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Farmer Management of Production Risk on Degraded Lands: The Role of Wheat Genetic Diversity in Tigray Region, Ethiopia

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ABSTRACT

This paper investigates the effects of wheat genetic diversity and land degradation on risk and agricultural productivity in less favored production environments of a developing agricultural economy. Drawing production data from household survey conducted in the highlands of Ethiopia, we estimate a stochastic production function to evaluate the effects of variety richness, land degradation, and their interaction on the mean and the variance of wheat yield. Ethiopia is a centre of diversity for durum wheat and farmers manage complex variety mixtures on multiple plots. Econometric evidence shows that variety richness increases farm productivity. Variety richness also reduces yield variability but only for high levels of genetic diversity. Simulations with estimated parameters illustrate how planting more diverse durum wheat varieties on multiple plots contributes to improving farmer's welfare.

Keywords: Wheat genetic diversity; productivity; risk; land degradation; Ethiopia

TABLE OF CONTENTS

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Salvatore Di Falco,[1] Jean-Paul Chavas,[2] and Melinda Smale[3]

1. INTRODUCTION

Coping with chronically low and variable yields of food crops is critical for the survival of farm households in dry environments of developing agricultural economies where agro-climatic conditions are challenging, technological progress is slow, and market institutions are poorly developed. Often, use of improved seed is limited by poor adaptation to local conditions, while use of fertilizers is uneconomic, either because moisture cannot be controlled through irrigation, or transport and transactions costs are prohibitive. Land degradation, brought about through a prolonged interface between human-induced and natural factors, exacerbates low productivity.

Managing risk exposure is an important preoccupation of agricultural households, particularly in such environments (Bromley and Chavas 1989, Paxson 1992, Fafchamps 1992, Deaton 1992, Fafchamps et al. 1998, Fafchamps and Pender 1997). Insurance mechanisms, whether formal or informal, often function imperfectly due to credit constraints, information asymmetries and commitment failures (Deaton 1990, Fafchamps 1992, Kurosaki and Fafchamps 2002). Off-farm, non-covariant income may be restricted. Although farmers can accumulate grain and livestock as buffer stocks, drawing down farm assets to meet consumption needs has long-

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term consequences. Therefore, *ex ante* crop production decisions remains an important strategy for farm households (Just and Candler 1985, Fafchamps 1992, Chavas and Holt 1996).

Tigray region in the northern Ethiopian highlands is an example. During the last millennia, at least 25 severe drought periods were recorded, and crop production in most areas of Tigray “never topped subsistence levels” (REST: 137). Ethiopia has one of the highest rates of soil nutrient depletion in Sub-Saharan Africa (Stoorvogel and Smaling 1990; Grepperud 1996; FAO 2001). Hurni (1993) estimated that 42 t/ha of soil were lost on the sloped cropland of Ethiopia each year. More than half of the area in the highlands of Tigray is highly degraded. Concerted efforts have been made to rehabilitate the environment in Tigray over the past decade, although it remains one of the harshest in Ethiopia (Gebremedhin 1998; Gebremedhin and Swinton 2003).

Rainfall is sparse and unpredictable in Tigray, both over space and over time. Mean annual rainfall has been estimated at 650 mm or less over the past few decades (REST 1995; Pender and Gebremedhin 2004), and the coefficient of variation for yield in Tigray is four times the national level (REST 1995). Farms are characterized by highly varied micro-environments that differ in topography, soil type, rainfall, temperature and soil fertility, and this heterogeneity varies over relatively small distances (Bekele 1984; Hagos, Pender, and Gebreselassie 1999).

To manage *ex ante* the risks of food production in the highlands of Tigray, farmers have little other than their land and labour—and their crop genetic resources embedded in crop seeds. Having crop varieties that respond differently to weather randomness ensures that "whatever the environmental conditions there will be plants of given functional types that thrive under those conditions" (Heal 2000). Moreover, when harshness is an important feature of the physical environment, then facilitation (rather than competition) may increase as interactions among plants exhibit a greater reliance on positive synergies (Vandermeer 1989; Bertness and Callaway 1994; Callaway 1995; Callaway and Walker 1997).

Ethiopia is a recognized global center of genetic diversity for several crops, including durum wheat (Harlan 1992; Vavilov 1949; Pecetti et al. 1992), and the majority of durum wheat varieties grown in Ethiopia are farmers' varieties, or "landraces." Geneticists have argued that the genetic variation or heterogeneity found in landraces of durum wheat provides insurance against crop failures under adverse conditions (Tesemma and Bechere 1998: 324). Bechere et al. (1996) have reported a high amount of variation in morphogenetic traits and other breeding attributes, specifically in seed samples collected from Tigray and other northern regions. Geneticists have ascribed the wide range of morphogenetic diversity in Ethiopia durum wheat to environmental factors, and to natural cross-fertilization from farmers' practice of growing variety mixtures contiguously.

Most households in the Tigray region remain far from roads, transport, and markets. Based on the survey data used in this paper, the average walking time to the nearest all-weather road is more than 2 hours, with 4 hours walking to the nearest bus service, and 3.5 hours to the nearest *woreda* town. Access to information is also difficult: at the time of the survey in 1998, only 15 percent of household heads had had formal schooling (only 6 percent had more than 2 years of formal education), and only 7 percent had participated in a literacy campaign (Pender and Gebremedhin 2004).

The econometric analysis presented in this paper illustrates how farmers use the richness of wheat varieties to enhance productivity and reduce yield variability on degraded land. This research relies on data drawn from a detailed survey of 135 wheat-growing households in the Tigray region, conducted in 1999. A stochastic production function approach (Just and Pope

1978) is used to test the effects of variety richness, degraded lands, and their interaction on the mean and variance of durum wheat yield. The analysis relies on large variations in weather conditions across space to estimate production risk and evaluate the role of genetic diversity in risk management. To evaluate the effects on farmer welfare, the estimated parameters are used to simulate the insurance value of higher levels of variety richness in the presence of high levels of land degradation.

2. MODEL

Consider a farm household involved in the production of farm output y. The farm technology is represented by the production function

$$y = g(\mathbf{x}, \mathbf{v}),$$

where y is output, **x** is a vector of controllable inputs (e.g., fertilizer, land, labour, biodiversity), **v** is vector of non-controllable inputs (e.g., weather conditions), and $g(\mathbf{x}, \mathbf{v})$ denotes the largest feasible output given **x** and **v**. Of particular interest here are the interactions between the inputs **x** (including variety diversity) and the random variables **v** (representing production uncertainty), with implications for risk management.

Given our focus on subsistence farms, risk management decisions are made at the household level. In this context, the farm output y can be either consumed by the household or marketed: $y = c_1 + m$, where c_1 is the part of farm output consumed by the household, and m is the marketed surplus that can be marketed at price p_1. The marketed surplus can be positive ($m > 0$) when the farm household produces more that it consumes, or negative ($m < 0$) when the household produces less than it consumes. The household also consumes another good c_2 that it can purchase at price p_2. The household income is: $p_1 m + N(\mathbf{x})$, where $p_1 m$ is the income generated from the marketed surplus, and $N(\mathbf{x})$ denotes the net income from other activities (net of the cost of inputs **x**). Normalizing prices such that $p_2 = 1$, the household budget constraint is: $c_2 \leq p_1\, m + N(\mathbf{x})$. With $m = y - c_1 = g(\mathbf{x}, \mathbf{v}) - c_1$, and assuming that the budget constraint is binding, solving the budget constraint for c_2 yields: $c_2 = N(\mathbf{x}) + p_1\, [g(\mathbf{x}, \mathbf{v}) - c_1]$. Let $U(c_1, c_2)$ be a von Neumann Morgenstern utility function representing household preferences under risk. Under the expected utility model, the household makes decisions about c_1 and **x** so as to solve the optimization problem

$$\text{Max } \{EU(c_1, N(\mathbf{x}) + p_1\, [g(\mathbf{x}, \mathbf{v}) - c_1])\}, \qquad (1)$$

where E is the expectation operator based on the subjective probability distribution of the uncertain variables (including production uncertainty **v**) facing the decision maker.

Following Pratt (1964), consider measuring the implicit cost of private risk bearing by the risk premium R_a, where R_a satisfies $EU(c_1, N(\mathbf{x}) + p_1\, [g(\mathbf{x}, \mathbf{v}) - c_1]) = U(c_1, E[N(\mathbf{x}) + p_1\, [g(\mathbf{x}, \mathbf{v}) - c_1]] - R_a)$. The risk premium R_a is the sure amount of money the decision maker is willing to pay to eliminate risk exposure by replacing the random revenue $N(\mathbf{x}) + p_1\, [g(\mathbf{x}, \mathbf{v}) - c_1]$ by its mean $E[N(\mathbf{x}) + p_1\, [g(\mathbf{x}, \mathbf{v}) - c_1]]$. By definition, the decision maker is averse to risk, neutral to risk, or risk-loving when $R_a > 0$, $= 0$, or < 0, corresponding respectively to $\partial^2 U/\partial c_2^2 < 0$, $= 0$, or > 0 (Pratt 1964). The risk premium R_a depends in general on risk preferences and on the distribution of risk.

Given $\partial U/\partial c_2 > 0$, the maximization problem in equation (1) implies that all production decisions are made so as to solve the following maximization problem

$$\text{Max } \{E[c_1, N(\mathbf{x}) + p_1\, g(\mathbf{x}, \mathbf{v})] - R_a(\mathbf{x}))\}, \qquad (2)$$

where $E[c_1, N(\mathbf{x}) + p_1\, [g(\mathbf{x}, \mathbf{v})] - R_a(\mathbf{x})$ is the "certainty equivalent" measured as the expected revenue minus the cost of private risk bearing (captured by the risk premium $R_a(\mathbf{x})$).

The variance of yields can contribute to the cost of private risk-bearing. Letting $\pi = N(\mathbf{x}) + p_1 [g(\mathbf{x}, \mathbf{v})]$ and following Pratt (1964), the risk premium R_a can be approximated as

$$R_a \approx \tfrac{1}{2}\, r_a\, M_2 \quad (3)$$

where $M_2 = E[\pi - E(\pi)]^2$ is the variance of net revenue, and $r_a = -(\partial^2 U/\partial \pi^2)/(\partial U/\partial \pi)$ is the Arrow-Pratt coefficient of absolute risk aversion evaluated at $E(\pi)$. Therefore, the certainty equivalent, $CE = E(\pi) - R_a$, can be expressed as

$$CE \approx E(\pi) - \tfrac{1}{2}\, r_a\, M_2 \quad (4)$$

Risk-averse decision makers are adversely affected by risk, thus providing an incentive to reduce their risk exposure. To do so, farm households manage their production inputs in numerous ways. In dry, marginal environments of developing agricultural economies, *ex ante* risk management strategies involve planting decisions, such as sequential planting or multiple plots, crops and varieties. One hypothesis in the literature about on-farm crop genetic resources is that the genetic diversity of crop varieties enables farmers to better cope with production risk in marginal environments.

Equation (3) provides a convenient way to investigate this and related hypotheses concerning the cost of bearing risk, wheat diversity and land degradation. As a complement to (3), the "absolute risk premium" R_a can be expressed in relative terms as $R_r = R_a/E(\pi)$, where R_r is the "relative risk premium" measuring the risk premium as a proportion of expected return. Using (3), the relative risk premium can be approximated as

$$R_r \approx \tfrac{1}{2}\, r_a\, M_2/E(\pi). \quad (3')$$

The risk premium depends on the risk preferences of the decision maker. We consider the case of farmers who exhibit constant relative risk aversion (CRRA), where the Arrow-Pratt relative risk aversion coefficient $r_r \equiv r_a\, E(\pi)$ is constant with $r_r > 1$. Following Pratt (1964), this corresponds to the utility function $U(c_1, \pi) = a(c_1) - b(c_1)\ \pi^{1-r_r}$, with $b(c_1) > 0$. Assuming constant relative risk aversion is attractive for three reasons. First, CRRA with r_r between 1 and 4 represents typical forms of risk behaviour (e.g., Binswanger 1981; Gollier 2001). Second, CRRA allows for risk aversion, and implies decreasing absolute risk aversion (where the risk premium decreases with wealth; see Pratt (1964)). This is consistent with experimental evidence on farmers' attitudes toward risk in Ethiopian highlands (Yesuf 2004). Third, assuming CRRA and constant returns to scale, and taking the cultivated area as given, maximizing expected utility of net income implies maximizing expected utility of net income per hectare.[4] In this context, below, we will use equations (3), (3') and (4) to simulate the effects of risk and alternative management strategies on farmer's welfare.

3. BACKGROUND

The dataset used in the analysis is from a farm survey conducted in 1999 in the highlands (more than 1500 meters above sea-level (masl)) of Tigray region of Ethiopia by researchers from Mekelle University, the International Food Policy Research Institute (IFPRI), and the International Livestock Research Institute (ILRI). The survey involved a stratified sampling of farm households, with the strata being chosen according to agricultural potential, market access, and population density (Pender et al. 1999). In Tigray Region, peasant associations (PAs) were stratified by whether an irrigation project was present or not, and for those without irrigation, by distance to the *woreda* town (greater or less than 10 km). Three strata were defined, with 54 PAs randomly selected per strata. PAs closer to towns and in irrigated areas were selected with a

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[4] Let A denote farm size (measured by the area cultivated). Under constant return to scale, net revenue $\pi > 0$ is proportional to A: $\pi = k\,A$, where $k > 0$ is net income per hectare. Under CRRA with $r_r > 1$, the expected utility is $EU(c_1, \pi) = a(c_1) - b(c_1)\,(A^{1-r_r})\,E\,k^{1-r_r}$, where $b(c_1) > 0$. This shows that maximizing expected utility implies maximizing the expected utility of net income per hectare.

higher sampling fraction to assure adequate representation. Four PAs in the northern part of Tigray could not be studied due to the war with Eritrea. From each of the remaining PAs, two villages were randomly selected, and from each village, five households were randomly selected. A total of 50 PAs, 100 villages, and 500 households were then surveyed.

Usable data were available for 96 villages, or kushets. Out of 96 villages, 63 were growing wheat and modern varieties represented only about 23 percent of wheat area. These 63 villages are dispersed throughout the region of Tigray with the exception of the western part where no wheat producers are recorded in the sample. A total of 135 households grew wheat on 236 different plots in the survey year analyzed here. After controlling for outliers and observations with missing values for relevant variables, 118 observations remained.

Most of the population depends on mixed crop and livestock farming, and cereals are the most widely grown crops (85 percent of the cultivated land), including wheat, teff, barley, maize, finger millet, sorghum, and pearl millet. Oxen power is used for land preparation and threshing.

The wheat varieties named by farmers include a large number of local types as well as modern types. Varieties were selected by farmers from local germplasm and those they have adapted from modern varieties (Abay 2002). Twenty-seven named local varieties were grown in 50 kushets of Tigray during the survey period, and 10 modern wheat varieties, of which 9 could be traced to a known cultivar and pedigree history.

In and of themselves, these modern bread wheats are diverse with respect to breeding history, and release dates. They include 4 tall improved wheats, of which two originated in Kenya, in addition to a set of semi-dwarf wheats with ancestry from the International Center for Maize and Wheat Improvement (CIMMYT). CIMMYT ancestry entails complex genealogies with parental lines from international sources (Smale et al. 2002). The varieties with CIMMYT ancestry that are grown in Tigray span three decades (1970s, 1980s, 1990s). In each decade, they include a variety from the leading CIMMYT cross of that time period. Of the cultivars released during the early green revolution, most were selections from the 'Mexipak' cross. The 'Veery' cross, which widened the gene pool of spring bread wheat through the 1BL/1RS wheat-rye (Secale cereale L.) chromosomal translocation, was the leading cross among cultivars released during the 1980s. Cultivars selected from the Attila cross (cross made in 1984, first cultivar released from selection in 1995) are now of growing popularity.

Most of the named local varieties are likely to be durum wheat because bread wheat is a more recent introduction. All improved varieties of wheat named are bread wheat, and many of the bread wheat varieties were brought in through government seed programs because they lodge less than the taller, improved durum wheat varieties of Ethiopia. The relationship between wheat variety names and genotype diversity has not been established conclusively in Tigray. Some researchers maintain that a variety is not named unless farmers recognize its distinctive phenological or agronomic features. Others argue that different names may be given to varieties with the same genotypes, reflecting farmers' use preferences. Furthermore, varieties that differ in genotype may be given the same name. Evidence from research at University of Mekelle suggests that farmers deliberately enhance the existing diversity of their wheat cultivars, by selecting different types of plants for seed based on their differential response to environmental stresses—in particular, lack of moisture. Rust diseases of wheat are not common, and pesticides are not applied (Abay 2002; Sefera, Adal, and Teshome 2002).

Inspection of the data shows that six wheat varieties dominated the plots planted in wheat in Tigray from 1991 to 1998. The landraces "white" and "black" are likely to be mixtures or landrace classes of durum wheat, differentiated by color and other characteristics but with considerable within-variety genetic heterogeneity. The landrace Shehan or Shelan appears to be widely grown in much of Tigray, with many farmers producing it continuously and replacing the seed frequently from other farmer sources (Sefera, Adal, and Teshome 2002). Pavon and Enkoy also appear to be extensively grown in Tigray, and for some time. Enkoy has been described as a "rusticated" Kenyan improved variety introduced in Ethiopia in 1979. Enkoy is tall in stature, and although preferred for bread consumption, is vulnerable to stripe rust and performs poorly on less fertile soils. As a consequence, farmers tended to grow it with fertilizer (Hailye, Verkuijl, Mwangi, Yallew 1998).

4. EMPIRICAL APPLICATION

PRODUCTION FUNCTION ESTIMATION

In general, equations (1) and (2) allow for both price uncertainty and production uncertainty. Here we focus on the case of production uncertainty as represented by the stochastic production function $y = g(\mathbf{x}, \mathbf{v})$, where weather conditions ($\mathbf{v}$) are not known at planting time. We assume that the farmer has a subjective probability distribution about $\mathbf{v}$. Just and Pope (1978) proposed to specify $g(\mathbf{x}, \mathbf{v}) = f(\mathbf{x}) + [h(\mathbf{x})]^{1/2} e(\mathbf{v})$, where $h(\mathbf{x}) > 0$ and $e(\mathbf{v})$ is a random variable with mean zero and variance 1. In this context, the Just-Pope production function is

$$y = f(\mathbf{x}) + e(\mathbf{v})\, [h(\mathbf{x})]^{1/2}. \qquad (5)$$

This implies that $f(\mathbf{x})$ represents the mean production function, while $h(\mathbf{x})$ is the variance of output: $E(y) = f(\mathbf{x})$ and $Var(y) = Var(e)\, h(\mathbf{x}) = h(\mathbf{x})$. Given $\partial Var(y)/\partial \mathbf{x} = \partial h/\partial \mathbf{x}$, it follows that $\partial h/\partial \mathbf{x} > 0$ identifies inputs x that are risk-increasing, while $\partial h/\partial \mathbf{x} < 0$ identifies inputs that are risk-decreasing. Note that $e(\mathbf{v})\, [h(\mathbf{x})]^{1/2}$ behaves like an error term with mean zero and variance h(**x**). This reflects the fact that the Just-Pope specification corresponds to a regression model with heteroscedastic error term.

After choosing a parametric form for f(**x**) and h(**x**), the model can be consistently and efficiently estimated using maximum likelihood estimation. This provides consistent and asymptotically efficient estimates of the parameters, of the mean production $f^e(\mathbf{x})$, and of the variance $h^e(\mathbf{x})$.

The Just-Pope stochastic production function provides a convenient and flexible representation of the effects of inputs on means and variances. Widely applied, the approach has also been used in several previous studies that tested the effects of crop genetic diversity on productivity and yield variability (Smale et al. 1998; Widawsky and Rozelle 1998; Di Falco and Perrings 2005). We apply it to investigate the effects of variety diversity, land degradation, and their interaction on productivity and yield variability. The model and econometric approach enable us to explore the role of variety diversity in reducing the cost of risks borne by households farming degraded lands.

VARIABLES

Wheat yields are measured in kg per squared meter. Explanatory variables were constructed from the plot level data, which record the varieties of wheat grown, along with a set of cultivation and land management practices, input use and output in 1998. Table 1 defines explanatory variables and Table 2 reports summary statistics.

Table 1--Variables list and definitions

Labour	Quantity of labour in person day
Oxen	Quantity of oxen power, in days
Fertilizer	Fertilizer applied (1=yes; 0=no)
Improved seed	Seed technology shift variable represented by use of improved varieties (1=yes; 0=no)
Variety richness	Varieties richness index [(number of varieties)/ln(wheat area)]
Land degradation	Share of eroded land
Degradation*variety richness	interaction between variety richness and degradation
Slope	Share of land on steep slope
Altitude	Household altitude, masl
Burning	Burning of crop residues (Yes=1; 0=No)
Fragmentation	Number of plots planted to wheat

Table 1- Descriptive statistics

Variables	Mean	Std Deviation	Min	Max
Labour	22.7	16.38	2.8	94
Oxen	6.98	6.37	0	50
Fertilizer	0.33	0.47	0	1
Improved seeds	0.14	0.35	0	1
Variety richness	0.46	0.23	0.26	1.2
Land degradation	0.36	0.36	0	1
Degradation*variety richness	0.16	0.18	0	0.82
Altitude	2434	270	1840	2950
Slope	0.086			
Burning	0.088	0.28	0	1
Fragmentation	1.6	0.89	1	5

Conventional inputs are few in this wheat production system. Purchased input use on wheat plots consisted solely of fertilizer, but since only 25 of the 135 households applied it, a dummy variable was used to control for use. Similarly a dummy variable was added for the 15 farmers who burned crop residues. Labour and animal power is measured respectively in person days and oxen days. An intercept shift controls for differences in levels of yield between farmers' varieties and improved varieties, as categories of genetic resources. Two physical characteristics of wheat production are included. Plot altitude, which is associated closely with temperature and micro-climates, ranges from 1840 to 2950 masl for farmers surveyed. The dispersion or physical fragmentation of production is expressed by the number of plots planted to wheat. In the survey, farmers plant wheat on 1 to 5 plots.

Land degradation is a complex process affecting productivity and management decisions. Farmers' perception of the degree of degradation on plots was evaluated in the survey.[5] In our model, we used the share of wheat production on lands classified by the farmer as eroded as a proxy for land degradation. Other physical characteristics can also affect the productivity of the land. In our sample, about 10 percent of the plots cultivated by all farmers surveyed are on "steep" slopes, and 40 percent have shallow soils (Pender and Gebremedhin 2004). To control for the potential effect of slope and shallow soils on both productivity and risk, we incorporated the share of land under the category "steep slope" and the share of land with shallow soil into the analysis. However, the latter was found statistically not significant. As a result, it was not included in the model specification reported in Table 3.

Table 2- Econometric results for mean yield function and variance function

[5] Farmers' understanding of land degradation in Tigray has been analyzed in two studies Hunting (1976) and Tilahun (1996). These studies showed that farmers realized the consequences of land degradation on production and were aware of land quality differences.

Variables	Mean Yield Function (A)	Variance Function (B)
Constant	-0.417*** (0.062)	
Labour	0.000615*** (0.00017)	0.033*** (0.01)
Labour squared	0.000005 (0.73E-05)	-
Fertilizer	0.0053 (0.0086)	1.39*** (0.29)
Oxen	0.0019** (0.001)	-0.13*** (0.02)
Oxen squared	-0.000067*** (0.22E-04)	-
Variety richness	1.1*** (0.127)	35*** (6.7)
Variety richness-squared	-0.45*** (0.062)	-19.1*** (3.35)
Land degradation	0.029** (0.0145)	7.17*** (0.94)
Degradation*variety richness	-0.098*** (0.016)	-25*** (2.12)
Improved seeds	0.052*** (0.008)	1.95*** (0.39)
Altitude	0.000073*** (0.00001)	-0.001** (0.0005)
Fragmentation	-0.24*** (0.02)	-3.92*** (1.5)
Burning	0.0089* (0.0033)	-
Slope	-0.036*** (0.01)	4.1*** (0.78)

Breusch Pagan statistics = 62.54.; F- statistic (B)= 11.96; Log Likelihood function: 208. 64; Restricted Log Likelihood:169.5

n =116

Standard errors are in parentheses. Significance levels are denoted by one asterisk (*) at the 10 percent level, two asterisks (**) at the 5 percent level, three asterisks (***) at the 1 percent level.

Variety richness expresses one concept, or dimension of durum wheat diversity. No single indicator of genetic diversity can capture all dimensions of genetic diversity, nor all interactions between genes and the environment (Meng et al. 1998; Smale et al. 2002; Brock and Xepapadeas 2003). Here, we measure diversity by a modified Margalef index, adapted from the ecology literature. Variety richness is defined as the number of varieties that are grown and recognized as distinct by farmers, divided by the logarithm of wheat area cultivated by the household. Typically calculated over large areas and samples, the numerator of the Margalef index is defined as the number of species or sub-species less one.

Richness indices treat each unit as equal, accounting neither for relative abundance nor for genetic distance. Nonetheless, variety richness is an intuitive concept that has appeal in an applied study of farmer decision-making. Farmers observe variety richness, and policies can directly influence local levels of variety richness through encouraging the supply of new seed varieties or reducing the farmer's cost of obtaining them. Finally, to investigate the role of variety richness in possibly mitigating the effects of land degradation on productivity and yield risk, we introduce an interaction term between variety richness and land degradation.

5. EMPIRICAL RESULTS

We used a flexible quadratic functional specification for the mean function. This specification is particularly suited for the study of yield response and allows for zero values in the set of inputs. A linear specification was specified for the variance function, with a quadratic term for variety richness. Alternative specifications were also considered for the variance function.[6] In general, the estimated results reported below were found to be fairly robust to the model specification.

First, we examine whether the model may be subject to endogeneity issues. This would occur if some of the explanatory variables are correlated with the error term. For example, if variety richness were correlated with the error term, the least-squares estimate of the effects of variety richness on the mean and variance of wheat yield would be biased due to endogeneity. A similar situation may also arise with respect to land degradation. Thus, the potential presence of endogeneity must be tested.

A possible strategy to test for endogeneity is using a Durbin-Wu-Hausman test (see Davidson and MacKinnon 1993; Wooldridge 2002). The test involves estimating auxiliary reduced-form regressions for the right-hand side variables suspected to be endogenous, followed by estimation of an augmented original model including the reduced-form residuals as additional explanatory variables. The statistical significance of the coefficients associated with the residuals is then evaluated. First, the test was implemented for variety richness. The distance of the household from the nearest input supplier was used as an instrumental variable. The coefficient on the residual was not statistically different from zero. Thus, we failed to find statistical evidence of significant endogeneity related to variety richness. We also tested for endogeneity in our degradation measure in a similar way, using household distance from the nearest market town as instrument. Again, we found no evidence of endogeneity. On that basis, the econometric estimates reported below were obtained using weighted least squares.[7]

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[6] For instance, quadratic terms were used for land degradation along with interaction terms. However, these terms were found to be statistically insignificant. As a result, they are not included in the specification reported in table 3.
[7] Given that only one instrument has been used for one endogenous variable, the Sargan-Hansen-based test for exogeneity of instruments, such as the C test, cannot be calculated. The equation is exactly identified. However, the data do show that each instrument is correlated with each potentially endogenous variable. Note that maximum likelihood estimation is equivalent to iterated weighted least squares estimation.

The null hypothesis of homoscedasticity was tested against alternative hypotheses of: i) general heteroscedasticity and ii) multiplicative heteroscedasticity (e.g. Just and Pope 1978 1979) using the Breusch Pagan test and an F-test. Results strongly reject the null hypothesis of homoscedasticity and find support for the multiplicative heteroscedastic model. On that basis, the Just and Pope specification provides an appropriate framework for the analysis presented in this article. After controlling for agro-climatic conditions (e.g., altitude, land degradation), the analysis relies on the spatial variations in weather conditions to estimate production risk and evaluate the role of genetic diversity in risk management.

ESTIMATION OF YIELD MEAN AND VARIANCE

The econometric results are reported in Table 3 for the mean function and the variance function. Most of the estimated coefficients in the mean function are statistically different from zero at the 1 percent significance level (Table 3, column A). Conventional inputs have positive marginal effects, consistent with theory. Labour and oxen have positive effects. The joint effects of oxen use and oxen use-squared are statistically significant with evidence of declining marginal returns. The quadratic term of labour is positive, though not statistically significant. The estimated coefficient for fertilizer use (primarily urea) is positive but not statistically significant. The estimated coefficient for the use of improved seeds is positive and statistically significant. Therefore, the use of new varieties increases mean yield. The practice of burning the crop residue is also positively and significantly correlated with mean yields. Physical characteristics of wheat production are also important. Altitude positively affects wheat productivity, probably due to the relatively cooler temperatures that are associated with higher elevation. Fragmented production significantly reduces yields and the use of burning is positively and significantly correlated with yield. The share of land with a steep slope affects productivity negatively, and it is statistically significant.

The effects of wheat diversity on mean yield are captured through three terms: a linear term, a quadratic term, and an interaction term with land degradation. Both the coefficient of the linear term and the coefficient of the quadratic term are statistically significant. This shows that crop genetic diversity exhibit decreasing marginal productivity. Evaluated at sample means, the elasticity of mean wheat yields with respect to variety richness is 3.33. This indicates that wheat genetic diversity has a large and positive effect on mean productivity. This positive effect of variety richness holds for the full range of values found in the sample. However, the coefficient of the interaction term between diversity and land degradation is negative and significant. This means that the effects of diversity on mean productivity are relatively larger when there is less land degradation. Alternatively stated, land degradation tends to reduce the mean productivity benefits of genetic diversity.

All the estimated coefficients associated with land degradation are highly significant. The coefficient of the linear term is positive, but the interaction effect of land degradation with variety richness is negative. When evaluated at sample means, the elasticity of wheat yields with respect to land degradation is negative (-0.06). In fact, increasing the share of degraded land planted to wheat is found to reduce productivity through most of the range of the sample data. The negative coefficient of the interaction term "land degradation - variety richness" implies that the effect of land degradation on mean production is sensitive to the level of crop genetic diversity.

Regression results for the variance function are shown in Table 3, column B. Both the linear and quadratic coefficients of variety richness are statistically significant. The positive linear term and negative quadratic term imply that variety richness reduces the variance of yields but only above a certain wheat diversity level. Evaluated at sample means for the other variables, we find that the diversity decreases the variance when the richness index is above 0.68. Since the sample mean for the richness index is 0.45, this indicates that diversity reduces risk exposure for a significant part of the sample data. The coefficient of the interaction effect "land degradation - variety richness" is negative and statistically significant. This implies that the range of values where diversity reduces risk exposure tends to increase with land degradation. To illustrate, consider the situation in which 55 percent of operated plots are degraded. Then, diversity would reduce the variance when the richness index is above 0.55. If instead, 70 percent of the plots are degraded, then a richness index larger than 0.45 would suffice to obtain a beneficial risk-reducing effect of diversity. This underscores that the risk-reducing benefits of crop genetic diversity can be relatively larger when degradation is more severe. It can also indicate the presence of facilitative (rather than competitive) effects of diversity as it may help buffer weather shocks in the presence of highly degraded soils. Under severe environmental conditions, different plants may be able to exploit positive synergies among them to reduce the adverse effects associated with the harshness of environmental conditions.

The share of wheat production on degraded lands is found to have a significant effect on yield variance both through its positive linear term and its negative interaction term with variety richness. This shows that the extent of degraded land can affect farm household exposure to environmentally-induced risk. For example, land degradation is found to have a positive effect on yield variance for low levels of diversity.

Fertilizer use increases exposure to risk (which is consistent with the finding of Just and Pope (1979), Roumasset et al. (1979) and Rosegrant and Roumasset (1985)) and anecdotal evidence from Ethiopia. Households producing wheat at higher altitudes are less exposed to risk, perhaps because cooler temperatures reduce yield variability. Labour use has a positive marginal effect on yield variability, although more use of oxen appears to reduce risk. Production fragmentation across multiple plots has a negative and statistically significant effect on the variance of yields. This may be due to the diversification of production conditions. The steep slope of the plots is found to increase farmers' exposure to risk.

6. SIMULATIONS

The econometric estimates just discussed were used to simulate selected welfare effects, using equation (3), (3') and (4). Figure 1 shows the simulated effects of variety richness on expected revenue, on the absolute risk premium R_a given in (3), on the certainty equivalent in (4), and on the relative risk aversion given in (3'). The simulations are evaluated at market prices (e.g., price of wheat = 1.4 Birr) and at sample means otherwise. Risk preferences are assumed to exhibit CRRA, with a relative risk aversion parameter equal to 3.[8]

[8] We implemented the simulations also for a relative risk aversion parameter of 1 and 2. The results were qualitatively similar to the one reported below. This indicates that our main findings are not sensitive to the chosen risk aversion parameter.

Figure 1- Certainty equivalent (CE), expected revenue (E rev), absolute risk premium (R_a), and relative risk premium (R_r): simulation for increasing levels of variety diversity. Values are in Birr.

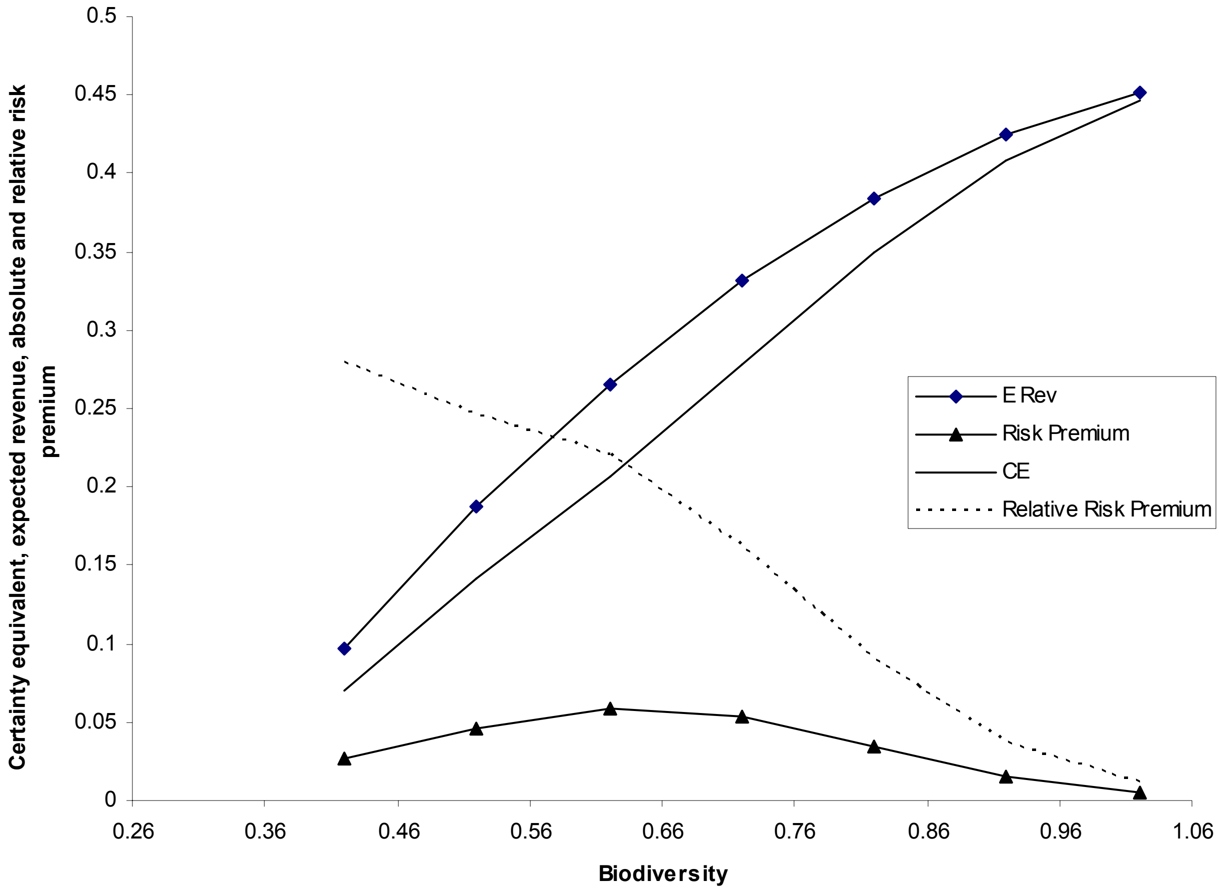

Figure 1 shows that expected revenue increases with variety richness, while the risk premium and the certainty equivalent exhibit more complex patterns. The effect of variety richness on expected revenue is relatively large for all levels of the richness index. This documents the strong productivity-enhancing role of variety richness. The risk-reducing benefit of variety richness is also illustrated in figure 1. It shows how both the absolute and the relative risk premium vary with variety diversity. The absolute risk premium R_a first increases with diversity up to 0.68, then declines. Thus, for higher levels of variety richness (i.e., above 0.68), diversity reduces risk exposure and the cost of private risk bearing. To be effective in reducing the cost of risk (as captured by the absolute risk premium), the level of crop genetic diversity must be moderate to high. The non-monotonic effect of diversity on the risk premium also affects the certainty-equivalent. For high levels of diversity, the certainty-equivalent becomes even larger because of an associated reduction in the risk premium.

Figure 1 shows that the risk-reducing effect of diversity does not apply for low levels of variety richness. However, it remains true that the relative risk premium $R_r = R_a/E(\pi)$ declines monotonically with diversity throughout the range of the sample data. It means that, for any level of diversity, increasing variety richness always reduces the relative cost of risk bearing (as measured by R_r). The reason is that, at low levels of diversity, a higher variety richness increases expected revenue $E(\pi)$ relatively more than it increases the absolute risk premium R_a. This illustrates that crop genetic diversity has important risk management implications for the whole range of sample values of the richness index. When the richness index is small, Figure 1 shows that the positive productivity effect dominates the cost-of-risk effect. And when the richness index becomes large, then diversity has two beneficial effects on farmer's welfare: it increases mean productivity and it decreases risk exposure.

These results illustrate the importance of high genetic diversity among the wheat varieties cultivated by farmers in Tigray, including a range of improved and local materials, and differentiated, genetically heterogeneous local materials. They show that growing more than one variety expands the function of the locally available gene pool, enhancing productivity and enabling farmers to better manage environmental shocks.

7. CONCLUSION

We have analyzed the role of wheat genetic diversity in supporting wheat productivity and mitigating exposure to risk on degraded lands in the region of Tigray, Ethiopia. Ethiopia is a globally important centre of wheat diversity. Farmers grow a spectrum of improved and local varieties of both bread and durum wheat. Durum wheat varieties, in particular, are heterogeneous, often containing several different genetic lines. Farm households face high costs of market transaction in Tigray and must rely on their own production to meet their food needs. Use of purchased inputs is minimal, and non-farm sources of income are few, so that farmers manage risk *ex ante*, largely through labour, land, and seed management.

A stochastic production function was estimated using data collected from a sample of farmers located in 63 villages, including 135 households growing wheat. The econometric results were then used to simulate the effects of varying levels of variety richness on wheat productivity, yield variability, and cost of risk exposure, with interacting effects with land degradation.

Estimated mean and variance functions are consistent with economic theory for conventional inputs. Findings provide empirical evidence that variety richness enhances productivity and can reduce yield variability. However, in order to capture the risk reducing benefits of crop genetic diversity, the richness index must reach a certain threshold level (0.68 compared to a sample mean of 0.46). We also found that the marginal effect of diversity on variance varies with to land degradation. Indeed, the range of values where diversity reduces risk exposure tends to increase with land degradation. In Tigray where land degradation is a serious issue, variety diversification is therefore an important farm strategy for managing production risk.

The econometric estimates were used to evaluate the economic implications of crop genetic diversity on farmer welfare. We found that variety richness strongly increases expected revenue from wheat and can reduce the cost of risk. For all levels of crop genetic diversity, the positive effect of wheat diversity on productivity is found to be large. Risk-reducing effects of variety richness are also found to be important, especially for high levels of diversity. To capture the relationship between the private cost of risk and biodiversity we used two related concepts: the absolute risk premium and the relative risk premium (measuring the cost of risk as a proportion of expected return). We found that the absolute risk premium decreases with the index of variety richness only beyond a certain threshold. This means that biodiversity must be moderate/high to contribute to a reduction in the cost of risk. However, we also find that the relative risk premium decreases monotonically with diversity. This is because, at low levels of diversity, higher variety richness increases expected revenue relatively faster than it increases the absolute risk premium. This reflects the fact that, at low levels of the richness index, the productivity effect of diversity dominates the risk exposure effect in welfare analysis.

Our analysis has some important implications. First, we documented the productivity benefits of variety richness in difficult agro-climatic environments. Second, the risk-reducing benefits of biodiversity appear to be significant, at least for high levels of diversity. While other risk-coping mechanisms might also provide needed income insurance to farm households in Tigray, within the range represented by the sample data, higher levels of variety richness help insure against risky agro-climatic conditions in wheat production. These results highlight the importance of assuring the richness and heterogeneity of varieties grown by farmers in challenging production environments. This includes appropriate seed interventions and the development and delivery of improved varieties. In a rain-fed, drought-prone environment with degraded land, maintaining genetic variation is a principal strategy for securing harvests and reducing the vulnerability of farm households. Indeed, an important part of the welfare benefits of crop genetic diversity is related to risk-related factors. This appears particularly important in harsh environments with imperfect markets for seed and products.

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