(41.1)	(74.7)	(72.3)	(77.1)	(79.5)	(83.1)
Sorghum	0.19	0.69	1.96	3.50	4.37	5.28	5.09
	(1.1)	(4.1)	(12.1)	(22.1)	(27.1)	(32.5)	(32.5)
Pearl	0.06	1.77	2.90	3.64	4.71	5.42	5.25
millet	(0.5)	(15.0)	(25.7)	(31.2)	(43.1)	(45.9)	(49.1)
Maize	0.21	0.44	1.13	1.60	1.72	1.91	2.06
	(4.2)	(7.6)	(19.3)	(26.7)	(30.1)	(32.4)	(36.2)

Source: Government of India: various issues of *Indian Agriculture in Brief, Agricultural Situation in India,* and *Economic Survey;* Dalrymple (1986a,b).
[a] First row for each crop is million hectares; second row is percentage of total crop area.

Adoption Ceilings: Concept and Context

The diffusion path of aggregate adoption of a new technology often resembles a sigmoid curve, largely reflecting the dynamics of the spread of information (Feder, Just, and Zilberman). The long-run upper limit or ceiling on aggregate adoption is determined by the economic characteristics of the new technology and by the state of the economy (Griliches 1980).

Although long-run upper limits are associated with permanency, these levels can shift upwards over time in response to "second generation" technical change. For example, in 1957 Griliches estimated aggregate diffusion ceilings on corn hybrids of less than 100% for many states and crop reporting districts in the United States. Shortly thereafter, hybrids had entirely replaced open-pollinated varieties in the same regions (Dixon).

The need for and the impact of second generation technical change in shifting up initial adoption ceilings is illustrated in figure 1 for two cereal-producing regions. The first is the idealized case; the second is what often happens. In homogenous region A, the first-released groups of MCs are economically and uniformly superior to the local varieties; consequently, the long-run level of adoption of 100% is quickly attained. In contrast in heterogenous region B, the first-generation MCs are more profitable than local varieties in only some selected locales, probably those of higher production potential. As a result, the adoption ceiling falls far short of 100%. Suppose at time t^* second-generation MCs are released to farmers. If the second-generation MCs are successful in addressing the location-specific problems of earlier MCs, full

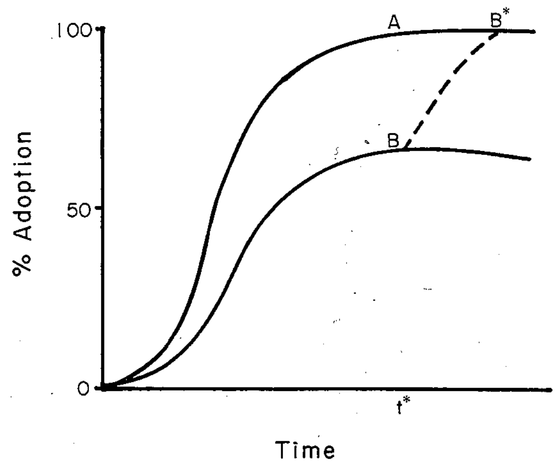

Figure 1. Adoption ceilings and second generation technical change in two regions

adoption may still occur but on a secondary diffusion path such as the dotted line in figure 1.

Although the concept of an adoption ceiling is potentially useful, it can be empirically elusive. Because agricultural technologies are ultimately location specific and because administrative reporting units are usually comprised of multiple soil and rainfall environments, ceiling levels of adoption can vary substantially. More important, data on area planted to specific cultivars are often not available. Usually, one has access only to the area planted to MCs as a whole. Therefore, one cannot distinguish between the adoption profiles of the first and second generation MCs in figure 1.

In other words, estimating an aggregate adoption curve on *OBB** may give results that are neither fish nor fowl. As Griliches (1980) points out, the slow upper tail may be associated with the lack of well-adapted MCs, thereby confounding summary information on the speed of acceptance of the innovation. To overcome this problem, Griliches recommends that aggregate adoption analysts use a model with an endogenous and shifting ceiling parameter. Alternatively, one can choose a time horizon that largely restricts the analysis to the first wave of MCs, as occurs in this paper.

With the exception of some maize composites, the first wave of modern coarse cereal cultivars was largely synonymous with hybrids. Exotic lines and foreign breeding efforts played a crucial role in their development, and selection procedures in breeding were heavily biased towards yield potential and wide adaptability. Improved open-pollinated sorghum and pearl millet varieties were introduced commercially on a wider scale only in the early to mid-1980s.

By the mid-1980s in India, second and third generation modern coarse cereal cultivars had been introduced only recently or were not that qualitatively distinct from their first generation counterparts. Incentives in public-sector plant breeding still centered on national yield performance in multilocational trials. The emphasis on wide adoption did not explicitly address the more specific problems of ecological niches. Hence, except for the second generation pearl millet hybrids and to a lesser extent later maize hybrids and composites, the period ending in 1983–84 corresponds mainly to the diffusion of the first batch of MCs.

Later generation technical change is not the only plausible explanation for upward shifts in adoption ceilings in figure 1. Expanding and deepening rural infrastructure could also lead to increasing equilibrium adoption levels. But changes in rural infrastructure likely would have a greater effect on the earlier than on the later properties of the diffusion process. Improving rural infrastructure can result in higher profitability of the more input-intensive MCs, but it cannot fully compensate or directly substitute for susceptibility to physical and biotic stress that constrain profitability of MCs.

Estimation

The research method is a modified version of Griliches' (1957) two-stage approach that has been widely used to examine adoption behavior (e.g., Martinez, Globerman, Romeo, Rapoport, Wattleworth, Jarvis).

First Stage

The first stage consists of fitting a logistic curve to the historical diffusion data, thus summarizing, for each cross-sectional entity, the adoption process in two parameters: the diffusion speed and the adoption ceiling.[2] The first-stage logistic equation is

$$(1) \qquad F_i(t) = y_i/(1 + \exp(-a_i - b_i t)),$$

where $F_i(t)$ is the cumulative percentage of area sown with MCs for production region i and time t, y is the ceiling coefficient or long-run equilibrium value, b is the diffusion speed coefficient, and a is a constant of integration that positions the curve on the time scale. Treating the ceiling level of adoption as endogenous results in a nonlinear estimation problem which can be solved only through numerical optimization. Marquardt's method was used to generate the nonlinear logistic estimate of the ceiling coefficient y (Judge et al.).

Second Stage

The second stage examines the determinants of the variation in the first-stage estimates by hypothesizing that the adoption ceilings are functions of specific sets of variables. Because the estimated adoption ceilings lie between 0 and 1 (or between 0 and 100%), the dependent variable is truncated, and a linear probability model (LPM) estimated with ordinary least squares (OLS) is inappropriate (Judge et al.). A popular alternative to a LPM is the logistic specification (2).

$$(2) \qquad y_i = (1 + \exp(-a - bX_i - e_i))^{-1}.$$

Equation (2) is often transformed into the linear logit model (3) which can be estimated by OLS:

$$(3) \qquad \ln (y_i/(1 - y_i)) = a + bX_i + e_i.$$

Two methodological improvements on (2) or (3) are offered for the second-stage estimation. The first improvement derives from the notion that the slope of the cumulative logistic probability function is greatest at the midpoint. Therefore, changes in explanatory variables will have their greatest impact on the dependent

[2] Weibull and Gompertz functions were also fitted to the time-series adoption data to allow for asymmetry in aggregate adoption behavior (Dixon). Based on goodness-of-fit criteria, neither the Weibull nor the Gompertz was a significant improvement over the logistic (Jansen).

variable at the midpoint of the distribution. Similarly, the low slopes near the endpoints of the distribution imply that relatively large changes in the independent variables are necessary to bring about a small change in the dependent variable. Because the tail values of the dependent variables are associated with large errors, in a proportional sense, the logit model in (2) with its multiplicative error structure is not ideal. To redress this implicit weighting imbalance, the logit model in (4) with an additive error structure was used.

$$(4) \qquad y_i = (1 + \exp(-a - bX_i))^{-1} + e_i.$$

The second improvement is an application of generalized least squares. It was first applied in aggregate diffusion analysis by Wattleworth. The information embedded in the different standard errors of the adoption ceilings estimated in the first stage can be used to derive more accurate second-stage parameter estimates. Consequently, each error term e_i is assumed normally distributed with variance σ_i^2, where $\mathrm{Var}(e_i) = E(e_i^2) = \sigma_i^2$ is not constant across production regions. Each observation on all variables in the second stage was divided by the standard error of the estimated adoption ceiling, and weighted least squares was used to estimate (4).

In addition, each observation in the second stage was also weighted by the average area under the crop in each producing region. Consequently, as a result of the two weighting procedures, a producing region attained more importance the smaller is the estimated standard error of its adoption ceiling and the larger is its area under the coarse cereal.

Data

The analysis was based on secondary district data from a ten-state, time-series data base assembled by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the World Bank largely from the state season and crop reports and statistical abstracts. The time-series spanned 1966–67 to 1983–84.[3]

For each coarse cereal, the production regions correspond to major producing districts which are equivalent to large counties in the United States. A district was included in the sample if it accounted for at least 0.5% of the average total production of the crop during the 1981–82, 1982–83, and 1983–84 agricultural years. Applying this rule gave sample sizes of sixty-six districts for sorghum, sixty for pearl millet, and fifty-eight for maize.

In the early 1980s, the study districts for sorghum and pearl millet accounted for virtually the entire all-India production. The study districts for maize covered only 70% largely because the important maize growing state of Bihar was excluded due to lack of data.

First-Stage Estimates of Adoption Ceilings

The hypothesis of logistic adoption ceilings received considerable empirical support for both sorghum and pearl millet but not for maize. For sorghum and pearl millet, the estimated ceiling was statistically significant at the .05 level for, respectively, forty-seven (out of 66) and thirty-five (out of 60) districts. Out of those, thirty-nine sorghum districts and nineteen pearl millet districts exhibited a ceiling significantly different from 1.00 (table 2). For maize, the first stage results are characterized by a relatively large number of districts reporting negligible adoption. In general, the logistic did not fit the data that well for many of the maize districts. In districts where adoption was negligible or where the logistic did not converge or did not give a statistically significant estimate of the adoption ceiling, the ceiling estimate was generated by

Table 2. Evidence (in Number of Producing Districts) for Adoption Ceilings of Modern Coarse Cereal Cultivars in India from 1966–67 to 1983–84

	Coarse Cereal		
Adoption Status	Sorghum	Pearl Millet	Maize
Full adoption[a]	8	16	5
Partial adoption and no ceiling[b]	16	20	23
Partial adoption and ceiling[c]	39	19	8
Negligible adoption[d]	3	5	22

[a] Estimated ceiling with a logistic specification greater than 0.90 and statistically significant at the .05 level.
[b] Estimated ceiling with a logistic specification not statistically significant at the .05 level.
[c] Estimated ceiling with a logistic specification less than 0.90 and statistically significant at the .05 level.
[d] The proportion of MC area never exceeded 0.10 during any year in the period of analysis.

[3] The ten states were Andhra Pradesh, Madhya Pradesh, Karnataka, Tamil Nadu, Maharashtra, Gujarat, Rajasthan, Punjab, Haryana, and Uttar Pradesh.

averaging the last five years of data in the time series.[4]

Pearl millet districts with a nonsignificant adoption ceiling largely correspond to areas where the first-released pearl millet hybrids became susceptible to downy mildew, resulting in significant economic losses in the early 1970s. In response to those losses, many farmers reverted to local types. In the mid- and late-1970s, hybrid adoption again picked up as farmers accepted the second-generation hybrids which, at that time, were much less susceptible to downy mildew. Therefore, several pearl millet districts had a diffusion curve that better resembled a roller coaster than the conventional S-shape.

In the case of maize, of the thirty-six districts where some diffusion of MCs had occurred, only thirteen were associated with a statistically significant adoption ceiling at the .05 level. The relatively recent release and partial adoption of "second generation" shorter duration MCs in some districts of North India in the early 1980s is a plausible explanation for the poor fit of the logistic to the time-series data from 1966–67 to 1983–84.

A comparative statement of the adoption experience between the modern coarse cereal cultivars and the wheat and rice MCs is made in table 3. For wheat and rice, the ten-state data base is the same as was used for the coarse cereals, and the procedures described earlier were employed to estimate the ceiling levels of adoption.

The contrast between coarse cereal MCs and wheat and rice MCs is marked in table 3. The distribution of the major wheat- and rice-producing districts in the ten-state sample is concentrated in the higher frequencies of more than 50% MC adoption. The coarse cereal districts display a much wider range of diffusion experience.

Coarse cereal MC ceilings approaching full adoption have been confined to specific regions of peninsular India. These eminently successful cases of diffusion of MCs correspond to central Maharashtra where sorghum hybrids are grown in an environment of high production potential, to Gujarat where pearl millet hybrids are widely cultivated, and to regions in South India where maize is nontraditionally produced. Explaining the interregional variation in adoption ceilings is the objective of the next section.

[4] For those districts, the standard errors used in the second-stage estimation were also calculated from the last five years of the data series.

Table 3. Distribution (in Number of Producing Districts) of Estimated Ceiling Levels of Adoption by Cereal

	Cereal				
Frequency Range in %	Sorghum	Pearl Millet	Maize	Wheat	Rice
<10	11	7	22	0	0
10–25	12	2	9	1	1
26–50	20	13	12	4	7
51–75	13	16	7	9	20
76–90	2	3	1	19	18
>90	8	19	7	34	21
Total	66	60	58	67	67

Second-Stage Model Specification

The explanatory variables, corresponding to the X vector in equations (2), (3), and (4), can be classified into two groups: (*a*) agroclimatic and (*b*) infrastructural variables.

Agroclimatic Variables

The agroclimatic variables reflect the quality of the production environment and the potential sources and incidence of yield reducers on each crop. They were identified from literature reviews and discussions with crop improvement scientists (Jansen).[5]

The agroclimatic variables can be subdivided as follows: (*a*) soil by mean annual rainfall dummy variables, (*b*) growing season monthly rainfall and its variability, for months where prior expectations were strong, and (*c*) other considerations related to the physical and biotic production environment. In general, the soil by rainfall interactions represent the physical quality of the production environment; the monthly rainfall variables are associated with specific types of physical and/or biotic stress.

Expectations regarding the influence of specific yield reducers are based on perceptions on the quality of the production environment (better endowed regions should be more conducive to MC adoption) or on expected differences in tolerance to stress and disease or in growing duration between local varieties and MCs which results in the ability to avoid physical or biotic stress.

[5] A table containing a description of the agroclimatic variables, their sample means and ranges, their expected signs, and associated yield reducers by coarse cereal is available from the senior author upon request.

Average pre-MC yield in the early 1960s is a regressor in the subset of other considerations for each coarse cereal. This variable controls for aspects of the production environment that are not captured by the soil-rainfall interactions or by the monthly rainfall levels or variabilities. *Ceteris paribus,* one expects that higher pre-MC yields are positively associated with MC adoption (Griliches 1957).

Other agroclimatic variables include (*a*) the percentage of rainy season area in the sorghum equation (sorghum MCs have been successfully developed for rainy season cultivation but not for post-rainy season sorghum cultivation) and (*b*) a low rainfall-irrigation interaction because of the high expected productivity of maize in a dry production environment with assured irrigation.

Infrastructural Variables

The infrastructural variables, described in table 4, reflect use of irrigation and access to fertilizer, markets, and roads.[6] In contrast to the agroclimatic variables, they were the same for each coarse cereal.

In the spirit of Boserup; and Pingali, Bigot, and Binswanger, a demographic variable reflecting population pressure on land was also included as a regressor for each coarse cereal. *Ceteris paribus,* a higher ratio of persons to land should be accompanied by increased demand for yield-increasing technical change.

Six models were specified for each of the three cereals; each specification differed in functional form, combination of independent variables, and sample size (Jansen). The nonlinear logit with the additive error structure in equation (4) gave a consistently better statistical fit than either a linear probability or a conventional logit model for all three crops.

[6] Other infrastructural variables (e.g., literacy rate and percentage of villages electrified) were tried in some initial runs of the second-stage estimation. They were highly collinear with the other regressors and did not contribute significantly to the explanatory power of the model. District data on credit or extension infrastructure were not available at the time of the analysis.

Second-Stage Results

Before discussing the second-stage estimated coefficients for each coarse cereal, the overall contribution of the agroclimatic variables and infrastructural variables in explaining the variation in adoption ceilings among major producing districts is considered.

Relative Importance of Agroclimatic and Infrastructural Variables

To test the relative importance of agroclimatic and infrastructural variables, the R^2s are compared for the following three models in table 5: (*a*) an infrastructural model with the independent variables in table 4, (*b*) an agroclimatic model with agroclimatic independent variables, and (*c*) a combined or full model containing both sets of variables as regressors.

The infrastructural variables explain a large share of the interregional variation in MC adoption particularly for pearl millet and maize, but the agroclimatic variables have higher explanatory power. The additional explanatory power of the infrastructural variables in the combined model is not statistically significant at the .05 level with an F-test for both sorghum and pearl millet. Inclusion of the agroclimatic variables to the infrastructural model does lead to significantly enhanced explanatory power for each of the coarse cereals.

Investment in infrastructure has been biased toward the agroclimatically superior regions. This

Table 4. Means of the Infrastructural Variables by Coarse Cereal

		Coarse Cereal		
Variable	Unit of Measurement	Sorghum	Pearl Millet	Maize
Irrigation	Proportion of cropped area	0.03	0.07	0.28
Fertilizer outlet density	Distribution points/10 km^2	0.35	0.41	0.52
Road density	km of road/10 km^2	3.24	2.68	2.70
Market density	Number of regulated markets/10 km^2	0.02	0.02	0.04
Population	People/ha	2.26	1.82	2.07

Table 5. Proportion of Variation in Estimated Adoption Ceilings Explained by Different Models by Coarse Cereal

Model	Coarse Cereal		
	Sorghum	Pearl Millet	Maize
	($\bar{R}^2$)		
Infrastructural	0.43	0.67	0.78
Agroclimatic	0.80	0.93	0.90
Combined	0.84	0.94	0.95

translates into multicollinearity between the agroclimatic and the infrastructural variables. Such multicollinearity explains why infrastructural variables on their own can explain a substantial part of the variation in adoption ceilings, while at the same time their marginal contribution in the combined model is small.[7]

Sorghum

Rainy season area as a percentage of total sorghum area has the strongest effect on adoption of any of the statistically significant regressors in the sorghum model (tables 6 and 7). Varietal change has been negligible in the postrainy season when sorghum is grown under the relatively assured but low productivity environment of receding soil moisture.

The estimated coefficients of the dummy variables for soil by growing season all tell the same story: too much rain limits the adoption of sorghum MCs. Moving from the reference point of medium black soil and medium rainfall to a higher rainfall regime on black soil is accompanied by a significant fall in the adoption level. Contrary to a priori expectations on drought as a constraint to adoption, switching to a lighter rainfall regime on either medium black, deep black, or red soils results in a significant shift upwards in the estimated ceiling level of adoption. Sorghum in general and MCs in particular are sensitive to water stagnation and to untimely rains favoring pest and disease infestation.

Early growing season rainfall in June also is a significant constraint to the adoption of sorghum MCs. The significance and size of the corresponding coefficient indicate the importance of stand establishment in influencing the adoption of MCs.

[7] Another potential problem consists of a simultaneous equation bias caused by the possibility that infrastructure investments were spurred by the availability of modern cultivars in the favorable areas.

Table 6. Estimated Coefficients and *t*-Values of the Determinants of the Estimated Ceiling Levels of Adoption of Modern Cultivars by Coarse Cereal

Determinants	Estimated Coefficient	*t*-value
	Sorghum	
Agroclimatic		
Deep black soil low rainfall	1.28	2.26
Deep black soil medium rainfall	0.11	0.22
Deep black soil high rainfall	−1.96	−2.88
Medium black soil low rainfall	1.17	2.45
Medium black soil high rainfall	−1.56	−2.78
Red soil low rainfall	2.04	2.76
Red soil medium rainfall	−0.19	−0.36
June rainfall (mm)	0.03	4.13
September rainfall (mm)	0.005	0.63
Annual rainfall (cv)	−0.10	−2.08
June rainfall (cv)	0.015	0.93
September rainfall (cv)	−0.05	−2.88
Rainy season cropping (% sorghum area)	0.06	6.39
Pre-MC yield (tons/ha)	−0.74	−0.46
Infrastructural and Demographic[a]		
Irrigation (% sorghum area)	9.24	2.18
Fertilizer outlet density (distribution points/10 km^2)	2.71	2.33
Population density (people/ha)	−0.54	−2.39
Intercept	−4.98	−2.30
$\bar{R}^2$	0.83	
Correlation[b]	0.80	
Number of observations	66	
	Pearl Millet	
Agroclimatic		
Alluvial soil low rainfall	−0.43	−0.84
Alluvial soil medium rainfall	−0.52	−1.02
Alluvial soil high rainfall	−3.86	−6.87
Black soil low rainfall	3.18	3.24
Black soil medium rainfall	−0.96	−2.04
Black soil high rainfall	−1.18	−1.41
Sandy soil low rainfall	−3.05	−6.47
Sandy soil high rainfall	−0.79	−1.81
June rainfall (mm)	0.019	2.38
July rainfall (mm)	−0.007	−1.89
August rainfall (mm)	0.006	1.67
September rainfall (mm)	−0.017	−3.53
Annual rainfall (cv)	0.09	4.94
June rainfall (cv)	−0.03	−5.17
July rainfall (cv)	−0.07	−5.91
August rainfall (cv)	−0.02	−2.88
September rainfall (cv)	0.035	5.83
Pre-MC yield (tons/ha)	4.04	4.91
Infrastructural and Demographic[a]		
Irrigation (% pearl millet area)	−2.49	−1.75
Fertilizer outlet density (distribution points/10 km^2)	−1.08	−1.50
Population density (people/ha)	−0.53	−2.41
Intercept	3.89	3.71
$\bar{R}^2$	0.95	
Correlation[b]	0.78	
Number of observations	58[c]	

Table 6. Continued

Determinants	Estimated Coefficient	*t*-value
	Maize	
Agroclimatic		
Alluvial soil low rainfall	−7.76	−1.62
Alluvial soil high rainfall	−5.66	−2.10
Black soil low rainfall	1.65	0.63
Black soil medium rainfall	4.87	3.51
Black soil high rainfall	5.22	2.92
Sandy soil low rainfall	1.28	0.82
Sandy soil medium rainfall	4.22	3.96
Sandy soil high rainfall	−4.75	−2.83
July rainfall (mm)	0.008	2.73
August rainfall (mm)	−0.02	−3.80
Annual rainfall (cv)	−0.13	−3.64
June rainfall (cv)	0.007	0.66
Dry and irrigated	10.42	2.05
Pre-MC yield (tons/ha)	−0.57	−0.77
Infrastructural and Demographic[a]		
Irrigation (% maize area)	−1.69	−0.97
Fertilizer outlet density (distribution points/10 km^2)	5.26	5.44
Market density	2.66	0.34
Road density	0.34	2.35
Population density	0.16	0.42
Intercept	−1.93	−1.35
$\bar{R}^2$	0.95	
Correlation[b]	0.95	
Number of observations	58	

[a] The road and market density variables were dropped from sorghum and pearl millet second stage analysis because they were statistically insignificant and were collinear with several of the other regressors.
[b] Pearson correlation coefficient between actual and predicted values.
[c] The Tamil Nadu districts of South Arcot and Tirichurapalli were excluded because they rely heavily on the Northeast monsoon which is not active in other millet-growing regions.

Table 7. Elasticity Values of Significant Regression Variables

Variable	Coarse Cereal: Sorghum	Pearl Millet	Maize
Agroclimatic			
Deep black soil low rainfall	0.31		
Deep black soil high rainfall	−0.47		
Medium black soil low rainfall	0.28		
Medium black soil high rainfall	−0.37		
Red soil low rainfall	0.49		
Alluvial soil high rainfall		−0.90	
Black soil low rainfall		0.74	
Black soil medium rainfall		−0.22	
Sandy soil low rainfall		−0.71	
Alluvial soil low rainfall			−1.71
Alluvial soil high rainfall			−1.24
Black soil medium rainfall			1.07
Black soil high rainfall			1.15
Monthly Rainfall (mm)			
June	2.28	0.48	
July		−0.47	1.33
August		0.33	−2.91
September		−0.66	
Rainfall Variability (cv in %)			
Annual	−1.49	1.11	−2.45
June		−0.93	
July		−1.35	
August		−0.51	
September	−1.72	1.04	
Other Agroclimatic			
Rainy season cropping (%)	2.46		
Pre-MC yield (tons/ha)		0.64	
Infrastructural			
Irrigation (proportion of cropped area)	0.19		2.91[a]
Fertilizer availability (distribution points/10 km^2)	0.56		1.84
Road density (km of road/10 km^2)			0.61

Note: Elasticity values for continuous variables in logistic-based models equal $bx(1 - y)$, where b is the estimated regression coefficient, x the regressor value, and y the estimated ceiling value. Elasticities were evaluated at arithmetic means of the variables. For the soil-rainfall dummy variables the reported figures are simple marginal coefficients which equal by $(1 - y)$.
[a] Dry districts only.

Regions with more variable September rainfall are also less likely to adopt sorghum MCs than other producing zones. Because sorghum MCs are usually harvested before the monsoon recedes in October and rainfall just before harvesting favors the development of grain mold and earhead pest infestations, sorghum MCs should be more affected by rainfall variability in September than the later-maturing, photoperiod-sensitive local varieties.

The infrastructural variable with the strongest effect on sorghum MC adoption is the density of fertilizer distribution points. Under good rainfall conditions, sorghum MCs can be highly responsive to fertilizer. Irrigation is also statistically significant although its effect on adoption is relatively small.

The negative and significant coefficient of the person-to-land ratio in table 6 is also contrary to a priori expectations. The importance of sorghum as a fodder could explain this finding. The demand for milk, particularly in urban areas, is high in India, and sorghum stover is widely fed to dairy cattle. Because local varieties produce more fodder and less grain per plant, they might be preferred in areas where the urban demand for milk fuels rising stover to grain price ratios (Walker).

Pearl Millet

Explanations for the interregional variation in MC adoption in pearl millet centered on the levels and variability in monthly rainfall. Six of the eight monthly rainfall-related regressors are statistically significant in table 6. Variability in June, July, and August rainfall, associated with early, mid-, and end-of-season drought, have a negative impact on the ceiling level of adoption. More abundant early season rain in June should result in improved stand establishment and, as expected, June rainfall was signed positive. Heavier rain later in the season should foster panicle diseases and, as expected, was signed negatively.

The significant results for the variabilities in annual rainfall and in September rainfall are inconsistent with a priori expectations. Those results imply that *ceteris paribus,* the adoption of pearl millet MCs is greater in more variable annual and September rainfall conditions. Perhaps these results attest to the robust character of pearl millet MCs which suffer from fewer yield reducers than either maize or sorghum MCs. Shorter duration pearl millet MCs may also better escape variable drought stress in September than longer duration locals.

Three of the eight soil by growing season rainfall regions have adoption ceilings significantly different from the benchmark sandy soil, medium rainfall region. In the dry sandy soil, low rainfall region comprised mainly of Rajasthan, pearl millet MCs have made limited headway. Districts with heavier black soil and low rainfall represent a high potential production environment for pearl millet hybrids. Waterlogging limits the profitability of pearl millet hybrids in districts with alluvial soils and high rainfall.

Unlike sorghum and maize, pre-HYV millet yields do contribute significantly to explaining the interregional variation in MC adoption. Net of the included climatic, soil, and infrastructural variables, districts with heavier pearl millet yields before the MCs were released also had higher levels of adoption.

Consistent with the sorghum result, population density significantly and inversely affects adoption. The urban demand for milk may apply equally well for pearl millet as for sorghum.

Maize

The results for maize were more sensitive to model specification. Infrastructural variables, particularly fertilizer, loomed larger in explaining interregional variation in adoption than for sorghum and pearl millet. Unlike the sorghum and pearl millet hybrids, the maize MCs are mostly of longer duration than local varieties, and they may not fit as well in farmers' cropping systems. In general, the yield differences of the MCs over the local varieties are less for maize than for sorghum or millet. Maize is also less drought tolerant, more responsive to inputs, and less susceptible to panicle diseases than the other two coarse cereals. Thus, the size and significance of the fertilizer density variable and the low rainfall-irrigation binary variable is consistent with a priori expectations.[8] Because more maize is marketed than sorghum and millet, a finding of the significant bearing of road density on adoption is also not surprising.

Similar to the results for millet, too much or too little water can erode productivity and incentives for MC adoption. Within production regions, mainly in North India, where alluvial soil is common, both the high and low rainfall districts are inferior in adoption performance to the more moderate rainfall regions. Excess rainfall can also be a problem in the sandy soil regions but does not appear to be a constraint to adoption in the nontraditional, predominantly black-soil, maize-producing belt in South India.

A positive and significant estimated coefficient on July rainfall and a negative and significant coefficient on the variability of annual rainfall indicate the presence of drought as a yield reducer. More support from drought as a yield reducer comes from the linear logit specification (not reported) where the coefficient of the variability in June rainfall was signed negatively and significant.

The negative influence of August rain on MC adoption is attributed to waterlogging and stalk rot, which is a problem in areas of higher rainfall during the early August preflowering period. In some years, shorter duration local varieties can escape the adverse consequences of excess rainfall in August.

Implications and Conclusions

This study finds evidence for (*a*) ceiling levels of adoption, (*b*) the importance of agroclimatic variables relative to infrastructural considerations in conditioning those ceilings, and (*c*) the use of diffusion analysis of secondary data to

[8] In order to separate out the effect of irrigation in "dry" maize districts (annual rainfall < 750 mm) and "wet" maize districts (annual rainfall > 750 mm), a new variable was created consisting of the product of a dummy variable (equaling one for dry districts and zero otherwise) and a variable measuring the percentage of irrigated maize area. The effect of irrigation on the adoption ceiling is then measured by the sum of the estimated coefficients of the newly created variable and the irrigation variable for dry districts and by the coefficient of the irrigation variable for the wet districts.

shed some light on priorities for agricultural research in coarse cereals to shift the adoption ceilings.

For agroclimatic variables, excess moisture significantly influences adoption of coarse cereal MCs in some producing regions. Sorghum in particular is highly susceptible to rainfall-induced disease and pest infestations. While early season drought can curtail MC adoption, the possible influence of mid- to end-season drought on adoption ceilings was not supported empirically. Thus, except for the sandy soil, low rainfall pearl millet growing regions and the post-rainy sorghum growing belt, the findings suggest that early season moisture stress warrants higher priority in drought research than mid- to late-season stress.

For infrastructure, the inverse relationship between population pressure and the ceiling levels of sorghum and pearl millet MC adoption suggests that more weight should be given to fodder as an end use in MC development.

The findings also indicate that expanding and deepening input and output market infrastructure alone are unlikely to substantially increase the present adoption ceilings. Qualitatively different MCs from those now released appear necessary to change regional adoption behavior. Fertilizer availability, especially for sorghum and maize, was the most important infrastructural variable in explaining interregional variation in MC adoption. The significance of the dummy variables for soil by growing season rainfall associated with excess moisture also suggest that investment in drainage could stimulate adoption of MCs in some producing districts.

The results highlight the importance of regionally specific production conditions in crop improvement research in India. The past emphasis on wide adaptation in breeding research has stimulated aggregate productivity growth and aided in identifying the regions of higher production potential. With growing private sector research on coarse cereal hybrids (Pray et al.), the public sector could reallocate its resources to more location specific and difficult problems of the lagging adoption regions. In addition, as suggested by the results for maize, the total cropping system rather than individual crops should be emphasized.

[Received August 1989; final revision received December 1989.]

References

Boserup, E. *The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure*. London: Allen and Unwin, 1965.

Dalrymple, Dana. *Development and Spread of High-Yielding Rice Varieties in Developing Countries*. Washington DC: Bureau for Science and Technology, Agency for International Development, 1986a.

——. *Development and Spread of High-Yielding Wheat Varieties in Developing Countries*. Washington DC: Bureau for Science and Technology, Agency for International Development, 1986b.

Dixon, R. "Hybrid Corn Revisited." *Econometrica* 48(1980):1451–61.

Feder, G., R. Just, and D. Zilberman. *Adoption of Agricultural Innovations in Developing Countries: A Survey*. Washington DC: World Bank Staff Work. Pap. No. 542, 1982.

Gerhart, John. "The Diffusion of Hybrid Maize in West Kenya." Ph.D. thesis, Princeton University, 1984.

Globerman, S. "Technological Diffusion in the Canadian Tool and Die Industry." *Rev. Econ. and Statist.* 56(1974).

Government of India, Department of Agriculture and Cooperation. *Indian Agriculture in Brief*. New Delhi, various volumes.

Government of India, Ministry of Agriculture and Irrigation, Directorate of Economics and Statistics. *Agricultural Situation in India*. New Delhi, various volumes.

Government of India, Ministry of Finance, Economics Division. *Economic Survey*. New Delhi, various volumes.

Griliches, Zvi. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25(1957):501–22.

——. "Hybrid Corn Revisited: A Reply." *Econometrica* 48(1980):1463–65.

Jansen, Hans G. P. "Adoption of Modern Cereal Cultivars in India: Determinants and Implications of Interregional Variation in the Speed and Ceiling of Diffusion." Ph.D. thesis, Cornell University, 1988.

Jarvis, L. S. "Predicting the Diffusion of Improved Pastures in Uruguay." *Amer. J. Agr. Econ.* 63(1981):495–502.

Judge, George G., William E. Griffiths, R. Carter Hill, and Tsoung-Chao Lee. *The Theory and Practice of Econometrics*. New York: John Wiley & Sons, 1980.

Martinez, J. C. "On the Economics of Technological Change: Induced Innovation in Argentina Agriculture." Ph.D. thesis, Iowa State University, 1973.

Pingali, P., Y. Bigot, and H. P. Binswanger. *Agricultural Mechanization and the Evolution of Farming Systems in Sub-Saharan Africa*. Baltimore MD: Johns Hopkins University Press, 1987.

Pray, C. E., S. Ribeiro, R. A. E. Mueller, and P. Parthasarathy Rao. "Private Research and Public Benefit: The Private Seed Industry for Sorghum and Pearl Millet in India." Economics Group Progress Rep. No. 89. Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics, 1989.

Rapoport, J. "Diffusion of Technological Innovation Among Non-Profit Firms: A Case Study of Radioisotopes in U.S. Hospitals." *J. Econ. and Bus.* 30(1978):108–18.

Romeo, A. "Interindustry and Interfirm Differences in the Rate of Diffusion of an Innovation." *Rev. Econ. and Statist.* 57(1975):311–19.

Walker, T. S. "Economic Prospects for Agroforestry Interventions in India's SAT: Implications for Research Resource Allocation at ICRISAT." Economics Group Progress Rep. No. 79. Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics, 1987.

Wanmali, S. *Service Provision and Rural Development in India: A Study of Miryalguda Taluka.* Washington DC: International Food Policy Research Institute Res. Rep. No. 37, 1983.

Wattleworth, Michael Allen. "Diffusion of Technology in Malaysia's Rubber Estate Sector." Ph.D. thesis, University of California, Berkeley, 1980.