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Econometric estimation of a global spillover matrix for wheat varietal technology¹

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Abstract

An econometric approach using international and national yield trial data is employed to estimate a spillover matrix for wheat varietal technology. The global spillover matrix is estimated based on international yield trial data from 1979–80 to 1987–88, that include 195 international trial locations and 209 wheat varieties. The locations were classified across countries using the CIMMYT's wheat megaenvironment system and varieties were classified by both their environmental and institutional origin. The model gave good explanatory power and confirmed the location specificity hypothesis, at least, for the varieties developed by national programs (NARS). The spillover matrix shows that NARS varieties developed in the 'home' environment generally perform better on average than varieties developed in other megaenvironments. Also, the matrix is not symmetric. CIMMYT varieties perform better on average in irrigated and high rainfall environments than NARS varieties developed for these environments. The yield advantage of CIMMYT varieties in many test megaenvironments indicates the potential of CIMMYT varieties to spill-over to these test megaenvironments. Results also indicate that national programs are efficient in selecting from among imported technologies.

Analysis of international data is complemented by the analysis of country-level data for Pakistan and Kenya that confirms the above results. The country-level analysis, however, indicates that CIMMYT germplasm does not do so well in some sub-environments, such as the irrigated short-duration environment.

The results of the spillover matrix have implications for the design of crop breeding programs both at the national and international levels. Information provided by the spillover matrix can be utilized by national programs to deploy their resources more efficiently by following a mixed strategy of direct importation of technology in some environments and local development of technologies in other environments which are unique to the country.

1. Introduction

Quantitative assessment of spillovers of agricultural research across environments is important for several reasons. They can be used for stimulating

consistent debate on research policy to support decision making in resource allocation and to enhance research evaluation methodology (Davis, 1994). However, little formal quantitative analysis to measure spillovers (or spillins)² of agricultural technol-

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² Spillins and spillovers refer to the same phenomenon of externality. The terms are used interchangeably depending on whether a research program is receiving or producing the externality.

ogy and its implications for research system design has been undertaken.

Most of the early empirical studies to evaluate the impact of agricultural research ignored technology spillovers. Later studies in the 1970s and 1980s incorporated spillovers between states within a country and across countries utilizing agro-climatic zones (e.g. Evenson and Kislev, 1975; White and Havlicek, 1981; Evenson, 1989). Research spillovers in these studies were estimated as a function of ‘research stock,’ which was typically measured by expenditures or publications aggregated by agroclimatic zone. This research spillover variable was then included in an aggregate productivity or production function specification to estimate the relationship between expenditures on research in one agroclimatic zone on the output in others. Aggregate studies of this nature can provide useful information to assist general research policy discussions. However, the aggregate nature of these models and the nature of these spillover variables on which model estimation is based, restrict their usefulness for resource allocation decisions and priority setting in a given environment for a given type of research.

Several case study analyses have identified spillover benefits from research (e.g. Brennan, 1989). These studies provide meaningful estimates of actual spillover benefits of particular technologies by measuring the impact of technologies imported from an external source. Such estimates are, however, specific to a region and institution and not generalizable at a national or international level.

Some recent attempts have included a ‘spillover matrix’ to model potential spillovers between regions. For example, Edwards and Freebairn (1984) used a two-region spillover model in which spillover coefficients were subjectively estimated in a range from zero to one. Davis et al. (1987) extended this two-region model to include many regions and subjectively assessed spillovers across FAO-defined agroclimatic zones.

Davis (1994), Pardey and Wood (1994) and Evenson (1994) discuss the need for improving the subjective estimates of spillover matrix employed by previous studies and suggest methods for quantitative assessment. Evenson (1994) provides empirical procedures for estimating spillover coefficients from research trial data. There is a vast amount of yield

trial data that can be used to assess the potential transferability of varietal technology. However, with the exception of Englander (1991) and Evenson (1994), such data have not been exploited to estimate spillover matrices.

In this paper we use an econometric approach to estimate the coefficients of a global spillover matrix for wheat improvement research.³ We demonstrate the value of international and national yield trial data in estimating spillover effects of an international wheat improvement research system to address the following issues: (a) To what degree is wheat varietal technology environment specific?⁴ In other words, is there a yield advantage of varieties developed for a specific target environment compared with varieties developed for other environments and by the international research system? (b) What are the implications of the findings for the design of national and international wheat research systems. We open with a brief discussion of the concept of a spillover matrix and relate it to the basic model used in this study to estimate spillover coefficients.

2. Spillover matrix: a conceptual framework

A critical feature of much agricultural technology is its environmental specificity. Transfer of agricultural technology, particularly biologically based technology such as improved varieties, is limited by the spatial and temporal variation of environmental factors such as climate, biotic and abiotic stresses, photoperiod and soil type. For instance, no one wheat variety will excel everywhere and at all times. The concept of a spillover matrix, C , makes the notion of environmental heterogeneity more tractable. The matrix C is usually an $m \times m$ matrix (where m is the number of agro-ecological environments) with spillover indexes or coefficients, c_{ij} . These technology spillover effects, c_{ij} , measure the performance of a technology developed for environment i , in environment j , in relation to the technology developed for environment j .

³ Englander (1991) also used an econometric approach to analyze potential spillovers across countries.

⁴ This notion is usually referred in the literature as ‘location specific.’

In discussing research spillovers, it is important to distinguish between the two spillover matrices often used in research evaluation models: $S[s_{pq}]$ and $C[c_{ij}]$. Regional research spillovers, s_{pq} , are usually defined as the unit cost reduction (or production increasing) effects in region ⁵ q from application of technology that was developed for region p . Since, regions generally do not coincide with agro-ecological environments, the s coefficient is estimated through a weighted aggregation of the potential technology spillover effects, c_{ij} between agro-ecological environments. The spillover matrix discussed and estimated in this paper refers to the potential technology spillover matrix $C[c_{ij}]$.

Potential sources of technology spillins are not only research programs in other environments, but also international and regional research programs that develop crop varieties not specific to a particular environment in a country. In such cases, technologies emerging from international programs are considered as an additional source of spillins but there is no corresponding target environment, implying that the spillover matrix need not be square.

As noted by Pardey and Wood (1994), two major issues need to be addressed in constructing such a matrix. The first relates to the estimation of spillover coefficients and the second is the environmental classification system employed. These two issues are discussed below within the context of varietal technology.

2.1. Spillover coefficients

In the case of varietal improvement research, the elements c_{ij} can be defined as the potential decline (or increment) in the yields of varieties developed for environment i when evaluated in environment j (Y_{ij}), relative to the yields of varieties developed for environment j (Y_{jj}):

$$c_{ij} = Y_{ij}/Y_{jj} \quad (1)$$

Because of environment specificity, it is expected that $c_{ij} < c_{jj}$ – that is yields are less in environments for which the varieties are not specifically designed. Because of the differential response of genotypes to environmental variation (genotype by environment

interactions), the matrix C may not be symmetric. That is to say, $c_{ij} \neq c_{ji}$. $G \times E$ interactions result when test environments are heterogenous for properties which evoke different responses in the genetic lines evaluated. Those environmental properties are referred to as ‘selective’ to distinguish them from other environmental properties (Antonovics et al., 1988).

Most studies in the past have used subjective estimates of Y_{ij} in order to estimate spillover coefficients, c_{ij} . In this study, we use econometric procedures to quantify these estimates based on the following phenotypic yield response model used by plant breeders:

$$Y_{hg} = f(E_h, T_g, T_g \times E_h) \quad (2)$$

Thus, yield of genetic line g in location h , Y_{hg} , is a function of T_g , the additive effect of its genetic technology or genotype, E_h , the additive effect of the environment or circumstances in which genetic line g was evaluated, and $T_g \times E_h$, the non-additive interaction effects associated with the specific combination of genetic technology and environment. The interaction term in this model implies that the relative performance of a set of genetic lines can vary with environment, i.e. they exhibit environmental specificity. It is important to recognize that the additive and non-additive effects of environmental heterogeneity (among occurrences of a trial) depend on the genotypes of the lines evaluated. In turn, the additive and non-additive effects of genetic heterogeneity (among lines in a trial) depend on the test environments.

Here we employ the ‘spillover matrix’ approach to assess the degree of selective environment heterogeneity manifested in sets of genetic lines classified by megaenvironment origin or originating institution. Unlike the conventional approach used by plant breeders, we specify the three components in terms of a number of relevant dummy and non-dummy variables in a regression model discussed in Section 3.

2.2. Environmental classification system

The environmental classification system determines not only the dimensions of the spillover matrix but also the biological basis for estimating and interpreting the spillover coefficients. Unless disag-

⁵ Region refers to the usual geo-political or administrative and statistical reporting unit.

gregated, it will be extremely difficult to delineate geographical areas that respond differentially to new technologies (i.e. $G \times E$ interactions). However, it should not be so highly disaggregated that the dimensions of C become impractically large, leading to estimation problems. The environmental classification system should, therefore be crop specific and based on those delineating biological characteristics (i.e. classification criteria) that allow for the expression of genotype by environment interactions.

Most studies in the past, including Englander (1991) and Davis et al. (1987) have either used the Papadakis (1966) or the FAO climatic classification to characterize a location. In this study, we, however, use the global megaenvironment classification system developed by the International Maize and Wheat Improvement Center (CIMMYT) (Appendix A). CIMMYT defines megaenvironments specifically for wheat improvement research, in terms of areas of similar biotic and abiotic stresses, cropping system requirements, and consumer preferences for types of wheat (Rajaram et al., 1996). The CIMMYT megaenvironment classification system is used in this study instead of Papadakis or FAO, because the latter is inadequate for a specific commodity like wheat. Unlike the general Papadakis system, the CIMMYT system is based explicitly on selective environmental properties such as the moisture and temperature regimes in the season when wheat is grown. It delineates irrigated from non-irrigated areas within an agro-ecological environment, a distinction that is especially important for wheat.

3. Econometric procedure and data sources

CIMMYT's International Spring Wheat Yield Nursery (ISWYN) trial data for the years 1979–80 to 1987–88 were used to estimate a global spillover effects matrix for wheat improvement research.⁶ Started in 1964, CIMMYT's ISWYN trials are conducted each year by CIMMYT, Mexico, with the cooperation of national research programs both in developed and developing countries primarily to

quantify adaptive pattern of genotypes with a secondary germplasm dissemination function (Pfeiffer, 1992). About 40 to 50 entries (including advanced lines, and ready to be released and already released varieties) developed by CIMMYT and national programs are annually planted at about 60 to 75 locations around the world. In general ISWYN trials are grown on stations using the recommended experimental design (e.g. replication, size of plot, number of rows, etc.) and production technology (e.g. level and type of fertilizer, chemicals and irrigation) for a given agro-climatic zone (Fox, 1996).

The data set used in this study includes more than 24000 yield observations, of which about 23000 were used after excluding all observations pertaining to triticale and durum wheats. Also, local checks were excluded because many were either not reported by the cooperators, not identifiable because of lack of information on cross and selection history, or were duplicated as one of the non-local check entries.⁷ There were 209 unique wheat varieties in the 364 entries over the period of 8 years. The number of different locations in 81 countries totaled 195. The trial locations were classified according to CIMMYT's megaenvironments discussed above (Appendix A). The wheat varieties were classified by their institutional origin as either: (a) NARS (National Agricultural Research Systems) varieties (i.e. crossed, selected and tested by national programs) or, (b) 'CIMMYT varieties'⁸ (developed through the international CIMMYT–NARS research collaborative system – i.e. crossed and initial selections done by CIMMYT but with testing conducted by national programs). The NARS varieties were further

⁶ With the exception of ISWYN year 1982–83, which was not included because data were incomplete.

⁷ Since local checks are likely to be the best cultivars grown by the farmers in a given location, their exclusion from the analysis may bias the results downward. However, local checks are not synonymous with locally developed varieties. In fact, about 70% of the local checks that were reported and identified were CIMMYT bred cultivars released by the national programs.

⁸ CIMMYT is an international research center with the mandate to provide improved germplasm that can be used by a national program either as parent materials in their breeding program or released after local screening and testing. 'CIMMYT variety' as used in this paper is a short for "advanced breeding line developed by CIMMYT in collaboration with NARS" and should not be equated with the notion that these are varieties released by CIMMYT in any given country.

classified by their environmental origin based on the dominant megaenvironment in the country or region of development and information on the environmental niche (rainfed, irrigated, etc.) for which the variety was released. CIMMYT varieties were classified into two classes: (1) those released in Mexico (CIM1); and (2) those released in countries other than Mexico or not released by any national program (CIM2).⁹

The question addressed in estimating a global spillover matrix is: how do varieties developed in a given megaenvironment (i.e. the megaenvironment in which all the varieties are tested) perform relative to varieties developed in other megaenvironments (irrespective of their country of origin).¹⁰ Also, we are interested in the issue of transferability of wheat varieties developed by the international wheat improvement research system spearheaded by CIMMYT. This international research system consists of the collaborative research and testing efforts by CIMMYT and the NARS around the world. Its aim is development of high yielding, widely adapted wheat varieties that can be used by NARS either as seed products or breeding parents in their wheat improvement programs.

The regression model used to estimate the spillover matrix is as follows:

$$Y_{hgt}^j = a + \sum_{h=1}^H b_h \text{DLOC}_h + \sum_{t=1}^T c_t \text{DYEAR}_t + v \text{VINT} + \sum_{i=1}^m w_i \text{DORIG}_i + r \text{MR} + \epsilon_{hgt}$$

for $j = 1, 2, \dots, n$ (3)

⁹ CIMMYT's headquarters is located in Mexico. However, cultivars developed by CIMMYT have to undergo the same procedure for release in Mexico as they would in any other country.

¹⁰ Since technology transfer is constrained by differences among environments, the objective is to analyze technology transfer across megaenvironments and not across political boundaries (i.e. countries) as done by Englander (1991). Relating the transferability of a technology to environmental zones is important because it allows us to determine the yield change as a function of variables which are based on $G \times E$ knowledge. Moreover, estimates of technology transferability based on political boundaries are often difficult to interpret (since it is very unlikely that a country or politically defined region will have a homogenous crop growing environment).

where,

- j is the test megaenvironment in which the yield data point is observed. The equations were estimated separately for the following seven megaenvironments – ME1, ME2, ME3, ME4A, ME4B, ME5A and ME6 described in Appendix A.¹¹
- Y_{hgt}^j is the observed yield (kg per ha) of the g th entry at the h th trial location in environment j and in t th trial year.
- DLOC_h is a vector of dummy variables equal to one if the data point belongs to location h , zero otherwise.
- DYEAR_t is a vector of dummy variables equal to one if the data point belongs to trial year t , zero otherwise.
- VINT is a variable to reflect the age or vintage of a variety approximated by the trial year in which the g th variety first appeared.
- DORIG_i is a vector of dummy variables equal to one if the g th variety belongs to the origin group i (i.e. developed for megaenvironment i), zero otherwise. There are nine such dummy variables – seven correspond to NARS varieties classified by their megaenvironment origin (DOME1, DOME2, DOME3, DOME4A, DOME4B, DOME5A, DOME6) and two correspond to CIMMYT varieties released in Mexico (DCIM1) and elsewhere (or not at all) (DCIM2).
- MR is the inverse Mill's ratio (described further below).
- ϵ is the error term.

Thus, the performance of a variety is assumed to be a function of environmental variables (DLOC, DYEAR) and technology variables (VINT, DORIG). The variables VINT and DORIG represent characteristics of a varietal technology. Since we are using panel data, the location and year dummies (DLOC

¹¹ Because of insufficient number of observations the equations were not estimated for two spring wheat megaenvironments defined by CIMMYT (ME4C and ME5B in Appendix A).

and DYEAR) are included to factor out the site and time effect (such as different levels of management) on the observed yields.

The yield trial data are characterized by varietal attrition due to the replacement of older varieties by better yielding varieties in successive years of the trials. Since the probability of varietal attrition is correlated with experimental response (i.e. yield), the traditional statistical techniques for panel data estimation will provide biased and inconsistent estimators (Hsiao, 1986). The variable MR (inverse Mill's ratio) is included in the equation to correct for this selection bias of non-randomly missing varieties in the yield trials conducted over a number of years (Hsiao, 1986).

Since the model is estimated separately for each megaenvironment, the coefficients for DORIG represent the performance of varieties of different environmental origins in a given megaenvironment relative to the 'home varieties.' The varietal group originating from the test megaenvironment were considered as the benchmark variable (i.e. dummy variable DORIG_{*i*} were dropped from the equation for each megaenvironment). Therefore, the coefficients of DORIG_{*i*} are the differential yields defined as ($w_i^j = Y_{ij} - Y_{jj}$). These coefficients can be used to estimate Y_{ij}/Y_{jj} to give the elements of the spillover matrix, c_{ij} , based on the constant Y_{jj} (approximated by the arithmetic mean) for each megaenvironment.

4. Empirical results and the estimation of global spillover matrix

Model parameters in Eq. (3) were estimated using the ordinary least squares method. The statistical results of the regression analyses are summarized in Table 1. The results indicate that the inclusion of dummy location variables had a significant positive effect on the R^2 of all the seven regression models. Similarly, the dummy variables for trial years also significantly increased the R^2 of the estimated models.

The coefficient of VINT variable measures the gain in average yield $\text{ha}^{-1} \text{ year}^{-1}$ of new varieties in a given megaenvironment. Note that the coefficient is an average for all the varieties and is not specific to a particular origin group. Except in ME3

(high rainfall, acid soils) and ME4B (low rainfall, winter drought), yield improvements are not significantly different from zero. The non-significant coefficients of VINT variable in many environments including ME1 (irrigated, temperate) confirm the difficulty that wheat breeders have faced in maintaining significant growth rate in yield potential since 1980s (Bell et al., 1994). As indicated by coefficients of the MR variable (inverse Mill's ratio), there is a positive and highly significant (in most of the megaenvironments) relationship between observed yields and the probability of retention in the trials.

The coefficients of origin variables (w_i) estimate the yield advantage (or disadvantage) of varieties originating in different environments relative to the test environment (kg per ha). The zeros on the diagonal indicate that the coefficient of variety group of the same environmental origin as the test environment is defined as the 'benchmark' and all the other coefficients in that column represent deviations from that value.

The negative values of NARS technology in all the megaenvironments confirm the hypothesis that varieties developed in a test megaenvironment perform better than varieties developed in other megaenvironments. For example, the second number in the first column shows that NARS varieties of ME2 (high rainfall) origin yield 232 kg ha^{-1} less on average in ME1 (irrigated) than the NARS varieties developed for ME1 (after adjusting for other variables). The strength of this relationship is shown by the fact that nearly all the off-diagonal elements are negative and usually statistically significant. Significant negative values in a given column result from either: (a) both genetic differences among varieties and a difference in the selective environment at the test versus origin environments, or (b) only a difference in the genetic properties of the varieties tested. The latter circumstances could reflect different levels of breeding success and would result in symmetrical relationship such that $w_i^j = -w_j^i$. The abundance of negative values both above and below the diagonal show that CIMMYT's megaenvironment system reflects true differences in selective environmental properties.

The last two rows show that CIMMYT varieties perform well in most megaenvironments, especially in ME1 (irrigated) and ME2 (high rainfall). For

Table 1
Regression results of potential spillovers at the megaenvironment level using ISWYN data, 1980s

Independent variables	ME1 irrigated	ME2 highrainfall	ME3 acid soils	ME4A winter drought	ME4B early drought	ME5A high temperatures	ME6 high latitude
1. Constant ^a	4880 ***	3390 ***	336 **	2041 ***	1942 ***	222.1 ***	3394 ***
2. Dummies for year							
R^2 change ^b	0.02	0.02	0.23	0.17	0.17	0.05	0.08
F change ^c	35 ***	32 ***	184 ***	144 ***	46 ***	15 ***	124 ***
3. Dummies for location							
R^2 change ^b	0.56	0.44	0.27	0.40	0.21	0.29	0.52
F change ^c	166 ***	131 ***	287 ***	159 ***	59 ***	113 ***	154 ***
4. VINT ^a	4.27	31.2	10.9 *	2.5	28.1 **	−2.2	4.7
5. Mill's ratio, MR ^a	155 ***	135 ***	111 ***	93	141 **	97 **	87.7 **
6. Origin, DORIG ^{a,d}							
DOME1: irrigated		−189 **	−406 ***	−374 **	−346 **	34	−223 ***
DOME2: high rainfall	−232 ***		−509 ***	−307 *	−275 *	−177	−175 **
DOME3: acid soils	−507 ***	−141		−568 ***	−282 *	−31	1
DOME4A: winter drought	−66	−226 *	−565 ***		−483 **	−154	−259 **
DOME4B: early drought	−486 ***	−101	−290 **	−334 *		−161	−56
DOME5A: high temperature	−593 ***	−525 ***	−219	−672 ***	−328		−334 **
DOME6: high latitude	−588 ***	−395 ***	−414 ***	−507 ***	−270 *	−264 **	
DCIM1	527 ***	490 ***	−14	20	191	23	−91
DCIM2	227 ***	230 ***	−138	−105	16	7	−131 **
Number of observations	4641	4248	719	1824	850	935	2913
R^2	0.61	0.53	0.78	0.65	0.40	0.53	0.68

^a Number given is the estimated coefficient (kg ha^{−1}).

^b Number given is the change in R^2 when a given set of dummy variables is entered in the equation that includes all the other variables.

^c Number given is the change in the F -ratio when a given set of dummy variables is entered in the equation that includes all the other variables.

^d Origin groups DOME1 to DOME6 represent cultivars developed by national programs for respective megaenvironments. DCIM1 indicates

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

CIMMYT cultivars released in Mexico and DCIM2 indicates CIMMYT cultivars released in countries other than Mexico or not released anywhere.

Table 2

Estimated spillover matrix for wheat improvement research at the global megaenvironment-level

Origin of variety	Megaenvironments where varieties are tested ^a						
	1 irrigated	2 high rainfall	3 acid soils	4A winter drought	4B early drought	5A high temperature	6 highlatitude
ME1 irrigated	1.00	0.95	0.84	0.90	0.88	1.02	0.94
ME2 high rainfall	0.95	1.00	0.81	0.92	0.90	0.89	0.96
ME3 acid soils	0.89	0.96	1.00	0.85	0.90	0.98	1.00
ME4A winter drought	0.99	0.94	0.78	1.00	0.83	0.91	0.93
ME4B early drought	0.90	0.97	0.89	0.91	1.00	0.90	0.99
ME5A high temperature	0.88	0.86	0.92	0.82	0.89	1.00	0.92
ME6 high latitude	0.88	0.89	0.84	0.87	0.91	0.84	1.00
CIM1 CIMMYT/Mexico	1.11	1.13	0.99	1.01	1.07	1.01	0.98
CIM2 CIMMYT/other	1.05	1.06	0.95	0.97	1.01	1.00	0.97

^a Yield expressed relative to the yield of cultivars originating in that megaenvironment (= 1.00).

example, CIMMYT varieties released in Mexico (DCIM1) enjoy a yield advantage of 527 kg ha⁻¹ in ME1 (irrigated) compared with NARS varieties of ME1 origin. The positive yield advantage of CIM1 in many test megaenvironments indicates the potential of CIMMYT varieties to spill-over to these test megaenvironments.¹²

Akin to previous studies, the spillover coefficients are presented in Table 2 in terms of percentage coefficients based on the average yields of the benchmark variable (i.e. $c_{ij} = Y_{ij}/Y_{jj}$). Off-diagonal values less than one indicate that directly introduced wheat varieties from other megaenvironments yield less than those developed by local breeding programs in the test megaenvironment. Similarly, values greater than one (as in the case of CIMMYT varieties) indicate that directly introduced wheat varieties from these sources yield more than those developed by local breeding programs in the test megaenvironment.

The significant yield advantages expressed by varieties developed and evaluated in ME1, ME2, ME3 and ME6 (implying less direct spill-ins of

NARS varieties from other megaenvironments) can be explained by the fact that these megaenvironments are comprised of countries with a strong experience in wheat research – for instance, India and Pakistan in ME1 (irrigate), Turkey and Spain in ME2 (high rainfall), Brazil in ME3 (acid soils) and the developed countries of Europe and North America in ME6 (high latitude). On the other hand, the ‘environmental distance’ plays a role in explaining the significant yield advantage enjoyed by domestic varieties in ME4A and ME4B (drought environments). To a certain extent this also holds true for ME3 (acid soils) and ME6 (high latitude). For example, the growing conditions in ME3, except for the acid soil, is very similar to that in ME2 in terms of water supply and temperatures (i.e. ‘environmental distance’ is less). Thus, ME3 varieties perform relatively well in ME2. However, in ME3 the soil toxicity adds to the distance between the two environments and constrains the transferability of technology from ME2. This is evident from the highly significant yield disadvantage of ME2 varieties (19%) when planted in ME3 compared with the small and lower significant yield disadvantage of ME3 varieties (4%) planted in ME2. The asymmetry in the ‘environmental distance’ between two environments explains the asymmetry in the spillover matrix (i.e. $c_{ij} \neq c_{ji}$).

If we examine the performance of CIMMYT varieties (CIM1 and CIM2) across megaenvironments, the prominent result of the regression analyses is the wide adaptability and transferability of CIMMYT

¹² A note of caution is needed on the comparability of the coefficients across columns. The values of the coefficients reported in Table 1 are relative to the benchmark origin group (represented by zeros), and are therefore comparable across rows (technologies) but not across columns (environments). Thus, we can say that in ME2, ME1 technology yields 189 kg ha⁻¹ less than ME2 technology, but it is erroneous to say that ME1 technology yields 189 kg ha⁻¹ less in ME2 than in ME1.

varieties to different environments. The environmental specificity and associated selective environmental heterogeneity evident in the comparison of NARS varieties are minimized when CIMMYT varieties are compared across different megaenvironments. This points to the success of the international research system in reducing $G \times E$ interactions and developing widely adapted varieties, at least in the irrigated and high rainfall environments, which account for about 70% of the spring wheat production in developing countries.

These results are however based on spillover analysis at the global megaenvironment level using data from ISWYN trials conducted by CIMMYT and which have a considerable representation of CIMMYT varieties (about 50%). In order to see if the evidence of high transferability of CIMMYT varieties is sustained, the model in Eq. (3) was estimated at the country-level environments using ISWYN data and national yield trial data from Pakistan and Kenya.

5. Estimating wheat improvement spillover matrix at the country-level

5.1. Econometric procedure and data sources

The multiple regression model of Eq. (3) was estimated using ISWYN data for the specific megaenvironments and countries as follows: (1) ME1 (irrigated) – India and Pakistan; (2) ME2 (high rainfall) – Kenya; (3) ME3 (acid soils) – Brazil; (4) ME4B (low rainfall winter drought) – Argentina; (5) ME5A (high temperature/high humidity) – Bangladesh.

The trial entries were classified by their origin as follows:

- DORIG1 varieties developed by a given NARS for the test environment
- DORIG2 CIMMYT varieties released in the test environment
- DORIG3 all other CIMMYT varieties
- DORIG4 varieties developed by other NARS for the test environment
- DORIG5 all other varieties developed by NARS

A model similar to Eq. (3)¹³ was estimated using country-specific environmental classification system for Pakistan (normal and short duration irrigated environments) and Kenya (high rainfall environment) and the national yield trial data. In the national yield trials, the entries were either locally developed NARS varieties or CIMMYT varieties. Thus, only two origin groups (DORIG1 and DORIG2) are defined for Pakistan and Kenya equations using national yield trial data.

For Pakistan, the National Uniform Wheat Yield Trial (NUWYT) data were used. Two types of yield trials with different sets of varieties are conducted each year. The ‘normal planting’ trials, (with the date of planting ranging from 10–24 November), are of the same duration as CIMMYT’s ISWYN trials and represent the optimal planting period for the region. The ‘late planting’ or ‘short duration’ trials, (with the date of planting after December 1), represent an environmental niche that is becoming more important due to increasing cropping intensity in the irrigated regions of Pakistan (Byerlee et al., 1987).

The analysis is based on 14 years of data (1978–79 to 1981–82) for the normal duration trials and 12 years (1978–79 to 1989–90) for the short duration trials. The number of entries in the normal duration trials varied from 16 to 24 each year with a total of 274 entries over the 14-year period. Similarly, the number of entries in the late planting trials ranged from 7 to 15 entries each year with a total of 129 entries over the 12 years analyzed. The data set analyzed includes 158 unique varieties in the normal

¹³ The variable MR (Mill’s ratio) was not included in models using national yield trial data. The estimation of Mill’s ratio requires average yield data over all the locations in a given year of the trial. Since, we used the average yields for three provinces and only one environment (irrigated) in the case of Pakistan, data were not sufficient to estimate the Mill’s ratio. The potential danger of its exclusion from the model is that it may over- or under-estimate the yields of an origin group depending on its rate of attrition in the trial data set. However, this is not likely to be an important problem in the data set since only two or three origin groups are compared in the model. Also, as a group, there is not much attrition over the years analyzed.

Table 3
Regression results of the spillover analysis at country-level using ISWYN data, 1980s

Independent variables	ME1 irrigated		ME2 high rainfall, Kenya	ME3 acid soils, Brazil	ME4B low rainfall, Argentina	ME5A high temperature, Bangladesh
	India	Pakistan				
1. Constant ^a	4688 ***	3161 ***	994 *	811 ***	2945 ***	1817 ***
2. Dummies for year						
R^2 change ^b	–	0.47	0.41	0.36	0.26	0.23
F change ^c	–	138 ***	54 ***	236 ***	62.4 ***	42 ***
3. Dummies for location						
R^2 change ^b	0.73	0.00	–	0.27	0.22	0.01
F change ^c	248 ***	1.79	–	289 ***	87.4 ***	11.4 ***
4. VINT ^a	–5.35	–2.39	58.7 ***	7.15	25.6 ***	–11 *
5. Mill's ratio, MR ^a	49.4	234 ***	207 *	116 **	212 **	146 ***
6. Origin, DORIG ^a						
DORIG2: CIMMYT/test ME	53	142	261	–85	463	294
DORIG3: CIMMYT/other ME	–111	73	333	–104	25	64
DORIG4: other NARS/test ME	–506 **	–196	178	–	–310	226
DORIG5: NARS/other ME	–706 ***	–658 ***	–265	–422 **	–386 **	–75
Number of observations	213	646	270	728	683	362
R^2	0.80	0.64	0.50	0.78	0.67	0.61

^a Number given is the estimated coefficient (kg per ha).

^b Number given is the change in R^2 when a given set of dummy variables is entered in the equation that includes all the other variables.

^c Number given is the change in the F -ratio when a given set of dummy variables is entered in the equation that includes all the other variables.

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

duration yield trials and 76 unique varieties in the short duration trials.

For Kenya, the National Performance Trial (NPT) data for the years 1980–1984 and 1986–1992 were used. About 25 entries are planted each year at different locations in Kenya. Most of these varieties were developed by Kenyan national program or CIMMYT's program in Mexico. The data set includes 287 entries and 140 unique varieties from 12 trial years.

5.2. Empirical results and estimation of spillover coefficients

The results of the regression analysis are given in Tables 3 and 4. The interpretation of the year, location and vintage variable is as in the previous models. The coefficients of the DORIG variables indicate the yield effects of a given origin group. As in the previous models, the yields of locally developed varieties are used as the benchmark coefficients. Thus, the coefficients of other origin groups indicate the yields relative to locally developed NARS varieties in the test environment.

Comparison of the results in Tables 3 and 4 reveal that results of country-level analysis using the ISWYN data are very similar to those using national yield trial data. The 101 kg ha⁻¹ and 314 kg ha⁻¹ yield advantages of CIMMYT varieties in Pakistan and Kenya, respectively, are comparable with the 142 kg ha⁻¹ and 261 kg ha⁻¹ yield advantages estimated using the ISWYN data set. This indicates that the results based on the international trials are a good proxy of the yield advantages of varieties of different origins, at least for the environments with a normal duration growing season.

Three results of these regressions are worth noting. First, as indicated by the positive coefficients of the DORIG2 variable (Tables 3 and 4), varieties developed by CIMMYT out-yield locally developed varieties for the respective environment. This implies that even large countries like Pakistan, India and Argentina can import much of their wheat varietal technology, especially in the normal duration irrigated environments. However, compared with varieties developed by other NARS for the same environment (DORIG4), locally developed varieties did yield higher in three out of five cases (Table 3),

Table 4
Regression results of the country-level analysis using the national yield trial data of Pakistan and Kenya, 1980s

Independent variables	Pakistan (irrigated)		Kenya (high rainfall)
	Normal duration	Short duration	
1. Constant ^a	3304 ***	3312 ***	1715 ***
2. Dummies for year			
R ² change ^b	0.23	0.23	0.14
F change ^c	19.6 ***	9.2 ***	37.0 ***
3. Dummies for location			
R ² change ^b	0.02	0.12	0.20
F change ^c	12.3 ***	27.5 ***	51.0 ***
4. VINT ^a	6.55	-3.01	53.8 ***
5. Origin, DORIG ^a			
DORIG2: CIMMYT/test ME	101 ***	14.2	314 ***
Number of observations	694	321	1834
R ²	0.37	0.35	0.37

^a Number given is the estimated coefficient (kg per ha).

^b Number given is the change in the R² when the given set of dummy variables are entered in the equation that includes other variables.

^c Number given is the change in the F-ratio when the given set of dummy variables are entered in the equation that includes other variables.

* P < 0.05, ** P < 0.01, *** P < 0.001.

indicating the advantage of a local breeding program in the absence of the international research system. These results confirm the findings of the global analysis discussed earlier.

Second, CIMMYT varieties released for a test environment in a country generally yielded higher than other CIMMYT varieties (Table 3), indicating that NARS are efficient ‘borrowers’ from the international research system. They select and release the best suited varieties in the local environment from the available pool of potential spillovers from the international research system.

Third, in Pakistan the yield difference of locally developed varieties and CIMMYT varieties is insignificant in the late planting trials (14 kg ha^{-1}) relative to the normal planting trials (101 kg ha^{-1}) (Table 4). In other words, the length of the season is an important factor constraining research spillins from other sources, thus creating scope for locally developed varietal technology. The CIMMYT megaenvironment classification has only recently recognized the importance of late planted irrigated wheat and have further classified ME1 into normal and late planting for breeding purposes (Rajaram et al., 1996).

6. Conclusions and implications

Many important results pertaining to the issue of technology transferability emerge from the estimation of the spillover matrix at the global and country levels. Research evaluation models have often used spillover matrix to account for the benefits of research conducted by other research programs in similar and different environments. These estimates have been based solely on subjective guesses and on the assumption of location specificity, which implies that the values of the off-diagonal elements in the spillover matrix are less than those of the diagonal elements.

The results for wheat presented in this paper, do not sustain this ‘location specificity’ argument (at least in terms of yields) when the international research system is considered as a source of research spillins. Wheat varieties originating from collabora-

tive CIMMYT–NARS international research system have proven to be highly transferable within megaenvironments and across different countries around the world. The yield advantage of varieties developed by the international research system, was as high as 13 and 11% in the high rainfall and irrigated environments, respectively. In other megaenvironments (such as low rainfall, acid soils, high temperatures, etc.), the yields of CIMMYT varieties, although higher than imported NARS varieties, were not significantly different from yields of locally developed varieties.

Also, at a country-level, the yields of domestic varieties relative to varieties developed by the international research system were not significantly different. This was also indicated by the results of the analysis based on the national yield trial data of Pakistan and Kenya. In other words, there was no evidence of substantial yield gains for these countries from having a breeding program to develop new varieties specifically targeted to the respective environments.

Thus, the overarching result of the global and country-level analyses is that varieties developed by the international research system perform better than or at par with the NARS cultivars in most of the major spring wheat environments indicating the success of the international research system in developing widely adapted wheat varieties. This success in combining high yield potential and wide adaptation can be attributed to: (a) large number of crosses (12000 year^{-1}) made by CIMMYT breeders in Mexico; (b) the use of ‘shuttle breeding’ that allows CIMMYT scientists to alternate selection cycles in different environments with high yield potential that differ in altitude, latitude, photoperiod, temperature, rainfall, soil-type and disease spectrum, and (c) the wide testing of advanced lines in collaboration with NARS throughout the world (Romagosa and Fox, 1993). The comparative advantage of this international research system lies in its ability to conduct such a large breeding operation.

However, it should be noted that wheat varieties are probably more ‘environmentally robust’ than varieties of many other crops in terms of international transferability because the differences among production environments and local quality preferences are not as marked as in other crops such as rice,

maize or beans. Evidence on the origin of varieties released in developing countries support these results of the spillover matrix. Byerlee and Moya (1993) report that more than 50% of total wheat varieties released in developing countries in the 1980s were directly transferred CIMMYT varieties (Byerlee and Moya, 1993). Also, ten out of 36 countries surveyed by CIMMYT, report that 100% of all wheat varieties released in 1965–90 in these countries were based on direct transfers from the international research system (Maredia, 1993). Even a large wheat producing country like Pakistan depends heavily on direct transfers from this international research system. For example, 80% of all varieties released in the Punjab for the normal planting date, in the period 1980–90 were CIMMYT-origin.

These empirical findings based on the origin of the released varieties in developing countries and the coefficients of the spillover matrix estimated in this paper, suggest that potential spillovers of wheat breeding research are larger than have been reported to date. They also suggest the comparative advantage of the international research system in producing widely adapted wheat varieties. The possibilities of direct spillins of varieties developed by other programs that might be utilized effectively in a given area should therefore be taken into consideration in determining the appropriate type of wheat research in a given environment. Countries where wheat is not an important crop or where national agricultural research systems are not highly developed, can consider the option of direct transfer of varieties developed by CIMMYT or other national wheat breeding programs as an alternative. This is especially so for countries where wheat is grown under irrigated or high rainfall conditions. These countries can benefit substantially from only a testing program without incurring large costs in adaptive breeding (crossing and selection) research. There are also implications for countries with large wheat growing areas or diverse environments and which have a strong national wheat research programs. These countries need not devote resources for each and every environmental niche in the country. They can utilize their resources more efficiently by following a mixed strategy of direct importation of technology in some environments and local development of technologies

in other environments which are unique to the country.

There are however, few caveats to be noted about this study. First, given the fact that ISWYN trials are conducted by CIMMYT for the purpose of disseminating its germplasm, there is an overwhelmingly large representation of CIMMYT varieties (about 50%) in the data analyzed in this paper. However, the results of the analysis based on national trial data for Pakistan and Kenya do substantiate the conclusions from the analysis of ISWYN data.

Second, the results are based on the megaenvironment classification system that may overlook important within megaenvironment variations such as late planting in intensively cropped irrigated areas. As the results based on NUWYT data for Pakistan indicate, the transferability of CIMMYT varieties may differ within a megaenvironment depending on the cropping system of a region and other country-specific factors.

Third, this analysis ignores other important factors like grain color, quality and stability which may be important in determining the local acceptability of varietal technology. If the technology available from other sources is high yielding in the local environment but not compatible with the socio-economic environment, then national programs can justify a local breeding program on the basis of other traits. But breeders agree that in field crop like wheat, yield is the most important trait used in making decisions about releasing wheat technology to farmers.

This paper has provided empirical estimates of spillover coefficients, which have hitherto been based on subjective guesses. In the age of shrinking budgets for agricultural research, national programs will have to seek advantage of research spillins from not only other NARS in similar or other environments, but also from the regional and international research systems. This paper has demonstrated the usefulness of national and international yield trial data in providing estimates of potential spillins from other research programs and international research system. Such information can be used to make strategic decisions about the design of crop breeding programs both at national and international levels that would lead to a more efficient global system of agricultural research.

Appendix A. Classification of spring wheat megaenvironments (MEs) used by CIMMYT wheat program

ME	Latitude (°)	Moisture regime ^a	Temperature regime ^b	Sown	Breeding objectives ^c	Representative locations/regions
ME1 ^d	< 40	Low rainfall, irrigated	Temperate	Autumn	Resistance to lodging, SR and LR	Yaqui valley, Mexico; Indus valley, Pakistan; Gangetic valley, India; Nile valley, Egypt
ME2	< 40	High rainfall	Temperate	Autumn	As ME1 + resistance to YR, <i>Septoria</i> spp., <i>Fusarium</i> spp. and sprouting	Mediterranean basin; Southern cone; Andean highlands; East African highlands
ME3	< 40	High rainfall	Temperate	Autumn	As ME2 + acid soil tolerance	Brazil, Andean; Highlands, Central Africa; Himalayas
ME4A	< 40	Low rainfall, winter dominant	Temperate	Autumn	Resistance to drought, <i>Septoria</i> spp. and YR	Aleppo, Syria; Settati, Morocco
ME4B	< 40	Low rainfall, summer dominant	Temperate	Autumn	Resistance to drought, <i>Septoria</i> spp., <i>Fusarium</i> spp., LR and SR	Marcos Juarez, Argentina
ME4C	< 40	Mostly residual moisture	Hot	Autumn	Resistance to drought	Indore, India
ME5A	< 40	High rainfall/irrigated, humid	Hot	Autumn	Resistance to heat, <i>Helminthosporium</i> spp., <i>Fusarium</i> spp., and sprouting	Pozos Rica, Mexico; Joydepur, Bangladesh; Encarnacion, Paraguay
ME5B	< 40	Irrigated, low humidity	Hot	Autumn	Resistance to heat and SR	Gezira, Sudan; Kano, Nigeria
ME6	> 40	Moderate rainfall, summer dominant	Temperate	Spring	Resistance to YR, <i>Fusarium</i> spp., <i>Helminthosporium</i> spp. and sprouting	Harbin, China

^a Rainfall refers to just before and during the crop cycle. High = > 500 mm, low = < 500 mm.

^b Hot = mean temperature of the coolest month > 17.5°C; cold = < 5.0°C.

^c Factors additional to yield and industrial quality. SR = stem rust, LR = leaf rust, YR = yellow (stripe) rust.

^d Further sub-divided into: (1) optimum growing conditions, (2) presence of Karnal bunt, (3) late planted and (4) problems of salinity.

Source: Byerlee and Moya (1993).

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