

ECONOMIC GROWTH CENTER

YALE UNIVERSITY

P.O. Box 208269
New Haven, Connecticut 06520-8269

CENTER DISCUSSION PAPER NO.805

TECHNOLOGY–CLIMATE INTERACTIONS IN THE
GREEN REVOLUTION IN INDIA

James W. McKinsey, Jr.
Bryant College

Robert E. Evenson
Yale University

August 1999

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James W. McKinsey, Jr.

Robert E. Evenson

Abstract

This paper presents a model of the Green Revolution in India, in which the development and diffusion of HYVs, the expansion of irrigation and the expansion of multiple-cropping are treated as endogenous responses to more basic investments in agricultural technology and infrastructure, as well as to climate and edaphic endowments. We incorporate explicit climate-technology interactions in the model, in order to identify climate effects on the diffusion of HYVs, irrigation and multiple-cropping, and on Net Revenue to agriculture. We find that climate affects technology development and diffusion, and that technology development and diffusion affect the impacts of climate on agricultural productivity in India.

Key words: Green Revolution, India, HYV, Rice, Wheat, Climate, Agricultural Research

JEL classifications: 112, 121, 226, 620, 710

McKinsey: Department of Economics, Bryant College, Douglas Pike, Smithfield, RI
jmckinse@bryant.edu

Evenson: Economic GrowthCenter, Yale University, Box 208269, New Haven,
CT, 06520 robert.evenson@yale.edu

* This paper is based on McKinsey's unpublished 1998 Yale Ph.D. dissertation *HYV's, Multiple-Cropping, Irrigation, Climate and the Green Revolution in India*, written under the direction of Prof. Evenson. The assistance of Bruce Dixon, Robert Mendelsohn, Ariel Dinar and three anonymous referees is gratefully acknowledged; all usual disclaimers apply

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I. INTRODUCTION

During the past thirty years significant portions of India's agriculture have undergone a transformation known as the Green Revolution, which can largely be characterized by three processes: the development and diffusion of new, high-yielding varieties [HYV] of food crops¹, the expansion of (especially tube-well) irrigation, and the expansion of multiple-cropping.

A number of studies of the productivity growth in Indian agriculture associated with the Green Revolution have been completed. Most prior studies have treated the three main components of the Green Revolution as exogenous variables in district-level empirical analyses (Evenson and McKinsey [1991]; Evenson, Rosegrant and Pray [1999]). In spite of the importance to agricultural production of land, water and sunlight, the prior studies included no edaphic or climate variables beyond area planted and current rainfall.

Alternative models have been developed during the past decade, explicitly including edaphic and climate variables, which are designed to explain land values or farm profits. Called Ricardian models, they were first applied to US agriculture by Mendelsohn, Nordhaus and Shaw [1993; 1994], and more recently in essentially the same form to agriculture in India by Kumar and Parkikh [1998] and by Sanghi, Mendelsohn and Dinar [1998]. These latter two studies have taken some features of agricultural technology into account but have not developed a full treatment of the technology dimension in Indian agriculture.

¹ Primarily rice and wheat, but to a lesser extent maize and some minor food crops.

McKinsey [1998] has developed a model of Indian agriculture which treats the three components of the Green Revolution as endogenous responses to more basic investments in agricultural technology and infrastructure. We extend the Ricardian idea into McKinsey's technology model, and incorporate explicit climate-technology interactions, in order to identify climate effects on the diffusion of HYVs, irrigation and multiple-cropping, and on Net Revenue to agriculture. We thus investigate whether district-level climate differences conditioned the regional pattern of investment and technology adoption as the Green Revolution unfolded, and conversely whether the processes of change which constitute the Green Revolution might modify or ameliorate the effects of future climate change. We recognize the difficulty inherent in trying to predict future climate change, let alone future technological change; but we expect some continuity in the processes underlying these three technological developments and thus use current cross-section differences in climate and technology as proxies for future time-series changes in both sets of variables.

Part II of the paper reviews the methodology underlying the specifications. Part III reports estimates of the four equations in our model which capture the processes of the Green Revolution and Net Revenue to crop production. Based on these estimates Parts IV and V report the climate sensitivity of (that is, the impact of differences or changes in climate on) technological change and of Net Revenue, and the effects of technological change on the climate sensitivity of Net Revenue.

II. METHODOLOGY

A. The Model

In this paper we capture the technical core of the Green Revolution in three simultaneous equations, estimated by 2SLS. The endogenous variables measure the processes described above: the

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development and diffusion of HYVs (determined by multiple-cropping, irrigation, public agricultural research (RESEARCH) and extension (EXT), and edaphic (EDAPH) and climatic (CLIMATE) variables); investment in irrigation (driven by its 1957 level (IRRIG57), the adoption of HYVs, and edaphic and climatic variables); and the expansion of multiple-cropping (driven by its 1957 level (DBLCRP57), HYV adoption, irrigation intensity, and edaphic and climatic variables).

To complete our model we add a fourth equation in which deflated “out-of-pocket” Net Revenue per hectare (hereafter simply Net Revenue) is determined, *inter alia*, by the predicted values of the three dependent variables in the first three equations, based on the results of the 2SLS procedure, the logarithms of the imputed value of family labor per hectare (CULTIVAT) and bullock labor per hectare (BULLOCK), research, infrastructural variables (INFRA), the edaphic and climate variables, and the three endogenous technology variables and their interactions with climate variables. This equation allows us to compute the effects of climate on Net Revenue, and the impact of technological change on the climate sensitivity of Indian agriculture.

So our econometric model contains four equations with the following structure:

- (1) **HYV** = f_1 (**DBLCROP**, **IRRIG**, RESEARCH, EXT, EDAPH, CLIMATE)
- (2) **IRRIG** = f_2 (IRRIG57, **HYV**, EDAPH, CLIMATE)
- (3) **DBLCROP** = f_3 (DBLCRP57, **HYV**, **IRRIG**, EDAPH, CLIMATE)
- (4) **NETREV** = f_4 (CULTIVAT, BULLOCK, INFRA, RESEARCH, **HYV**, **IRRIG**,
DBLCROP, EDAPH, CLIMATE, HYVxC, IRRIGxC, DBLCROPxC)

in which

HYV measures the proportion of land planted to high-yielding varieties;

IRRIG measures irrigation intensity (Net Irrigated Area divided by Net Cropped Area);

DBLCROP measures the expansion of multiple-cropped area (Gross Cropped Area (area planted more than once during the year) divided by Net Cropped Area);

NETREV measures Net Revenue per hectare;

RESEARCH measures the cumulated stock of public research services;

EXT measures public extension services;

EDAPH is a vector of edaphic (soil-related) variables: soil type, pH, slope, etc;

CLIMATE is a vector of climate variables: normal temperature, rainfall, etc.;

CULTIVAT is family members (not hired laborers) who work on the farm;

BULLOCK is a measure of animal power;

INFRA is a vector of infrastructure; and

IRRIG57 and DBLCRP57 are the values of irrigation and multiple-cropping in 1957.

To compute Net Revenue we first sum the products of all crop outputs multiplied by their farm harvest prices, then subtract the cost of purchased inputs (which are fertilizer, tractors, and hired agricultural labor), then deflate the net value, then divide the deflated amount by net cropped area, then take its natural logarithm, yielding the variable NETREV. Two important inputs are excluded from this computation: bullocks and family labor. Bullocks are primarily used by their owners (with little renting in or out), as obviously is true for family labor; these inputs are treated as quasi-fixed factors, and the logarithms of the imputed values of these inputs, per hectare, are included as independent variables. The climate variables already appear in quadratic [flexible] form, so the logarithmic form is not inconsistent with them.

All variables are described in detail in Appendix A of McKinsey and Evenson [1998] or in McKinsey [1998]. The variables are measured at the district level, covering nearly all of the districts in the 13 major crop-producing states of India. Appendix Table A-1 displays the variable names, descriptions and summary statistics of the major variables used. The variables used as instruments in the

2SLS system are denoted in Appendix Table A-1 by an asterisk following the variable name. These instruments include fundamental climatic and edaphic variables, as well as two technology variables and a number of price ratios proxying institutional factors.

The climate variables are computed from 30-year averages recorded at various Climatological Observatories and Rainguage Stations by the Indian Meteorological Department, usually using data between 1931 and 1960. These variables represent long-term norms, to which farmers have responded in their decisions about cropping patterns, input use, investment in technology and infrastructure, and so forth. These climate norms obviously vary only across districts, with no time-series variation.

This study applies to the years 1970/71 through 1987/88. By 1970 the use of modern high-yielding varieties of several crops had become established in nearly every district, and partly in concert with the expansion of HYV there was substantial new investment in irrigation, fertilizer distribution, research and extension activities, and so forth.

B. Adaptation and Interaction

Expressions such as (1) through (4) allow for farmer adaptation to regional climate conditions (and to changes in climate which might occur over long periods of time into the future). This adaptation includes investments in farm level irrigation and drainage as well as changes in farm practices including cropping patterns. There is, as well, potential adaptation by the organizations producing technology and infrastructure for farmers. These organizations include private firms which conduct R&D to develop improved factors to be supplied to the agricultural sector, and the public sector agricultural research and extension organizations which also provide improved technology to agriculture. It also includes public sector units providing, and maintaining, infrastructure.

Implicitly, this suggests that there may be important climate-technology and climate-infrastructure interactions. These interactions enable us to estimate two dimensions of the technology-climate

relationship. In the system (1) through (3) we estimate the effects of (current regional differences in) climate [C] on the production and diffusion of technology [T]. (That is, we can compute dT/dC .) From these estimates we can ask: How might an increase in normal temperatures and rainfall affect the development and diffusion of agricultural technology? From the estimation of (4) with interaction terms we can ask the following question: What might be the impact of an increase in rainfall and temperature on Net Revenue [NR] (including the effects operating through technology)?

$$(5) \quad dNR/dC = \partial NR/\partial C + \partial NR/\partial T \cdot dT/dC$$

We can also capture two sets of secondary impacts. The first is the impact of technology on the climate effects:

$$(6) \quad d(dNR/dC)/dT$$

which enables us to ask whether the climate sensitivity of Net Revenue per hectare was influenced by changes in the technology variables during the period of the Green Revolution, indicating whether this process of technological change might continue to benefit Indian agriculture in the context of projected warming in the future. The second set of secondary impacts is the impact of climate change on the technology effects:

$$(7) \quad d(dNR/dT)/dC$$

(which of course is equal to equation (6)), indicating what impact future climate change might have on the benefits which the processes of technical change have conferred on Indian agriculture.

III. ESTIMATION

The models described thus far impose no restrictions on the functional form to be estimated. We use a very general form, with quadratic and interaction terms in order to capture non-linearities and moderating impacts of technology on climate effects and *vice versa*. The **modern varieties, multiple-cropping and irrigation intensity** equations are estimated in the 2SLS system with linear and quadratic terms for climate variables.

Obvious econometric issues in this study involve the existence of heteroscedasticity, multicollinearity, and specification issues of variable inclusion or exclusion.

The Net Revenue equation is weighted by net cropped area, to adjust for heteroscedasticity. Standard errors have been estimated by White's consistent estimator of the least squares covariance matrix, and the resultant estimated t-ratios are consistent.

The problems of multicollinearity are likely to be severe, given the inclusion of so many climate terms, and their squares. Their inclusion is crucial and the squared terms are necessary to allow for nonlinearities in climate effects. One should use caution in interpreting or using any **individual** coefficient estimate: its true value may substantially differ from its estimated value, and the variable may be a valid, important regressor even if the estimated t-ratio is below the customary critical value. But the computations of estimated effects of climate change, using all the estimated coefficients, are likely to be valid, for any mis-estimation of the value of one coefficient is likely to be compensated for in the estimation of the values of the coefficients of the other collinear variables; thus the joint impact of all the variables together is probably much more accurate (Segerson & Dixon, [1996]).

In the Ricardian estimates of Mendelsohn *et al.*, [1994] a cross-section of land values was regressed on climate (CLIMATE), edaphic (EDAPH) and infrastructure (I) variables. Prices and technology variables were excluded on the grounds either that prices did not vary in their single-year cross-section for specific commodities or that transport-related differentials would continue in the future, and that technology was "equally" accessible to all farmers in the United States; obviously this precluded climate-technology interaction estimates. In the analysis reported here, multiple years are compared so that prices do vary across the sample and must be included.

Furthermore, a large number of agricultural productivity studies have measured significant differences in cross-section productivity levels which are at least partly due to edaphic and climate differences. More importantly, the studies have also measured time series differences in rate of change of partial or

total factor productivity change for different regions (Huffman & Evenson [1993] (U.S.), Avila & Evenson [1995] (Brazil), Evenson & McKinsey [1991] (India)). These differences have persisted over long periods of time and have been related to cross-section [and time-series] differences in investments in regionally oriented agricultural research programs.

One might argue (as Mendelsohn *et al.* [1994] do in the context of the United States) that regional differences in productivity growth are likely to “converge” over time as technology from the leading regions is diffused to the laggard regions. If so, the regional productivity differences would not be capitalized into land values. Yet this is quite unlikely in India, given the nature of agricultural technology which is highly location-specific. Studies of agricultural research (again, Evenson & McKinsey [1991]; Evenson, Rosegrant & Pray [1999]) indicate that regions with little or no research effort targeted to their particular climate and edaphic conditions remain laggard regions. And even if productivity were to converge over time, current Net Revenues would still reflect existing productivity differences.

Similarly, variables measuring current weather are important in Net Revenue specifications, but not in land value specifications where current weather gets averaged into climate.

IV. ESTIMATES

A. Technology

The first four columns of Appendix Table A-2 display the results from the second stage regression on HYV, DBLCROP, and IRRIG. A number of striking results emerge. First is the degree to which this system captures the modeled behavior. Grossly, all three second-stage regressions have highly significant F-statistics and high R-squareds, with low Root MSE. Even more important than the general goodness-of-fit of these regression equations, and the significance of groups of variables, are the patterns revealed within each equation.

Slope significantly influences multiple-cropping. Irrigation intensity tends to be higher in the flattest districts, and in districts above aquifers which are geologically thickest². The adoption of modern high-yielding varieties, multiple-cropping and irrigation are mutually-reinforcing: the coefficients of both DBLCROP and IRRIG on HYV are significantly positive, as are the coefficients of both HYV and IRRIG on DBLCROP and the coefficient of HYV on IRRIG. (See Section V.A below.)

The adoption of modern varieties also responds favorably to greater extension activity and to higher public and private research. Public research and extension are substitutes in determining HYV adoption.

There is considerable inertia in this behavior: both the extent of multiple-cropping and irrigation intensity are highest in those districts in which such activity had been largest in 1957.

B. Net Revenue

The first and last columns of Appendix Table A-2 display the results of the regression of Net Revenue on edaphic, climatic, and geographic variables, the predicted values of the technology and infrastructure variables from the two-stage system described above, interactions between climate and technology or between climate and infrastructure, and dummy variables for time. This equation also fits the data well: the R^2 is above 0.5, and the F-statistic is highly significant although perhaps the fit is not quite as good as it is in the three technology equations.

The edaphic variables are important determinants of Net Revenue: thirteen of the nineteen soil type dummies have significant coefficients, and alkali soil (pH of eight, nine or higher) reduces Net Revenue. While the coefficients on the predicted values of modern varieties [HYV_P], multiple-cropping [DBLCRP_P], and irrigation intensity [IRRIG_P] are not significantly different from zero, those variables are interacted with climate terms, as discussed below, and more than half of the interactions'

² This does not measure the annual water depth **within** the aquifer, but rather a long term geological potential. Farmers may respond to this in their cropping choices; farmers and probably governments also respond in their irrigation investments.

coefficients are significant, two-thirds of them positive. Research contributes significantly to Net Revenue.

Net Revenue is lower in districts with relatively more bullocks, perhaps reflecting the use of an older (and less profitable) package of inputs and practices in those districts. An increase in the ratio of off-farm wages relative to agricultural wages reduces Net Revenue, which may denote a decline in the quality of available farm workers, or even a reduction in the amount of time devoted to agriculture by owner-cultivators, as off-farm opportunities attract more and more of the best and most-highly-skilled laborers. Current weather, and its timing, also obviously influences current Net Revenue: given a normal seasonal rainfall, higher rainfall in July and August (the variable JUAURAIN) will increase Net Revenue³. Interestingly a higher coefficient of variation of rainfall contributes to Net Revenue⁴. This model displays quite rich (normal) temperature and rainfall effects on Net Revenue. The squared and “raw” terms are usually of the opposite sign. The impacts of temperature and rainfall differ by month.

A key focus of this study is the interaction of climate with technology, infrastructure, and geographic variables, beyond the so-called “purely climate” variables. Six such interactions each month are included. The interactions of normal temperature and rainfall with the predicted values of modern varieties, multiple-cropping and irrigation intensity are complex, yielding fourteen significant coefficients out of twenty-four, nine of them positive. Higher HYV adoption tends to increase Net Revenue in districts with higher July temperature and rainfall, but to be associated with lower Net Revenue in districts with higher January rainfall (which are likely to be districts in which irrigated winter wheat is not grown) and with higher April temperatures. Higher cropping intensity tends to increase Net Revenue in districts with higher April rainfall and with higher October temperature and rainfall (which, in most areas

³ Probably occurring during crucial maturation phases of many important crops in most states; actual June rain [holding constant the level of normal seasonal rainfall] had a negative but insignificant coefficient, perhaps reflecting the difficulty in planting when the ground is too wet.

⁴ This may reflect monsoon timing: a higher coefficient of variation may indicate that the rains were spread more evenly across the monsoon season.

of India, is a month when the “second” crop is growing), but is associated with lower Net Revenue in districts with higher July temperature and rainfall (which, in many areas of India, is a month when the primary crop is growing). And higher irrigation intensity tends to increase Net Revenue in districts with higher January, April and July temperatures as well as higher April rainfall, but is associated with lower Net Revenue in districts with higher October temperature.

V. INTERPRETATION OF RESULTS

A. Technological Change Relationships

The first three equations in our model describe the technology components of the Green Revolution experience in India. Recall that we model the adoption of modern varieties as a function, *inter alia*, of investment in irrigation and the spread of multiple-cropping; we model the spread of multiple-cropping as a function, *inter alia*, of the adoption of modern varieties and investment in irrigation infrastructure; and we model the spread of irrigation as a function, *inter alia*, of the adoption of modern varieties.

From the estimated coefficients in those three equations we can compute the impact of an increase in any of the technology variables on the adoption or spread of the other two. Those effects are presented in Table 1 in elasticity form, showing the proportional change in the variable in the columns in response to a one percent increase in the variables in the rows. For example, the second entry in the HYV column indicates that a one percent increase in multiple-cropping would induce approximately two-fifths of one percent increase in the adoption of modern varieties.

It is clear from Table 1 that the increased adoption of modern varieties has been an important spur to the investment in irrigation facilities and to the expansion of multiple-cropping (the top row of estimates) at the same time that the adoption of the modern varieties themselves have responded strongly to the expansion of irrigation and multiple-cropping (the left column of estimates). The effects of multiple-cropping and irrigation on each other, while positive, have been less pronounced. Taken as a whole,

Table 1 supports the idea of the importance of a “package” of inputs and practices, reinforcing each other, in the success of the Green Revolution.

Table 1
TECHNOLOGICAL CHANGE RELATIONSHIPS

effect of a 1% Δ in:	resultant %Δ in:		
	HYV	DBLCROP	IRRIG
HYV		0.3111	0.3349
DBLCROP	0.3960		0.1326
IRRIG	0.6164	0.2253	

B. Climate Effects on Technology and Infrastructure

Based on the regression results reported above, and the actual district-level values of the climate and technology variables, one can compute the predicted effects of changes in normal temperature and rainfall on high-yielding variety use, multiple cropping, and irrigation intensity. Tables 2a and 2b report the predicted effects of a one degree Centigrade temperature increase, and a three percent rainfall increase, values which some models predict could be achieved from a generation to a century from now⁵. The impacts of different changes could easily be scaled. Predicted impacts are computed for each district; weighted averages of the district impacts are presented in Tables 2a and 2b as quasi-elasticities.

First consider the impact of a one degree Centigrade increase on the technology variables, displayed in Table 2a. The All-India average temperature impact on HYV adoptions is positive but small, about one half of one percent. It is significantly positive in Gujarat and Karnataka, significantly negative in Haryana and Punjab, the two states with the greatest adoption of HYV wheat. The temperature impact

⁵ The choice of predicted temperature and rainfall changes is mired in controversy. Lonergan (1998) uses three General Circulation Models to predict climate change in India under a doubling of atmospheric carbon dioxide, which he claims could occur by the year 2050 or so. The models predict average temperature increases for all of India between 2.3°C and 4.8°C, but Lonergan cautions that this range is likely too high for a number of reasons. The precipitation predictions are highly variable by model, and all show quite different patterns during the course of the seasons, often increasing in some months and decreasing in others. Some question the predictive power of the GCM models; many question the speed at which CO₂ doubling might occur. We have chosen to compute effects based on smaller changes -- 1°C temperature increase and 3% rainfall increase -- as less subject to controversy.

on multiple-cropping is negative in every state except Karnataka, significantly so in essentially the northern half of India, from Rajasthan to Bihar, from Punjab to Gujarat. The temperature impact on irrigation is predominantly positive, although significantly negative again in Haryana and Punjab, as well as in Rajasthan.

Table 2a
TEMPERATURE EFFECT ON TECHNOLOGY AND NET REVENUE

	HYV	DBLCROP	IRRIG	NETREV-A	NETREV-B
ALL-INDIA	0.0057	-0.0209	0.0125	-0.0109	0.0075
Andhra Pradesh	0.0221	-0.0008	0.0356	0.0563	0.1132
Bihar	0.0031	-0.0232	0.0109	-0.0208	-0.0009
Gujarat	0.0055	-0.0308	0.0047	-0.1486	-0.1434
Haryana	-0.0099	-0.0395	-0.0148	0.0320	0.0474
Karnataka	0.2342	0.0091	0.0381	0.0492	0.0814
Madhya Pradesh	0.0017	-0.0240	0.0141	-0.0434	-0.0513
Maharashtra	0.0101	-0.0149	0.0230	-0.0562	-0.0439
Orissa	0.0192	-0.0036	0.0357	0.0470	0.0962
Punjab	-0.0125	-0.0391	-0.0224	0.0559	0.0700
Rajasthan	0.0002	-0.0310	-0.0023	-0.0324	-0.0345
Tamil Nadu	0.0079	-0.0176	0.0111	-0.0085	0.0777
Uttar Pradesh	-0.0012	-0.0297	0.0030	0.0059	0.0137
West Bengal	0.0086	-0.1334	0.0146	0.0156	0.0520

The All-India effects of an increase in rainfall on HYV adoption, multiple-cropping and irrigation intensity, reported in Table 2b, are similar to the temperature effects: positive but very small on HYV and irrigation, negative but small on multiple-cropping. Thus, these estimates generally show that higher temperature or rainfall is associated with higher rates of HYV adoption and of irrigation, and are associated on balance with reduced multiple-cropping.

C. Climate Effects on Net Revenue

Based on the regression results reported above, the actual district-level values of the climate and technology variables, and the computed climate change effects on the technology variables, one can similarly compute the predicted effects on Net Revenue of changes in normal temperature and normal

rainfall; those effects are reported in the last two columns of Tables 2a and 2b. Consider first the column labeled NETREV-A in Table 2a, which reports the temperature effect computations based only on the fourth, NETREV, equation.

Table 2b
RAINFALL EFFECT ON TECHNOLOGY AND NET REVENUE

	HYV	DBLCROP	IRRIG	NETREV-A	NETREV-B
ALL-INDIA	0.0003	-0.0005	0.0010	0.0063	0.0064
Andhra Pradesh	-0.0046	-0.0041	-0.0046	-0.0222	-0.0220
Bihar	0.0021	0.0009	0.0035	0.0150	0.0151
Gujarat	-0.0016	-0.0016	-0.0018	0.0001	0.0003
Haryana	0.0058	0.0037	0.0081	0.0352	0.0352
Karnataka	-0.0052	-0.0045	-0.0057	-0.0256	-0.0254
Madhya Pradesh	0.0011	-0.0001	0.0019	0.0125	0.0125
Maharashtra	-0.0027	-0.0028	-0.0027	-0.0116	-0.0115
Orissa	-0.0017	-0.0019	-0.0009	-0.0056	-0.0055
Punjab	0.0078	0.0051	0.0107	0.0416	0.0416
Rajasthan	0.0011	0.0004	0.0009	0.0190	0.0191
Tamil Nadu	0.0006	-0.0003	0.0045	-0.0082	-0.0083
Uttar Pradesh	0.0032	0.0017	0.0044	0.0245	0.0245
West Bengal	-0.0014	-0.0013	-0.0014	-0.0028	-0.0027

Holding everything else constant, and thus excluding the temperature effects on technology which are modeled in the first three equations, warmer districts receive on average slightly lower Net Revenue, approximately one percent lower for each 1°C difference in [normal] temperature.

Of course, the All-India average conceals considerable regional variation. The states in which the average temperature effect is negative include Tamil Nadu and a wedge of states covering much of the Deccan plateau, starting on the West and tapering eastward to Bihar. But the temperature effect is on average positive in the northern wheat-producing states of Haryana, Punjab and Uttar Pradesh, as well as in a ribbon of coastal rice-producing states from Karnataka across to Andhra Pradesh, Orissa, and West Bengal.

Similarly, the column labeled NETREV-A in Table 2b reveals that holding everything else constant, thus excluding the rainfall effects on technology which are modeled in the first three equations, rainier

districts receive on average very slightly larger Net Revenue, less than one percent higher for each three percent difference in (normal) rainfall.

There is dramatic regional variation in the rainfall effects, which are on average negative in the southern, peninsular half of the subcontinent (Tamil Nadu, Orissa and West Bengal are barely negative, while Andhra Pradesh, Karnataka and Maharashtra are more so) and positive in the northern half of the country (Punjab, Haryana, Uttar Pradesh, and Bihar, as well as Gujarat, Rajasthan and Madhya Pradesh).

But consider now the last columns of Tables 2a and 2b, labeled NETREV-B, which report the climate effects computed from all four equations, including the climate effects on technology from the first three equations working through the subsequent technology effects on Net Revenue from the fourth equation.

According to these estimates, accounting for the effects of technology would slightly mitigate the temperature effect: it becomes barely positive on average, while the effects in Tamil Nadu go from negative to positive and the effects in Bihar go from negative to essentially zero. In the other four states in which the effect had been negative there is virtually no change. In the ribbon of coastal rice states the positive effect becomes twice or thrice as large; in the northern wheat-producing states the positive effect nearly doubles. Accounting for technology, however, does little to the rainfall effects, as seen in comparing the last two columns of Table 2b.

The rainfall effects deserve further discussion. It is widely recognized (e.g., Gopaldaswamy [1994]; Singh [1997]) that the true rainfall issue in most of India is not its average (or “normal”) amount, but rather its timing and its variability (expressed commonly as its “unreliability”). We include variables which measure the actual rainfall during key months of each year (June, and the sum of July and August), as well as the coefficient of variation of rainfall during those months, in order to pick up the timing of rainfall. Given the significance of the coefficients of these variables, and the relatively limited

role of “normal” rainfall compared to rainfall timing, it is remarkable that one would observe any systematic “normal” rainfall effects at all.

D. Technological Change Effects on Net Revenue

Table 3 displays the predicted effects of a one percent change in any of the technology variables on Net Revenue. The effects are reported in quasi-elasticity form: for example, on average across India, a one percent increase in the proportion of area sown to modern varieties would increase Net Revenue by 1.226%.

Table 3
TECHNOLOGICAL CHANGE EFFECTS ON NET REVENUE

	HYV	DBLCROP	IRRIG
ALL-INDIA	1.226	-0.201	0.076
Andhra Pradesh	0.566	0.507	0.389
Bihar	1.362	-0.419	-0.213
Gujarat	1.688	1.409	-1.345
Haryana	2.168	-2.487	0.554
Karnataka	0.379	1.211	0.247
Madhya Pradesh	0.743	-0.417	0.569
Maharashtra	0.631	0.116	0.441
Orissa	0.720	0.188	-0.117
Punjab	2.521	-2.823	0.212
Rajasthan	2.021	-0.494	-0.283
Tamil Nadu	0.707	0.595	0.440
Uttar Pradesh	1.616	-1.089	0.067
West Bengal	1.617	0.604	-0.288

Modern varieties increase Net Revenue in all states; in the northern half of the country the effect is highly elastic. Irrigation has a small but positive All-India average effect, negative in five states.

Interestingly, those five consist of the three eastern states of Bihar, Orissa and West Bengal in which rainfed rice is still important, and the two Western semi-desert States of Gujarat and Rajasthan.

Multiple-cropping's All-India average effect is negative, driven by negative values in six states, especially Punjab, Haryana and Uttar Pradesh. In these agriculturally-advanced northern states the primary winter (second) crop is wheat, nearly all of it HYV and irrigated. These negative effects are computed from coefficients which were estimated while holding HYVs and irrigation intensity constant:

the negative multiple-cropping coefficients and effects, then, probably reflect the revenue disadvantage of second crops other than irrigated HYV wheat.

E. "Secondary" Effects of Technology and Climate

The presence of both technology and climate variables in our model allows us to estimate the effects on Net Revenue of (both cross-section differences and time-series changes in) technology and (current cross-section differences and possible future changes in) climate. The presence of variables which measure the **interaction** of technology and climate allows us to estimate "secondary" effects, displayed in Table 4, which can be interpreted from the point of view of technology's influence on the climate effects which are reported above in Tables 2a and 2b (the rows of Table 4), or of climate's influence on the technology effects which are reported above in Table 3 (the columns of Table 4).

Table 4
"SECONDARY" EFFECTS

	Temperature	Rainfall
HYV	0.0663	-0.0154
DBLCROP	0.1380	-0.0007
IRRIG	0.0031	0.0151

From the first point of view, technology's influence on the climate effects, Table 4 reveals that increases in all three measures of technology -- the adoption of modern varieties, especially the expansion of multiple-cropping, and weakly the expansion of irrigation -- would mitigate any negative impact of higher temperatures. A one percent increase in the proportion of crops planted to modern varieties would increase the benefit to Net Revenue of higher temperatures by about one sixteenth of one percent; a one percent increase in the intensity of multiple-cropping would increase the benefit to Net Revenue of higher temperatures by nearly one sixth of one percent, and a one percent increase in irrigation intensity would increase the benefit to Net Revenue of higher temperatures by a tiny fraction of one percent. These results confirm the differences found between columns NETREV-A and NETREV-

B in Table 2a, which showed that accounting for the beneficial effects of technology-climate interactions, the temperature effects on Net Revenue go from slightly negative to slightly positive.

The reasons for these effects are not difficult to discern. HYV's impact on the temperature effect derives from the success of breeders in adapting increased yield characteristics to different climatic environments. Multiple cropping's relatively strong impact on the temperature effect captures the benefits of shifting production of high-value crops to a second, presumably cooler, growing season when overall temperatures are higher. And irrigation's impact on the temperature effects are nearly a wash, probably reflecting the positive benefits of irrigation on heat stress countered by the increased evaporation from canal and tank systems with higher temperatures.

Continuing the first point of view, technology's influence on the climate effects, Table 4 further reveals that increases in two of the three measures of technology -- the adoption of modern varieties, and the expansion of multiple-cropping -- would very slightly reduce the positive impact of higher rainfall, while increases in the third, irrigation intensity, would slightly increase rainfall's positive impact. Together, these three essentially cancel each other out, as suggested by the nearly identical values in Columns NETREV-A and NETREV-B of Table 2b, which showed that accounting for technology left the rainfall effects on Net Revenue virtually unchanged.

Again, the reasons for these effects are not difficult to discern. Nearly all modern varieties are highly sensitive to precise, controlled amounts and timing of water, which is obviously best provided by reliable irrigation systems; thus most HYVs are planted on irrigated land. Higher rainfall would likely provide little production benefit, and often creates flooding or waterlogging which hamper timely planting and harvesting operations or leach nutrients, reducing output and revenue. Similarly, almost all multiple-cropping occurs on irrigated land, so although the first crop may be rainfed the second seldom is, explaining the virtually zero effect. Irrigation's small but positive impact on the rainfall effect may derive

from the ability of some forms of irrigation to provide improved drainage, and temporary storage of excess water.

Now considering the second point of view, climate's influence on the technology effects, Table 4 further reveals that higher temperatures would increase the benefits from investments in all three forms of technology: that is, the payoffs to investments in improved varieties, multiple-cropping and irrigation systems will be even higher if temperatures increase, because these technologies can mitigate any harmful temperature impacts. However, higher rainfall would very slightly reduce the benefits of increased adoption of modern varieties and, by about the same small proportion, very slightly increase the benefits of increased irrigation intensity. Higher rainfall would leave the benefits of increased multiple-cropping virtually unchanged.

VI. CONCLUSIONS

We have constructed a four-equation model of the Indian agricultural sector which is designed to capture the major features and processes of technological and infrastructural change which have characterized India's Green Revolution. Each group of variables is significant and well-behaved. We find that climate affects technology development and diffusion, and that technology development and diffusion affects the impacts of climate on productivity in India. Technology and climate interact to affect Net Revenue in agriculture in India.

Higher temperatures and rainfall are associated, on average across India, with slightly higher irrigation intensity and with slightly greater adoption of modern varieties, with striking regional patterns. However, higher temperatures and rainfall are associated with somewhat lower cropping intensity in nearly every state of India. Because these effects are small, climate change is not expected to affect substantially the development and diffusion of technology in Indian agriculture.

The development and diffusion of technology has a small effect on climate sensitivity as well. Increases in the use of modern varieties and in the intensity of multiple-cropping slightly worsen (that is, reduce)

the estimated positive impacts of increases in rainfall on farm production, while increases in the intensity of irrigation would increase the benefits of increased rainfall. Increases in the use of modern varieties, in the intensity of irrigation, and especially in the intensity of multiple-cropping mitigate or improve the effects of an increase in temperature. Alternatively interpreted, increases in temperature would slightly increase the payoff to investments in technology and infrastructure, while increases in rainfall would slightly increase the payoff to investments in irrigation, and slightly reduce the payoffs to investments in modern varieties and to increases in multiple-cropping.

Finally, most global climate change scenarios also posit an increase in atmospheric carbon — usually, in fact, the climate change is initiated by an increase in atmospheric CO₂. Nearly every experimental crop model predicts higher crop yields associated with increases in available carbon. For example, de Siqueira *et al* [1994] used crop growth models developed by IBSNAT and calibrated for thirteen regions in Brazil, to simulate climate change effects on wheat, maize and soybean production. The crop growth models allowed simulation of the direct physiological effect of increases in atmospheric concentrations of CO₂ on photosynthesis and the efficiency of water use. They found that, ignoring the effect of CO₂, a 2°C increase in temperature would increase soybean production but would reduce wheat and maize production. However, doubling CO₂ concentrations (by 555 ppm) increased output of all three crops, essentially compensating for the negative temperature impact on wheat and maize.

This study deals with changes in temperature and rainfall, but not with changes in carbon; thus the actual effects on crop output [and thus on Net Revenue] of climate change, taking into account carbon changes as well as temperature and rainfall changes, would almost certainly be more beneficial than the results of this study predict.

Appendix Table A-1
Variable Dictionary

Variable Name	Description	Mean	Standard Deviation
A. ENDOGENOUS VARIABLES			
NETREV	Log of Deflated Net Revenue	5.57	.74
HYV	% of Land Planted to High-Yielding Varieties	.28	.25
DBLCROP	Multiple-Cropping Index	1.24	.20
IRRIG	Index of Irrigation Intensity	.29	.24
B. EXOGENOUS VARIABLES			
Edaphic Variables [EDAPH]			
DMSnn *	Soil Type Dummy Variables; nn: 03 to 21	--	--
DMpHn	Soil pH Dummy Variables; n: 5, 6, 8 and 9	--	--
DMTSn *	Topsoil Depth Dummy Variables; n: 1, 2 and 3	--	--
Geographic Variables			
DMSLPn	Slope Dummy Variables; n: 1 to 4	--	--
DMSEA	Dummy: 1 if District is on the seacoast	--	--
DMSEANEI	Dummy: 1 if District abuts one on seacoast	--	--
ALT	Altitude of District's weather station, meters	296.89	316.36
DMAQn	Aquifer Depth Dummies	--	--
[Normal] Climate Variables [CLIMATE]			
JANTEMP*	January Normal Temperature Midpoint [°C]	18.55	3.69
JANTEMPSQ*	January Normal Temp. Midpoint Squared [°C]	357.86	138.29
JANRAIN*	January Normal Rainfall [mm]	12.38	13.14
JANRAINSQ*	January Normal Rainfall Squared [mm]	325.75	725.31
JANTMPRN*	January Normal Temp. times Rainfall		
APRTEMP*	April Normal Temperature Midpoint [°C]	29.59	2.35
APRTEMPSQ*	April Normal Temp. Midpoint Squared [°C]	881.23	125.86
APRRAIN*	April Normal Rainfall [mm]	16.19	22.65
APRRAINSQ*	April Normal Rainfall Squared [mm]	775.13	2355.60
APRTMPRN*	April Normal Temp. times Rainfall		
JULTEMP*	July Normal Temperature Midpoint [°C]	28.34	2.55
JULTEMPSQ*	July Normal Temp. Midpoint Squared [°C]	809.90	134.44
JULRAIN*	July Normal Rainfall [mm]	245.77	234.42
JULRAINSQ*	July Normal Rainfall Squared [mm]	115342.86	430432.59
JULTMPRN*	July Normal Temp. times Rainfall		
OCTTEMP*	October Normal Temperature Midpoint [°C]	26.05	1.88
OCTTEMPSQ*	October Normal Temp. Midpoint Squared [°C]	682.01	90.17
OCTRAIN*	October Normal Rainfall [mm]	66.64	66.03
OCTRAINSQ*	October Normal Rainfall Squared [mm]	8800.36	15815.10
OCTTMPRN*	October Normal Temp. times Rainfall		
JURNCV	Coef. of Variation, June Rain, 1957 - 1987	.61	.21
JARNCV	Coef. of Var., July/Aug Rain, 1957 - 1987	.35	.21

Appendix Table A-1 (continued)
Variable Dictionary

Variable Name	Description	Mean	Standard Deviation
[Current] Weather Variables [W]			
JUNERAIN	Actual Rainfall in June [mm]	131.46	121.98
JUAURAIN	Actual Rainfall in July and August [mm]	561.55	364.05
YEARRAIN	Actual Annual Rainfall [mm]	1088.33	602.14
Additional Technology and Infrastructural Variables [T, I]			
RESEARCH	Cumulated Stock of Public Agri. Research	36.30	43.15
EXT *	Index of Extension Activity	7.39	5.65
LITERACY *	Literacy Rate, Adult Rural Males	.37	.11
RELWAGE	Ratio of Rural Factory Wage to Farm Wage	1.20	.60
PRIVRES	Private Research	247.94	187.08
Institutional Variables			
PRWTWG *	Price Ratio: Wheat to Wage	28.52	14.41
PRRCWG *	Price Ratio: Rice to Wage	28.60	17.76
PRMZWG *	Price Ratio: Maize to Wage	20.86	9.77
PRJWWG *	Price Ratio: Jowar to Wage	19.63	13.19
PRBJWG *	Price Ratio: Bajra to Wage	19.09	12.34
PRFRWG *	Price Ratio: Fertilizer to Wage	683.69	301.06
PRTRWG *	Price Ratio: Tractor to Wage	2309.40	811.41
POPDEN1	Population Density:	3948.41	2717.01
Interaction Terms			
JANTEMPHY	January temperature times Predicted HYV		
JANTEMPDB	January temperature times Predicted DBLCROP		
JANTEMPIR	January temperature times Predicted IRRIG		
JANRAINHY	January rainfall times Predicted HYV		
JANRAINDB	January rainfall times Predicted DBLCROP		
JANRAINIR	January rainfall times Predicted IRRIG		
	and similarly for April, July and October		

* Variables used as instruments in the first stage of HYV, DBLCROP and IRR regressions.

Appendix Table A-2
Regressions of HYV, DBLCROP, IRRIG and NETREV

	HYV		DBLCROP		IRRIG		NETREV	
R-sq	0.7274		0.6986		0.9019		0.5273	
Root MSE	.1248		.1058		.0741		.5130	
F	166.16		294.40		740.34		43.80	
	HYV		DBLCROP		IRRIG		NETREV	
	coeff.	t	coeff.	t	coeff.	t	coeff.	t
(constant)	-.9029	-2.176	-.9233	-3.358	.4022	1.693	-1.792	-0.355
HYV			.2945	15.995	.3349	26.910	.0106	.0005
DBLCROP	.3960	3.870					-2.2190	-0.627
DBLCROP57			.4158	14.097				
IRRIG	.5968	8.495	.0495	2.137			-.5383	-0.225
IRRIG57					.7611	61.478		
RESEARCH	.0011	2.471					.0022	4.394
EXT	.0107	7.223						
RES x EXT	-.0001	-2.346						
PRIVRES	.0001	3.748					.0008	4.605
DMSLP1			.0501	6.580	.0255	4.383		
DMSLP2			.0141	1.875	-.0157	-2.802		
DMSLP3			.0196	1.931	-.0062	-1.130		
DMSLP4			.0950	7.701	-.0231	-2.997		
DMAQ1					.0036	0.835		
DMAQ2					.0052	0.991		
DMAQ3					.0250	3.557		
DMPH5							-.0476	-1.266
DMPH6							-.0484	-1.522
DMPH8							-.1919	-6.128
DMPH9							-.2997	-6.822
ALT							.0007	0.483
CULTIVAT							.1534	4.930
BULLOCK							-.1298	-4.600
RELWAGE							-.0951	-3.271
DMSEA							.0192	0.269
DMSEANEI							.1098	2.565

—> Appendix Table A-2 is continued on the next page

Appendix Table A-2 (continued)
Regressions of HYV, DBLCROP, IRRIG and NETREV

	HYV		DBLCROP		IRRIG		NETREV	
	coeff.	t	coeff.	t	coeff.	t	coeff.	t
DMS03	-.0215	-1.610	.0173	2.078	-.0054	-.0915	.1222	2.269
DMS04	-.0101	-1.210	-.0059	-0.772	-.0144	-.2588	.0233	0.427
DMS05	.0295	4.109	-.0032	-0.589	-.0058	-1.467	-.0974	-2.265
DMS06	.0007	0.095	.0211	4.467	.0058	1.397	-.0683	-1.393
DMS07	-.0341	-4.774	-.0110	-1.307	-.0007	-.0127	.0496	1.321
DMS08	.0268	1.455	-.1414	-9.183	-.0305	-3.456	.2147	2.129
DMS09	.0213	1.452	-.1118	-11.82	-.0409	-5.062	-.2079	-2.308
DMS10	-.0111	-0.282	.0402	1.963	-.0452	-2.105	-.7358	-4.341
DMS11	.0776	4.475	-.0691	-5.759	-.0111	-1.148	-.3019	-2.020
DMS12	.0179	0.908	.0329	2.548	-.0918	-8.161	-.4180	-4.408
DMS13	-.2299	-10.42	.0006	0.050	.1633	14.711	.5438	5.494
DMS14	-.0175	-1.288	-.0162	-1.672	-.0417	6.628	-.2147	-2.520
DMS15	-.0222	-1.703	-.0002	-0.026	.0360	5.027	.0272	0.613
DMS16	.0379	5.156	-.0038	-0.646	.0128	2.824	-.0120	-0.328
DMS17	.0253	2.173	.0145	1.642	-.00002	-0.003	-.3421	-3.716
DMS18	-.3234	-8.118	.3041	9.399	.1263	7.715	.3227	2.248
DMS19	-.1010	-9.905	.0383	5.021	.0142	3.148	-.0665	-1.609
DMS20	.0365	1.944	-.0426	-5.251	-.0220	-2.892	-.2069	-2.451
DMS21	.2671	7.882	-.0704	-4.384	-.0025	-0.133	-.4506	-2.863
JANTEMP	.0693	3.720	.0342	3.431	-.0714	-8.412	.2462	1.673
JANTEMPSQ	-.0015	-3.126	-.0012	-4.940	.0019	9.125	-.0056	-2.538
JANRAIN	-.0013	-0.832	.0023	1.486	.0051	6.019	.0077	2.637
JANRAINSQ	.0001	8.169	.00004	2.872	-.0001	-8.217	.0004	5.666
JANTEMPRN	.0002	-2.522	-.0003	-4.214	-.0001	-2.787	-.0034	-6.137
APRTEMP	-.1131	-3.740	.0211	0.912	.1711	9.927	-.3175	-1.244
APRTEMPSQ	.0022	4.147	-.0008	-1.918	-.0030	-10.26	.0022	0.757
APRRAIN	.0099	4.022	.0066	3.780	-.0054	-3.958	.0148	0.904
APRRAINSQ	-.00002	-4.897	-7.3E-6	-1.687	3.9E-6	1.374	-.0001	-5.269
APRTEMPRN	-.0002	-2.967	-.0002	-3.535	.0001	2.991	-.0010	-2.615
JULTEMP	.1990	4.186	.1398	5.925	-.2139	-9.606	.6178	2.341
JULTEMPSQ	-.0033	-3.880	-.0027	-6.364	.0038	9.712	.015	0.396
JULRAIN	.0007	3.997	.0003	2.654	-.0003	-2.547	.0087	6.600
JULRAINSQ	-6.3E-8	-3.098	-8.6E-9	-0.482	1.2E-8	0.767	-3.8E-7	-2.352
JULTEMPRN	-.00002	-3.118	-.00001	-2.424	7.4E-6	1.898	-.0002	-4.915
OCTTEMP	-.1108	-2.539	-.0464	-1.564	.0404	1.886	.1122	0.283
OCTTEMPSQ	.0014	1.757	.0012	2.119	-.0003	-0.676	-.0167	-3.372
OCTRAIN	-.0062	-3.928	-.0063	-7.842	.0053	9.055	-.0297	-3.729
OCTRAINSQ	-1.7E-6	-1.765	-1.3E-6	-2.304	-5.9E-7	-1.507	-.00001	-3.636
OCTTEMPRN	.0002	3.837	.0002	8.108	-.0002	-9.032	.0016	6.544

—> Appendix Table A-2 is continued on the next page

Appendix Table A-2 (continued)
Regressions of HYV, DBLCROP, IRRIG and NETREV

	HYV		DBLCROP		IRRIG		NETREV	
	coeff.	t	coeff.	t	coeff.	t	coeff.	t
JUNERAIN							-.00004	-0.301
JUAURAIN							.0002	2.945
YEARRAIN							.00007	1.313
JURNCV							.2051	2.210
JARNCV							.5657	7.310
JANTEMPHY							-.0028	-0.039
JANTEMPDB							-.0979	-0.999
JANTEMPIR							.2364	2.630
JANRAINHY							-.0180	-2.017
JANRAINDB							-.0161	-1.022
JANRAINIR							-.0048	-0.485
APRTEMPHY							-.3398	-4.178
APRTEMPDB							.1291	0.946
APRTEMPIR							.2578	2.361
APRRAINHY							.0040	0.543
APRRAINDB							.0253	3.156
APRRAINIR							.0139	1.872
JULTEMPHY							.2907	2.768
JULTEMPDB							-.7432	-5.142
JULTEMPIR							.5306	4.502
JULRAINHY							.0014	3.090
JULRAINDB							-.0034	-3.398
JULRAINIR							.0009	1.065
OCTTEMPHY							.1182	0.740
OCTTEMPDB							.8500	3.677
OCTTEMPIR							-1.0217	-5.780
OCTRAINHY							-.0027	-1.103
OCTRAINDB							-.0065	-1.715
OCTRAINIR							-.0034	-0.994

—> Appendix Table A-2 is continued on the next page

Appendix Table A-2 (concluded)
Regressions of HYV, DBLCROP, IRRIG and NETREV

	HYV		DBLCROP		IRRIG		NETREV	
	coeff.	t	coeff.	t	coeff.	t	coeff.	t
DMYR71							-.0781	-1.443
DMYR72							-.1977	-3.347
DMYR73							.0391	0.803
DMYR74							-.0687	-1.200
DMYR75							.0325	0.625
DMYR76							-.1849	-3.220
DMYR77							-.0659	-1.141
DMYR78							-.1862	-3.077
DMYR79							-.5518	-8.029
DMYR80							-.3770	-5.129
DMYR81							-.4655	-5.850
DMYR82							-.5600	-6.193
DMYR83							-.4631	-4.757
DMYR84							-.6068	-5.651
DMYR85							-.6873	-6.379
DMYR86							-.7859	-7.068
DMYR87							-.7655	-6.523

Note: Regressions of HYV, DBLCROP and IRRIG are the second stage of 2SLS.

In the NETREV regression, the values of HYV, DBLCROP and IRRIG, and the values used to compute their interactions with climate variables, are the values predicted from the 2SLS results.

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