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WORKING PAPER

A Review of Agricultural Production Risk in the Developing World

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ABSTRACT

Many of the poor in the developing world rely on agriculture for their livelihood. Unfortunately, agricultural production is inherently risky, which puts these farmers at risk of not being able to meet even their basic subsistence needs. Therefore, understanding these farmers' attitudes towards and responses to production risk is an important piece of the puzzle for designing effective interventions to help them overcome poverty. The purpose of this paper is to provide an overview of the empirical literature that investigates farmers' risk attitudes and responses to production risk in developing countries. Some attention is given to the implications of production risk for the uptake and use of new technologies. The paper also provides a review of the theoretical foundations that have guided the bulk of this research. Finally, the paper discusses several opportunities for furthering the knowledge gained to date.

Keywords: Development, Production Risk, Risk Attitudes

A Review of Agricultural Production Risk in the Developing World

1. Introduction

There is a vast literature exploring the causes and consequences of poverty in the developing world. The consensus of this literature and the available statistical evidence is that a large fraction of the world's poor rely on agriculture as a means of food and income security. Agriculture production throughout the world is known to be inherently risky for many reasons. Agricultural production depends crucially on biotic and abiotic processes that are not completely understood (e.g., why some crops are less susceptible to drought than others). Even when there is a reasonable understanding of certain processes, there may still be little that can be done to control them (e.g., rainfall and drought). Agricultural production is a physically demanding occupation that subjects farmers to a variety of health risks (e.g., exposure to chemicals and the handling of animals). Markets for agricultural produce are often volatile, particularly in developing countries. Therefore, to fully understand the plight of many of the poor in the developing world, one must understand the causes and consequences of agricultural production risks.

A significant literature explores the causes and consequences of the risks faced by farmers. The purpose of this paper is to review the subset of this literature related to farmers' risk attitudes and the consequences of risk in relation to their productions decisions. Our interest rests primarily in understanding what has been found empirically with the hope of choosing intervention options that ameliorate the negative effects of production risk and identifying gaps for future research to fill in order to better inform development strategy choices. Of course, developing such an understanding requires some thought regarding the theoretical paradigms that have guided the empirics. Therefore, we review (i) the theoretical characterizations of risk attitudes and the effect of risk on agricultural production that permeate the literature; and (ii) the

empirical efforts to measure risk attitudes and the effect of risk on agricultural production based on this theory.

2. Characterization of Risk Attitudes

Risk is commonly thought of as the chance of something "bad" happening; though, it is also possible to give risk a more positive connotation by framing it as the chance of something "good" happening. Regardless of how risk is framed, there are two common features to most characterizations. The first is the notion that multiple outcomes are possible. For example, the amount of rainfall received during the cropping season. The second is the notion that the eventual outcome is a matter of chance. For example, before making important production decisions, like which crops to plant or when to plant, farmers do not know how much rain will fall during the cropping season. Furthermore, there is nothing a farmer can do to control rainfall, though there are opportunities to manage or mitigate its effects (e.g., irrigation and drainage).

The predominant theory in economics for explaining risky decisions is the expected utility hypothesis, which was first posited by Daniel Bernoulli in 1738 and later refined and reintroduced by Neumann and Morgenstein (1944).[1] The expected utility hypothesis asserts that an individual makes choices to maximize expected utility. There are three components to expected utility: the possible outcomes, the likelihood of possible outcomes, and the utility (or desirability) of possible outcomes. Possible outcomes were initially defined in terms of aggregate wealth, but alternatives to aggregate wealth (e.g., income or consumption) now permeate the literature. The likelihood of outcomes is characterized in terms of a probability distribution that is often conditioned on an individual's choices. This probability distribution was initially conceptualized in terms of objective measures of the likelihood of chance outcomes,

[1] Dillon (1971) and Anderson et al. (1977) provide an in depth and accessible discussion of the expected utility hypothesis with many examples in the context of agriculture.

but is now more commonly conceptualized in terms of subjective perceptions of the likelihood of chance outcomes (e.g., Savage, 1954). The utility derived from a particular outcome serves as a device for capturing individual attitudes toward risk. Bringing these three components together, expected utility can be defined as $EU(x) = \int_{\underline{c}}^{\overline{c}} U(c)\, f(c|x) dc$ where c is a continuous random variable, bounded by $\overline{c}$ and $\underline{c}$, that represents a set of mutually exclusive outcomes; x reflects an individual's choice over alternative activities that affect the distribution of outcomes (e.g., the amount of fertilizer and pesticides applied to a crop, or the adoption of improved hybrids); $U(c)$ is the utility of outcome c; and $f(c|x)$ is an individual's subjective perceptions about the likelihood of outcome c given the choice of x.[2] Unless otherwise noted we will typically refer to c in the context of income.

Chambers and Quiggin (2000) refer to the above characterization of risk as the parameterized distribution approach. An alternative that builds on Debreu's (1952) and Arrow's (1953) characterization of state contingent risk is $EU(x) = \int_{\underline{s}}^{\overline{s}} U\big(c(x|s)\big)\, f(s) ds$ where s is a continuous random variable, bounded by $\overline{s}$ and $\underline{s}$, that represents a set of mutually exclusive outcomes; $c(x|\, s)$ is the level of income for choice x given outcome s; and $f(s)$ is an individual's subjective beliefs about the likelihood of outcome s.[3]

The subtle distinction in interpretation between the parameterized distribution and the state contingent approach relates to how an individual's perceptions of the likelihood of chance outcomes are characterized. For example, if c were defined as crop income, the parameterized distribution approach characterizes an individual's perceptions over crop income even though the

[2] It also possible to define c as a discrete random variable such that $EU(x) = \sum_{k=1}^{K} p_k(x) U(c_k)$ where K is the number of discrete income levels, c_k is the kth level of income, and $p_k(x)$ is the probability of kth level of income given choice x.

[3] Again, it is possible and even common in the state contingent approach to think of possible outcomes as discrete rather than continuous, which simply requires modifications to expected utility similar to those shown in note 2.

variation in crop income may depend crucially on the likelihood of adequate rainfall. Alternatively, the state contingent approach characterizes an individual's perceptions over the likelihood of adequate rainfall rather than crop income. The basic idea is that individual choices cannot affect the likelihood of chance outcomes in a state contingent world, while choices determine the likelihood of chance outcomes in the parameterized distribution world. While the two approaches are mathematically equivalent provided a suitable transformation of the random variable exists, some questions are more easily addressed using the parameterized distribution approach and others are more easily addressed using the state contingent approach.

Within either framework, an individual's risk attitudes can be characterized by the risk premium, which we will refer to as $RP(x)$. The risk premium is the difference in the expected outcome and the certainty equivalent outcome, $RP(x) = Ec(x) - CE(x)$ where $Ec(x) = \int_{\underline{c}}^{\overline{c}} c\, f(c|x)dc = \int_{\underline{s}}^{\overline{s}} c(x|s)\, f(s)ds$ is the expected outcome and $CE(x) = U^{-1}\big(EU(x)\big)$ is the certainty equivalent given the inverse utility function U^{-1}. Intuitively, the risk premium measures how much an individual is willing to give up in order to receive the average outcome for certain, rather than some risky chance at the average outcome. Individuals with a positive risk premium are called risk averse. Individuals with no risk premium are called risk neutral. Individuals with a negative risk premium are called risk preferring.[4] Intuitively, if given a choice between (i) \$50 for certain or (ii) an equal chance at \$100 and nothing, a risk averse individual will always choose (i), a risk neutral individual might choose (i) or (ii), and a risk preferring individual will always choose (ii). While risk attitudes are often thought of in a global context (e.g., an individual is risk averse under all circumstances), they can also be thought of in a local

[4] Risk preferring attitudes have also been referred to as risk seeking, risk loving, or risk attracted attitudes.

context (e.g., an individual could be risk preferring with respect to some choices and risk averse with respect to others).

Whether an individual is risk averse, neutral or preferring depends on the shape of their utility function $U(c)$. Invariably, c is defined such that the utility function is strictly increasing (i.e., the first derivative of the utility function is positive: $U'(c) > 0$), which implies individuals always prefer more to less and a positive marginal utility (i.e., the change in utility given a change in income). An individual is risk averse if the utility function is increasing at a decreasing rate implying the utility function is strictly concave and a decreasing marginal utility (i.e., the second derivative of the utility function is negative: $U''(c) < 0$). An individual is risk neutral if the utility function is increasing at a constant rate implying it is linear and a constant marginal utility (i.e., $U''(c) = 0$). An individual is risk preferring if the utility function is increasing at an increasing rate implying the utility function is convex and an increasing marginal utility (i.e., $U''(c) > 0$).

Two common alternatives to the risk premium for characterizing risk attitudes are the Arrow-Pratt coefficients of absolute risk aversion $\left(ARA(c) = -\frac{U''(c)}{U'(c)}\right)$ and relative risk aversion $\left(RRA(c) = -c\frac{U''(c)}{U'(c)}\right)$ (Arrow, 1954 and 1970; and Pratt, 1964). Positive values for these coefficients indicate risk averse attitudes, zero values indicate risk neutral attitudes, and negative values indicate risk preferring attitudes. Note that both of these coefficients are dependent on income, which has led to further taxonomical delineations: Increasing Absolute Risk Aversion or IARA (i.e., the first derivative of the coefficient of absolute risk aversion is positive: $ARA'(c) > 0$), Constant Absolute Risk Aversion or CARA (i.e., $ARA'(c) = 0$), Decreasing Absolute Risk Aversion or DARA (i.e. $ARA'(c) < 0$), Increasing Relative Risk Aversion or IRRA (i.e.,

$RRA'(c)$>0), Constant Relative Risk Aversion or CRRA (i.e., $RRA'(c)$=0), and Decreasing Relative Risk Aversion or DRRA (i.e., $RRA'(c)$<0).

Another common measure of risk aversion used in the development literature extends the Arrow-Pratt coefficient of relative risk aversion by assuming some income is known for certain. Specifically, Menezes and Hanson (1970) and Zeckhauser and Keeler (1970) define the coefficient of partial relative risk aversion as PRRA(c^o, c) = $-c\frac{U''(c^o+c)}{U'(c^o+c)}$ where c^o is known income and c is random income. Like the absolute and relative risk aversion coefficients, partial relative risk aversion depends on c and can be characterized as increasing, constant, or decreasing.

While expected utility theory has been the predominant theory for explaining risky choices in the development economics literature, it is not without critics because there are numerous examples of its failure to adequately organize observed behavior in developed countries (for examples, see Chapter 8 in Davis and Holt 1993; and Camerer 1998). While the failures of expected utility theory have lead to a large variety of proposed alternatives, Kahneman and Tversky's (1979) prospect theory and Tversky and Kahneman's (1992) cumulative prospect theory have recently emerged as the preferred alternatives for evaluating risk attitudes in developing countries.

Prospect and cumulative prospect theory generalize expected utility theory to account for four observed regularities: (i) risk averse behavior for likely gains, (ii) risk preferring behavior for unlikely gains, (iii) risk averse behavior for unlikely losses, and (iv) risk preferring behavior for likely losses (Tversky and Kahneman 1992). To account for these regularities, prospect and cumulative prospect theory embellish expected utility theory in four ways. First, the shape of the utility function is assumed to depend on some reference point, say $c^r > 0$. Second, marginal

utility is assumed to be increasing at a decreasing rate above and at an increasing rate below this reference point (e.g., $U''(c^r + \Delta c) < 0$ and $U''(c^r - \Delta c) > 0$ for $\Delta c > 0$), such that individuals display risk averse attitudes above and risk preferring attitudes below this reference point. Intuitively, this assumption implies that preferences depend on whether an individual frames the risk in terms of a gain (i.e., an outcome above the reference point) or loss (i.e., an outcome below the reference point). Third, marginal utility is assumed to be increasing at an increasing rate faster below the reference point than it is increasing at a decreasing rate above the reference point, which implies losses are more salient than gains and is commonly referred to as loss aversion. Fourth, the probability of an outcome is weighted before it is summed with the utility of the outcome. For example, the value of a choice based on cumulative prospect theory can be written as $CPT(x) = \int_{\underline{c}}^{c^r} U(c - c^r) \frac{dw^-(F(c|x))}{dc} dc + \int_{\underline{c}}^{c^r} U(c - c^r) \frac{dw^+(1-F(c|x))}{dc} dc$, where $\frac{dw^-(F(c|x))}{dc} \geq 0$ and $\frac{dw^+(1-F(c|x))}{dc} \geq 0$ are the probability weighting functions for outcomes below and above the reference point; $w^-(0) = w^+(0) = 0$; and $w^-(1) = w^+(1) = 1$ (for an analogous derivation see Davies and Satchell 2004). These weighting functions capture the common observation that individuals seem to perceive that unlikely outcomes are more common and likely outcomes are less common than actuality. The key difference between prospect and cumulative prospect theory is how probabilities are weighted. For prospect theory, weights are based simply on the likelihood of an outcome rather than the cumulative likelihood of an outcome.[5]

[5] It is worth noting that many of the features that separate prospect theory from expected utility theory are described in Dillon (1971) in the context of expected utility theory. For example, Dillon describes utility functions that vary in terms of risk attitudes depending on whether there is a gain or loss. He also argues that individuals have subjective probabilities that differ systematically from some notion of objective probabilities in a way that is analogous to Kahneman and Tversky's weighting function.

Another alternative to expected utility theory that is occasionally found in the development literature is the safety-first principle (e.g., Roy 1952; and Kataoka 1963).[6] Roy's safety-first model hypothesizes that an individual makes choices to minimize the likelihood of income falling below some threshold or subsistence level of income. Roy's model can be recast such that an individual makes choices based on maximizing $RSF(x) = 1 - \int_{\underline{c}}^{c^s} f(c|x)dc = 1 - F(c^s|x)$ where c^s is the subsistence level of income. Alternatively, Kataoka's safety-first model hypothesizes that an individual maximizes their subsistence income subject to the probability of net income falling below subsistence being less than some specified probability. Kataoka's model can be recast such that an individual makes choices based on maximizing the value function $KSF(x) = m(x) - Ks(x)$ where $m(x)$ is expected net income, $s(x)$ is the standard deviation of net income, and K captures an individual's attitude toward risk, with higher values denoting an individual is more risk averse (e.g., see Moscardi and de Janvry 1977).

3. Characterization of Risk and Production Behavior

A substantial literature explores the implications of alternative risk attitudes on behavior from a theoretical perspective. One of the first questions addressed by this literature was the extent to which behavior could be predicted based on the general characteristics of the likelihood or distribution of outcomes. For example, suppose an individual is faced with a choice between two risky alternatives denoted by x_1 and x_2. What conditions on the distribution of outcomes, $f(c|x_1)$ and $f(c|x_2)$, would make it possible to say alternative x_1 will be preferred to x_2 for any risk averse individual? Two important sets of conditions that emerged from the answer to this question are referred to as first-order stochastic dominance (FOSD) and second-order stochastic

[6] Anderson et al. (1977) provides a more general discussion of safety first type models in the context of lexicographic preferences.

dominance (SOSD) (Hadar and Russell 1969; Hanoch and Levy 1969; and Rothschild and Stiglitz 1970).

If the cumulative distribution of income for alternative x_2 is always at least as large and sometimes larger than the cumulative distribution for x_1 (i.e. $F(k|x_2) = \int_{\underline{c}}^{k} f(c|x_2)dc \geq F(k|x_1) = \int_{\underline{c}}^{k} f(c|x_1)dc$ for all k in $[\underline{c}, \overline{c}]$ with strict inequality holding for some k), then the distribution for alternative x_1 satisfies FOSD over x_2 and the expected utility for x_1 will be greater than the expected utility for x_2. Intuitively, if x_1 satisfies FOSD over x_2, then an individual will certainly have higher income if x_1 is chosen over x_2. It can also be shown that average income for x_1 will be higher than for x_2, though the variability of income may be higher or lower. FOSD provides stark predictions of behavior with no restrictions on an individual's risk attitudes. Unfortunately, FOSD is very restrictive in the context of the distribution of chance outcomes and is seldom found to apply empirically.

Alternatively, if the integral of the cumulative distribution for alternative x_2 up to some threshold is always at least as large and sometimes larger than the integral of the cumulative distribution for x_1 up to the same threshold (i.e. $\int_{\underline{c}}^{k} F(c|x_2)dc \geq \int_{\underline{c}}^{k} F(c|x_1)dc$ for all k in $[\underline{c}, \overline{c}]$ with strict inequality holding for some k), then the distribution for alternative x_1 satisfies SOSD over the distribution for x_2 and the expected utility for x_1 will be greater than the expected utility for x_2 for any risk averse individual. Intuitively, the probability of having less income if x_1 is chosen over x_2 is lower for all possible outcomes. It can also be shown that if the mean of the two distributions is equal then the variance of income for x_2 will be higher than for x_1 (e.g., x_2 results in a "mean preserving spread" in the distribution compared to x_1). SOSD is more restrictive than FOSD in the context of an individual's risk attitudes — it only applies for risk

aversion. It is less restrictive in the context of the distribution of outcomes — if a distribution is FOSD, then it will be SOSD, but SOSD need not imply FOSD. Still, even assuming that an individual is risk averse, SOSD does not often apply empirically.

Menezes et al. (1980) extends these results further to the case where the marginal utility of income is either decreasing or increasing at an increasing rate (i.e., the third derivative of the utility function is positive: $U'''(c) > 0$) to show that if two alternatives lead to the same average level of income and the same variance (i.e., a mean-variance preserving transformation), but the distribution is skewed more to the left for x_2 than x_1 (e.g., relatively low consumption levels are more likely for x_2), then the expected utility for x_1 will be higher than the expected utility for x_2. Intuitively, if two income distributions have the same mean and variance, individuals will prefer the distribution with a lower chance of relatively low income. An important implication of this result is that when the marginal utility of income is increasing or decreasing at an increasing rate, then individuals will not like downside risk (i.e., a greater chance of relatively low income under a mean-variance preserving transformation).

Combined, these results provide testable predictions for behavior based on the shape of the utility function and the distribution of chance outcomes. While these predictions for behavior suggest that risk averse individuals will make choices by trading off average income with the variance of income, evaluating risky choices often is more nuanced. Factors that relate more specifically to how income varies (e.g., the probability of low-income outcomes or downside risk and the probability of high-income outcomes or upside risk) are also important.

Another set of questions that was explored early on in this literature in direct relation to production was the extent to which risk attitudes affect how much is produced and how it is produced. Rather than focusing on the choice between two discrete alternatives, this literature

considers the implications of risk when there are a continuum of alternatives (e.g., how much fertilizer to use rather than whether or not to use fertilizer). Generally speaking, it is interested in understanding how output and input choices differ when outcomes are a matter of chance rather than known for certain, which is typically referred to as the total effect of risk on behavior, and how increases in risk or risk aversion affect the choices of output and inputs, which is typically referred to as the marginal effect of risk on behavior. Risk in this early literature was typically framed in one of two contexts: risky output prices or risky input choices.

Classical economics posits several results from the analysis of production behavior when outcomes are known for certain and markets are competitive: (i) increasing the price of output leads to an increase in output (i.e., supply is positively related to the price of output), (ii) increasing the price of an input decreases the use of the input (i.e., input demand is negatively relate to the input price), (iii) the marginal cost of production (i.e., the increase in the cost of production for an increase in output) equals the price of output, (iv) the ratio of input prices is equal to the ratio of marginal products (i.e., the change in output for a change in an input holding other inputs constant), and (v) input and output decisions are independent of fixed costs (i.e., costs that do not depend on how much is produced) and wealth. When outcomes are a matter of chance, many of these results may no longer hold.

Baron (1970) and Sandmo (1971) explored production decisions assuming costs are known for certain, but the price of output is a matter of chance. Both used a single output model where the producer is assumed to maximize expected utility. Utility depends on profit where profit is defined as total revenue (i.e., the price of output multiplied by the quantity of output) minus the variable costs (i.e., cost that depend on how much is produced) and fixed costs. Both found that a risk averse (neutral, preferring) producer will produce less (the same, more) when

price is a matter of chance compared with when it equals the average price for certain. This total effect follows from the observation that it is optimal for the producer to choose output where the marginal cost of production is lower than the average price, contrary to when the price is known for certain. Furthermore, Sandmo found that more risk averse producers produce less (e.g., a negative marginal effect). An increase in the average price that does not affect the variability of price increases production for DARA, which is analogous to the positive relationship between the output price and supply when price is known for certain, but could possibly decrease production for IARA, which is contrary to the positive relationship between output price and supply when price is known for certain. For DARA (IARA), increased wealth or decreased fixed costs increases (decreases) production. Using Sandmo's model, Ishii (1977) also showed that DARA implies decreased production as price becomes more variable, but the average price does not change (e.g., a mean preserving spread in the output price).

Baron and Sandmo's analysis of production under output price risk assumed a known cost function, which subsumes input decisions. Therefore, while much can be said in relation to output, the analysis leaves a gap in terms of understanding the effect of risk on input choices. Batra and Ullah (1974) filled this gap by explicitly modeling the choice of inputs: labor and capital. Otherwise, the specification of their model is analogous to Baron and Sandmo. As such, the implications of their analysis in terms of how much to produce are identical to Baron and Sandmo. Of more interest, are their results related to input choices. Unfortunately, the authors wrongly concluded that when output prices are uncertain, a risk averse (neutral, preferring) producer will use less (the same, more) of all inputs than if the average output price was known for certain. Hartman (1975) showed this result is only obtained if labor and capital are complements in the sense that increasing one input increases the marginal productivity of the

other input and the production function is well behaved (i.e., is concave). What Batra and Ullah did correctly note is that the concavity conditions required for profit maximization when the price is known for certain are not required when the price is a matter of chance and a producer is risk averse. Regardless, input choices will be made based on the equality of the ratio of input prices and marginal products, which is identical to when the output price is known for certain, so risk averse producers should use the same mix of inputs even if they do not use the same amounts because it is optimal for them to produce less. This result implies that the demand for an input will be negatively related to its price when the production function is well behaved, but still leaves circumstances under which the demand for an input may be positively rather than negatively related to its price. They also noted that the marginal and total effects of risk on input choices can be qualitatively different (e.g., increasing risk aversion may increase the amount of an input used by a producer even though the producer will use less of the input compared with if the output price was known to equal the average price for certain); though Hartman showed the two effects will be the same for DARA.

Feldstein (1971) explored production risk in the context of production outcomes being a matter to chance rather than output price. In his model, he considered a constant return to scale Cobb-Douglas production function with two inputs: labor and capital. There were two sources of risk. The first was a multiplicative term that is actually analogous to having a random output price in the model. The second relates to parametric risk in the substitutability of labor and capital (i.e., there is uncertainty about the input exponent parameter in a two input, constant return to scale Cobb-Douglas production function). Feldstein analyzed the model in the context of a risk neutral and averse producer. He found that in these circumstances a risk neutral producer will produce less than if the average production function was known for certain. This

result is contrary to Baron, Sandmo, and Batra and Ullah and is due to the fact that chance does not affect profit linearly in Feldstein's model. It is a result that follows immediately from Jensen's inequality, which says that the expected value of an increasing function of a random variable is less than (equal to, greater than) that value of the function evaluated at the mean of the random variable if the function increases at a decreasing (constant, increasing rate). He still however found that a risk neutral producer should produce more than a risk averse one. The notion that risk can even affect individuals with risk neutral attitudes was also demonstrated more recently by Antle (1983). However, Antle's result is based on a producer making sequential decisions where some decisions are made before some chance events are realized, while others are made after. For example, a farmer may apply fertilizer before knowing how pests will infest her crop later in the year, and then apply pesticides after seeing the pest infestation, but before knowing the course of the weather through to harvest time.

Ratti and Ullah (1976) also explored the case where production rather than output price is a matter of chance, though their model is quite distinct from Feldstein's. Ratti and Ullah used a general production function, but assumed that the producer's input choices are subject to a proportional random shock. They also made some additional assumptions about the elasticities of marginal products that are satisfied for a variety of less general production functions commonly used in empirical analysis. The proportional shock was assumed to equal one on average; so, on average the producer's inputs are exactly what it chose. Like Feldstein, Ratti and Ullah found that a risk neutral producer should produce less than if the random shocks were known for certain. Again, this result follows immediately from Jensen's inequality. A risk averse (preferring) producer should produce less (more) than a risk neutral producer. Assuming labor and capital are complements, a risk averse (preferring) producer should use less (more) of

both inputs than a risk neutral producer. Increasing the average of the random shock to labor while holding the variability constant increases the demand for labor and capital assuming they are complements. Increasing the variance of the random shock to labor while holding the average constant reduces the demand for labor and capital assuming they are complements. An input's demand is decreasing in its price for CARA. Finally, it is worth remembering that many of these results rely on the assumption that capital and labor are complements, which is rather restrictive from an empirical perspective, particularly when considering inputs other than labor and capital.

Pope and Just (1978) was critical of the Ratti and Ullah model and its implications. Pope and Just argued that empirically, many risk averse producers often over employ rather than under employ inputs (e.g., use excessive amounts of pesticides in the face of potential pest problems). They also argued that some inputs can reduce risk rather than increase it (e.g., irrigation), which is not possible in Ratti and Ullah's formulation. To address these issues, they modified Ratti and Ullah's model by assuming that chance has a more general effect on inputs. With this modified model they were able to show that a risk averse producer may use more rather than less inputs than a risk neutral producer — a result that hinges on the assumption that the marginal productivity of an input can be negatively affected by chance outcomes, which again is impossible in Ratti and Ullah's model. Ratti (1978) critiqued Pope and Just's proposed modifications, and redeveloped the original model to include input utilization rates. In this redeveloped model, Ratti showed that risk averse producers still use fewer inputs, but will also utilize inputs less intensively, which reasonably address one of Pope and Just's two criticisms.

The notion that some inputs can increase risk while others can decrease it was more fully developed in Just and Pope (1978) and Pope and Kramer (1979). Just and Pope proposed a

general stochastic production function that allows the effect of an input on the variance of output to be either increasing or decreasing. Pope and Kramer defined an input as marginally risk increasing (decreasing) if under risk aversion the expected value of the marginal product is greater (less) than the factor price at the optimum. They then derived comparative static effects for an expected utility maximizing producer where utility depends on profit and there are two inputs: labor and capital. These comparative static effects depend crucially on stochastic complementarity and substitution (e.g., whether an increase in one input increases or decreases the marginal product of another input on average), and whether an input is risk increasing or risk decreasing. For example, assuming stochastic complementarity, if both inputs are marginally risk increasing (decreasing), then input use decreases as risk increases. Assuming stochastic substitution, capital (labor) decreases only if labor (capital) is marginally risk decreasing. If both factors are marginally risk increasing (decreasing) under stochastic complementarity (substitution), the demand for an input is negatively related to its price.

This literature looking at the effect of risk attitudes on production decisions provides a wide array of testable hypotheses the most robust of which is that risk tends to decrease output, though even this result has been challenged in certain developing contexts (e.g., Finkelshtain and Chalfant 1991). It also provides a variety of strategies for collecting and interpreting data to better understand risky behavior. However, it is important to realize that much of this theory has developed utilizing the expected utility hypothesis, which empirical evidence does not often support. Additionally, much of this early theory developed in the context of rather simple static models, which can be enriched by recognizing that many production decisions are more dynamic and complex. For example, there is a rich literature on the dynamics of technology adoption in the developing world in which risk is one of several important factors. Feder et al. (1985)

provides a review of early contributions to this literature, while Marra et al. (2003) updates this and other earlier reviews and provides a framework for thinking about the dynamics of new technology adoption in the context of learning how and when to implement a new technology; perceptions about the potential value of a new technology and how this value relates to existing technologies; individual risk attitudes; and the option value of delaying adoption when the fixed cost of adoption is high. While a comprehensive exploration of this literature is beyond the scope of this review, a key result that is of interest and has been explored empirically by several authors is that risk aversion slows the adoption of new technology because a lack of familiarity can lead farmers to view it as more risky.

Closing out our discussion of the effect of risk on production behavior, it is worth noting that a key assumption of the literature just reviewed is that producers have no way of dealing with risk other than their choice of output and inputs. There is however a substantial literature that assumes producers can use savings, credit, and insurance in addition to output and input choices to respond to risk. A key result from this literature is that the presence of savings, credit, and insurance can make it optimal for a producer to maximize expected profit rather the expected utility of profit (i.e., consumption and production decisions are separable), which means risk neutral behavior will match risk averse or preferring behavior in terms of production decisions. However, the types of savings, credit, and insurance required to eliminate the effect of risk attitudes on production behavior appear to be the exception rather than the rule in the developing world (e.g., see Alderman and Paxson 1994; Townsend 1994 and 1995; Morduch 1995; and Kurosaki and Fafchamps 2002). This underscores the need for a comprehensive understanding of decision making under uncertainty if interventions targeted to poor agricultural producers in risky production environments are to achieve their intended outcomes.

4. Evidence of Risk Aversion

A variety of authors have sought to empirically test whether farmers in the developing world are indeed risk averse and to characterize differences in risk attitudes based on observable characteristics or circumstances. Most of these efforts up until recently have used expected utility theory as the basis for framing these tests. More recent efforts have explored these questions in the context of prospect or cumulative prospect theory as well as expected utility theory. Two strategies that have predominated are the use of experimental lotteries and the analysis of production decisions based on data collected from household surveys.

Experimental Lotteries

Dillon and Scandizzo (1978) was one of the first papers to explore farmer risk attitudes in a developing context by employing experimental lotteries. The region of interest was Northeast Brazil where small farmers and share croppers were asked to make choices between certain and risky income where risky income had a low return in one out of every four years. The questions were structured in order to identify the certainty equivalent income. The respondents were first asked to make choices assuming subsistence was of no concern. They then answered a similar set of questions assuming subsistence was a concern. It is worth noting that the questions were hypothetical such that there was no monetary consequence based on the respondent's choices. Still, the authors found that most farmers were risk averse, more so when subsistence was at risk and more so for smaller farmers compared with share croppers. The authors also found that risk attitudes were heterogeneous and related to various socio-economic factors.

Binswanger (1980 and 1981) provided another early test for risk aversion among villagers in a developing context using lottery experiments. The experiments were conducted over a six week period with villagers from India who participated in the International Crops

Research Institute for the Semi-Arid Tropics (ICRISAT) survey. The experiment had individuals repeatedly make choices over a certain monetary payment and six random lotteries where the monetary payment was determined by the toss of a coin. The level of the monetary payments was varied proportionally across some repetitions. Some of the repetitions were hypothetical while others were real (i.e., villagers were actually paid based on their choices and the random outcome). The monetary payoffs for the lotteries were selected so that an individual's degree of risk aversion could be ascertained assuming expected utility theory guided behavior. They were also selected to test the predictive power of SOSD under risk aversion. The results of the experiments showed that most villagers were risk averse and that the degree of risk aversion tended to increase when the level of monetary payoffs was higher. They also found that a non-trivial number of individuals (anywhere from 2.5 to 13.7 percent depending on the scale of payoffs and whether the lotteries were hypothetical or real) chose lotteries in violation of SOSD given risk averse preferences, though no villager made such choices consistently. Based on these results, Binswanger concluded that almost all individuals exhibited DARA and IRRA preferences.

The risk preferences of small semi-commercial farmers in Northern Thailand were explored by Grisley and Kellog (1987) using experimental lotteries with real payoffs. In these experiments, farmers made choices over five sets of lotteries. There were 11 lotteries to choose from in each set and the payoffs of the lotteries varied across sets in order to determine if risk attitudes were sensitive to the size of the gamble. The farmers were found to be risk averse with preferences consistent with increasing PRRA. The degree of risk aversion was positively related to a farmer's expected variation in rice yields and farm size. It was negatively related to the

extent of multi-cropping, availability of non-land assets, and mathematical ability. It was not related to price variation, age, or abstract reasoning ability.

Henrich and McElreath (2002) reports the results of a series of lottery experiments with Mapuche and Huinca villagers from Chile, Sangu villagers from Tanzania, and undergraduate students at the University of California, Los Angeles (UCLA). In these experiments, subjects made a choice between a certain monetary reward and a binary lottery. The certain monetary reward was varied in an effort to identify an individual's certainty equivalent. The authors found that Mapuche and Sangu villagers were risk seeking, while Huinca villagers and UCLA undergraduates were risk averse over gambles representing as much as a third of the typical daily wage. Regression analysis relating the certainty equivalents to factors like wealth, age, income, gender, crops cultivated, and culture suggested that culture was the only factor that was consistently related to the observed variation, which lead the authors to conclude that cultural heuristics were an important driver of risk attitudes.

Barr (2003) conducted experiments with individuals from Zimbabwe following procedures similar to Binswanger. That is, subjects repeatedly chose between a certain outcome and one of several possible binary lotteries, including a choice that violated SOSD under risk aversion. A key difference is that Barr did not vary the level of payoffs across treatments. Instead, Barr varied the opportunities for individuals to pool risk. Specifically, in the first treatment, individuals were rewarded for their lottery choices regardless of what others did. In the second, individuals could form groups before making their choice. The payoff for individuals in a group was the group's average payoff. In the third, individuals could again join a group before making their choice. However, after making their choice and seeing the outcome, they could leave the group without other group members knowing. Individuals who joined and

left a group received the same payoff as if they never joined. Individuals who stayed in the group received the average payoff of individuals who remained in the group. The fourth was identical to the third except individuals could not leave the group without other members knowing. Like Binswanger, Barr found that most individuals were risk averse, though some occasionally made choices inconsistent with SOSD under risk aversion. Barr also found that individuals were less risk averse when they could pool risk by joining a group, but only if they could not leave the group either privately or publically.

Miyata (2003) also used procedures analogous to Binswanger, with payoffs as high as a month's income, to explore the risk attitudes of individuals from Indonesian village households. Miyata found that about three-quarters of the individuals exhibited extreme to moderate risk aversion. In general, individual risk attitudes appeared consistent with non-decreasing PRRA. Ordered probit analysis indicated that individuals who lived with their parents exhibited lower levels of risk aversion, as did individuals who lived in larger households, had more education, and were wealthier.

Wik et al.'s (2004) experiments with Zambian villagers closely mirrored Binswanger's with payoffs as high as a third of an individual's annual income. They found that when lottery payoffs were relatively low, risk attitudes ranged from severely risk averse to risk neutral, but for lotteries with relatively high payoffs 80 percent of individuals exhibited extreme to moderate risk aversion. The results lead the authors to conclude that risk attitudes were consistent with DARA and increasing PRRA. Interval regression results also indicated that risk attitudes were related to a variety of observable factors. Women were more risk averse than men. Individuals with more land were more risk averse, while those with more corn acres were less risk averse. Individuals from large households were less risk averse, as were individuals with higher incomes and more

education. Individuals who were lucky during the course of the experiment (e.g., received the high payoff in previous lotteries) became less risk averse. Whether the lottery was framed in terms of gains and losses also affected risk attitudes.

Mosley and Verschoor (2005) evaluated the risk attitudes of semi-subsistence farmers in Uganda, Ethiopia, and India. In their experiments, individuals made a choice over seven different lottery pairs, with only one actually played for real. They also had individuals answer two hypothetical certainty equivalent questions, which were used with the lottery pair choices to estimate risk aversion. Regression results provided no consistent evidence of a link between risk aversion and gender, age, literacy, income, and wealth. They did however find a significant relationship between risk attitudes and an individual's perceived vulnerability in their Ugandan and Indian samples. Perceived vulnerability was measured using a follow-up survey that queried individuals about their deprivation memories and expectations; short-term income expectations; risk perceptions related to investment and entrepreneurial behavior; and self-respect and perceived status. The authors also found many choices that were inconsistent with expected utility theory (32, 37, and 40 percent of the sampled individuals in Uganda, Ethiopia, and India respectively).

Engle-Warnick et al. (2007) estimated the degree of risk aversion and how it relates to various demographic factors in an experiment that also tested FOSD and ambiguity aversion (i.e., aversion to not knowing the probability of chance outcomes). The experiment was conducted with farmers from two different rural regions in Peru. During the experiment individuals made choices between four pairs of binary lotteries where one lottery in each pair had a higher average payoff as well as a higher variance. Individuals also made choices between five lottery pairs where one lottery in each pair was FOSD over the other. For the four lottery

pairs, the authors used the number of times an individual chose the lottery with a higher variance as their measure of risk aversion. For the five lottery pairs, they used the number of times an individual did not choose the lottery exhibiting FOSD as their measure of irrational behavior. The authors found that less than 15 percent of the individuals always chose the lottery with a higher variance, which suggests more than 85 percent exhibited some degree of risk aversion. However, they also found that fewer than 30 percent always chose the lottery exhibiting FOSD. Indeed, more than 40 percent chose two or more (out of five) lotteries that were FOSD dominated, which is inconsistent with expected utility theory. Using an ordered probit analysis with their measure of risk aversion, they found that household size was correlated with lower risk aversion, while land ownership and poverty were correlated with greater risk aversion, though the results must be interpreted with caution because the authors' measure of risk aversion has weak theoretical foundations. The lotteries varied the average payoff along with the variance, such that an increase in the variance does not necessary imply increased risk, and it is not clear that the SOSD risk rankings are consistent with the variance risk rankings used by the authors.

Drawing a sub-sample of Northern Ethiopian farm households that participated in a 2002 household survey, Yesuf and Bluffstone (2009) used a procedure similar to Binswanger to assess risk attitudes. An important procedural difference was that some of the lotteries were framed in terms of gains and losses, while others were framed only in terms of gains. The authors found that most individuals were risk averse in the gains only lotteries (79 to 98 percent depending on the magnitude of the payoffs). Risk aversion increased with the magnitude of the payoffs. In the gain and loss lotteries, a majority of individuals exhibited extreme risk aversion (66 percent), which was not as sensitive to the magnitude of payoffs. A small proportion (4 to 11 percent depending on the magnitude of the payoffs) was risk neutral or risk preferring. Using a probit

model with random farmer effects, the authors found that individuals with greater wealth, larger farms, more oxen, more valuable domestic animals, and greater cash liquidity were less risk averse. Individuals with older household heads and living in households with a greater percentage of children were more risk averse. The authors also note differences in risk attitudes across the two distinct regions of Northern Ethiopia that were sampled.

Unlike earlier experimental studies of risk preferences in the developing world, Tanaka et al. (2010) evaluated risk attitudes in the context of cumulative prospect theory rather than expected utility theory. The experiment was conducted with villagers from North and South Vietnam. Instead of simply having individuals make choices between various pairs of lotteries, the authors had individuals evaluate three separate lists of paired lotteries. The paired lotteries in a list were arranged in two columns and were ordered. Individuals were asked to identify the lottery pair in the list where they switched from preferring lotteries in the first column to lotteries in the second column. The lottery pairs in each list were chosen so that an individual's switching points could be used to identify the degree of risk aversion (over gains), degree of loss aversion, and extent of probability weighting based on a parsimonious three parameter cumulative prospect value function. One lottery pair was selected at random and played for real money. The authors found that few individuals made choices that were consistent with CRRA (a special case of the cumulative prospect value function that was used). On average, individuals were risk averse over gains (risk seeking over losses), and over-weighted low and under-weighted high probabilities. About 90 percent of the sampled individuals exhibited loss aversion. Instrumental variable regressions accounting for the endogeniety of income revealed that risk aversion over gains was negatively correlated with age, education, and the distance to the nearest local market. It was positively correlated with fishing as an occupation, but uncorrelated with income, relative

income, and average village income. Loss aversion was negatively correlated with Chinese ethnicity, being a government official, income, relative income, and village income. It was positively correlated with being from South Vietnam.

Harrison et al. (2010) also deviates from looking at individual risk preferences only from the expected utility perspective. Instead, the authors evaluated the choices of villagers from Ethiopia, India and Uganda over eight binary lottery pairs (one chosen randomly and played for real money) based on expected utility and prospect theory. The lotteries used in the experiment were for gains only, so the only difference between expected utility and prospect theory was whether individuals weighted the probability of outcomes. An interesting and novel feature of the analysis is that it considered the possibility that some choices were best described by expected utility theory, while others were best described by prospect theory using a finite-mixture model. Under the assumptions of expected utility theory, the authors found that individuals were risk averse on average. They also found that Ugandans were more risk averse, while older individuals and women were less risk averse. From the prospect theory perspective, they again found that individuals were risk averse on average and that risk aversion was higher for Ugandans and lower for older individuals and women. Contrary to Tanaka et al., they found that individuals tended to under-weight low and over-weight high probabilities, a tendency that was exacerbated for individuals from larger households. When considering expected utility and prospect theory simultaneously, the authors' results suggest that just under half of the choices were best explained by expected utility theory, while just over half were best explained by prospect theory. Choices best explained by expected utility theory indicated risk aversion on average, while choices best explained by prospect theory indicated risk preferring on average and under-weighting of probabilities. One interpretation of these results is that about half of the

individuals understood the prospect of a favorable outcome and did not like to take chances, while the other half were pessimistic about the prospect of a favorable outcome and liked to take chances. Another is that the authors' experimental design was not rich enough to adequately discern mixtures of behavior in the population.

Lottery experiments have proven quite useful in terms of measuring risk attitudes in the developing world. A question these experiments do not answer however is the extent to which the risk attitudes identified in these controlled experiments are consistent with the risk attitudes exhibited when making important decisions regarding more common activities such as how much time to devote to farming, which crops to plant, and how much fertilizer to use.

Risk Preferences Based on Household Surveys

A common alternative to lottery experiments that has been employed to evaluate the risk attitudes of farmers is the analysis of detailed production data from household surveys. Baron, Feldstein, Sandmo, Batra and Ullah, and Ratti and Ullah showed how various sources of risk can systematically influence production decisions based on individual risk attitudes. Given these insights, a variety of methodologies have been proposed for using farm household survey data to infer individual risk attitudes. While most of this research provides applications in the context of the developed world, a few studies concerned low-income producers in the developing world.

Antle (1987) proposed a structural econometric method for using household production data and moment-based approximations for the profit, revenue, and output distributions to estimate the distribution of absolute and downside risk aversion. The method is applied to data collected from rice farmers in south-central India as part of the ICRISAT village-level surveys. Antle found that the farmers exhibited both absolute and downside risk aversion on average. He also found substantial variation among farmers and that a farmer's absolute and downside risk

aversion was highly correlated. Finally, he notes that his results compared favorably with the experimental estimates obtained by Binswanger (1980) for a similar sample of farmers.

Antle (1989) proposed a nonstructural econometric method for using longitudinal farm level net returns to estimate the distribution of absolute and downside risk aversion. Antle applied his method to data for farmers from three Indian villages who participated in the ICRISAT surveys. The results of the analysis indicated significant absolute risk aversion on average for farmers in two of the three villages. In the third village, farmers appeared to have risk neutral preferences on average. Farmers in only one of the three villages exhibited significant downside risk aversion. The estimates of relative risk aversion for the two villages that exhibited risk aversion were consistent with Binswanger's (1980) experimental results. Finally, Antle noted that average net returns and total income were higher for farmers in the village with risk-neutral preferences, which could be interpreted as an indication of DARA.

Villano et al. (2005) estimated the degree of risk aversion exhibited by rice farmers in the Philippines. The data used for their analysis were an eight year panel survey administered by the International Rice Research Institute (IRRI). The authors used a stochastic production frontier model that was modified to take into account risk attitudes following the risk preference function approach developed by Kumbhakar (2002). The authors found that all farmers exhibited DARA, as well as downside risk aversion. The authors also concluded that the degree of risk aversion exhibited by farmers varied over time.

Using the same data as Villano et al, Kumbhakar and Tsionas (2008) estimated risk premiums for Philippine rice farmers. Their focus was on production risk, which they characterized based on the widely adopted Just - Pope specification. Using a non-parametric approach, rather than the parametric methods used by previous authors, they found that the

average risk premium (relative to expected profit) ranged from about 1 percent to almost 15 percent with an average of 3 percent. These estimates suggested that all farmers in their sample were risk averse. The estimates also supported Antle's conclusion that the degree of risk aversion can vary widely across individual farmers.

A variety of other researchers have estimated risk attitudes even though it was not of primary concern: Rosenzweig and Wolpin (1993) and Fafchamps and Pender (1997) for farm households in India using ICRISAT data, and Kurosaki and Fafchamps (2002) for farm households in Pakistan. These estimates share several common features. First, they were based on maximum likelihood estimates of structural dynamic models. Second, they assumed risk attitudes were characterized by a CRRA utility function. Rosenzweig and Wolpin found a CRRA coefficient of 0.964, while Fafchamps and Pender's estimates ranged from 1.77 to 3.10 depending on a variety of different modeling assumptions (e.g., whether or not farmers faced credit constraints). Kurosaki and Fafchamps found a CRRA coefficient of 1.83 on average, with a range of 1.34 and 4.12. They also reported that this coefficient is significantly decreasing in the amount of land and livestock a farmer owns, which suggests DARA.

Two studies that explored risk attitudes from a safety-first perspective using farm household survey data are Moscardi and de Janvry (1977) and Shahabuddin et al. (1986). Moscardi and de Janvry estimated farmer risk attitudes using a Kataoka's safety-first framework with production data collected in Mexico. Specifically, the authors estimated a generalized power production function in terms of fertilizer use and various soil characteristics. The production function estimates were then used to estimate each household's risk attitude parameter. Variation in this risk parameter across households was related to age, education, family size, off-farm income, land under control, and solidarity group membership. The results

showed that households were risk averse in the sense that increases in net income variability reduced the value of production. Households with greater off-farm income and more land under their control exhibited significantly lower levels of risk aversion as did households who belonged to solidarity groups.

Roy's safety-first framework was employed by Shahabuddin et al. with data from four different regions in Bangladesh. Based on this formulation, the authors used the difference in subsistence income and average income normalized by the standard deviation of income as their measure of risk aversion. In terms of interpreting this value, if subsistence income exceeds average income, the household must gamble or assume more risk in order to minimize the chance of falling below subsistence. Alternatively, if average income exceeds subsistence income, the household does not have to gamble or assume as much risk in order to minimize the chance of falling below subsistence. Therefore, higher values of the risk measure suggest more risky behavior. The risk measure was related to a variety of socio-economic factors using regression analysis under two alternative assumptions regarding subsistence income. The only consistent result found for all four regions was that education and assets did not significantly influence risk aversion. The coefficient for age was negative and significant in two regions for at least one measure of subsistence income; household size was positive and significant in three regions for at least one measure of subsistence income; farm size was negative and significant in three regions for at least one measure of subsistence income; and off-farm income was negative and significant for three regions.

Rosenzweig and Wolpin's, Fafchamps and Pender's, and Kurosaki and Fafchamp's estimates of risk aversion were generally consistent with other experimental and farm household survey studies based on expected utility theory. Due to significant differences in the underlying

methodology, comparisons between Moscardi and de Janvry and Shahabuddin et al. to each other or studies based on expected utility theory are not possible. While comparisons of risk attitude estimates between household survey data and experimental lottery data appear reasonably consistent, it is fair to characterize these comparisons as anecdotal.

5. Evidence of the Effect of Risk on Production

The ample evidence of risk averse attitudes in the developing world combined with the theory of production behavior under risk suggests that farmers would likely produce more if it were possible to reduce risk. It also suggests that farmers would use more or less of various inputs depending on how these inputs affect risk. A variety of studies have explored these conclusions empirically from a number of different perspectives.

A small and recently emerging literature attempts to empirically estimate the relationship between risk attitudes and farmer decisions by combining risk attitude and farm household survey data. Dhungana et al. (2004) explored the technical, scale, allocative, and economic efficiency of Nepalese rice farmers using a non-parametric data envelop method.[7] The authors estimated the relationship between these various measures of efficiency and various socio-economic factors using a Tobit regression. Of particular interest was the relationship between efficiency and risk attitudes, which were measured using the CARA coefficient implied by choices over binary lotteries presented in the household survey. They found that risk aversion was positively related to technical efficiency, but negatively related to scale, allocative, and economic efficiency, though the results are only significant for allocative efficiency. Note that a decrease in allocative efficiency as risk aversion increases is however consistent with Batra and

[7] Technical efficiency relates to farmers producing a given level of output with the minimum number of inputs. Scale efficiency relates to farmers producing at the highest average productivity. Allocative efficiency relates to farmers producing where the value of the marginal product equals marginal cost and economic efficiency relates to farmers producing at minimum cost.

Ullah (1974) and Hartman (1975) if farmers' utility functions satisfy DARA rather than CARA. They also found that more risk averse farmers used more household inputs and fewer purchased inputs, which suggest that purchased inputs were more risky.

Bezabih (2009) explored the effect of risk attitudes on a farmer's choice of tenancy arrangement (i.e., pure rental, rental with output sharing, pure share cropping, and share cropping with input cost sharing) in Ethiopia. Risk attitudes were measured categorically for both tenants and landlords following procedures similar to Binswanger (1980). The authors estimated a multinomial logit model for the tenancy arrangement choice dependent on the tenant's and landlord's risk attitudes in addition to a variety of other socio-economic factors. The authors found that both the tenant's and landlord's risk attitudes were significantly related to tenancy arrangements, but the categorical nature of the author's risk attitude information makes the interpretation of the directional impacts difficult to discern.

The effect of risk aversion on Ugandan coffee farmer labor demand was explored by Vargas Hill (2009) where risk aversion was measured based on a farmer's choice between five hypothetical and contextualized lotteries (i.e., lotteries were framed in the context of crop income). The author used multivariate regression to relate labor devoted to coffee production to risk aversion, wealth, and a variety of other control variables. The author concluded that increased risk aversion leads to reduced labor demand for coffee production when farmers were below the 75th wealth percentile, but not when farmers were in the top 25th percentile. Given that coffee production in Uganda is labor intensive, this reduced input use translates into reduced output as predicted by much of the theory.

Gine and Yang (2009) explored how risk affects a farmer's demand for credit and insurance. The authors' study was conducted with corn and groundnut farmers in Malawi using

a randomized field experiment. In the experiment, some farmers were offered the opportunity to buy improved seed and fertilizer on credit, while others could buy improved seed and fertilizer on credit only if they also purchased actuarially fair rainfall insurance. To understand how risk aversion affected choices, the farmers also completed a demographic survey that asked them to rank their aversion to the risk of trying a new crop on a scale of 0 to 10 with 10 being the highest level of risk aversion. To the authors' surprise, a higher percentage of farmers in the credit only treatment agreed to purchase improved seed and fertilizer. A result the authors surmise was related to the implicit insurance provided by limited liability. The authors were not surprised to find that risk aversion was negatively related to farmers agreeing to buy improved seeds and fertilizer on credit without insurance.

While these more recent studies have used direct measures of risk attitudes to help explain farmers' production decision, earlier studies relied more on indirect evidence. Dercon (1996 and 1998) for example discuss the relationship between crop choice and asset holdings found in survey data from Tanzania. He found that Tanzanian farmers with fewer assets like livestock tended to specialize in crops with lower variability and lower yields. While such a result might be taken to indicate DARA, Dercon (1998) offers an alternative explanation, the lumpiness of cattle as an asset because the author also observed that cattle ownership was low given its high returns and non-cattle owners tended to specialize in off-farm employment. A stochastic dynamic optimization model and simulation exercise was then used to demonstrate how the lumpiness of cattle could explain observed behavior.

Roy's safety-first model was used by Wale and Yalew (2007) to evaluate the effect of risk on the choice of coffee varieties by Ethiopian farmers. Risk was measured as the difference in risk-free income, including the value of livestock, and subsistence income. Using a

multinomial logit model, the authors found that farmers at greater risk tended to choose coffee varieties with greater yield stability and environmental adaptability, while farmers at lower risk tended to choose varieties with higher yields and more marketable attributes.

Many other studies have used climatic factors like the variability of rainfall to determine how risk affects production decisions. For example, Rosenzweig and Binswanger (1993) explored how productive and non-productive asset holdings varied with wealth and weather risk using the ICRISAT survey data. While the authors considered six different measures of rainfall to quantify risk, the monsoon season onset date was the only one that was significantly related to profits and the riskiness of a farmer's asset holdings. The greater the coefficient of variation in the onset date, the lower farm profit and less risky the farm asset portfolio, though wealthier farmers' profits was less sensitive to this variation. Reardon and Taylor (1996) used survey data from farmers in different agro-climatic regions in Burkino Faso during years of normal rainfall and drought. They found that poor farmers who relied heavily on crop income tended to sell livestock in years of drought. Kanwar (1999) used the ICRISAT data to estimate the relationship between labor demand and risk. First, the author estimated net revenues based on lagged revenue, changes in assets, rainfall, and a time trend. The author then estimated labor demand using the predicted average and standard deviation of net revenue and other demographic and production related variables. Interestingly, while many of the demographic and production related variables were significantly related to labor demand, the average and standard deviation of net returns was not. The effect of risk on non-farm labor decisions was evaluated for India in Rose (2001), which used the rainfall coefficient of variation to measure risk ex ante and deviations from average rainfall to measure risk ex post. The author found that the coefficient of variation and negative deviations were associated with greater non-farm labor market

participation, lower farm profits, and lower overall income. Using farm household survey data from Mozambique, Heltberg and Tarp (2002) found that farmers in regions that were more prone to flooding or drought were less likely to market food and cash crops. When they did market their crop, the quantity sold was typically less than what farmers in regions not prone to drought or flood sold. Dercon and Christiaensen (2007) found that less fertilizer was used by farmers who were at greater risk of crop failure due to inadequate rainfall using panel survey data from Ethiopia.

Barrett (1996) and Ghatak and Seale (2001) focus on price, rather than climatic, risk in assessing the effect of risk on production. Barrett first demonstrated how estimates of marketable surplus in relation to prices can be used to assess how price risk affects labor demand. He then used data from Madagascan rice farmers to obtain the estimates necessary for further evaluation. Drawing on estimates of risk aversion from other studies (e.g., Binswanger, 1980), he concluded that small farms tended to be price risk averse and over-employ labor, which he used to explain the common observation that smaller farmers are often more productive than larger ones. Ghatak and Seale (2001) directly incorporated price variability (i.e., the price standard deviation) into their estimates of crop acreage using data from China. Consistent with Sandmo, they found that increases in the average price (holding variability constant) increased crop acreage, while increases in the variability (holding the average constant) decreased crop acreage.

Rather than attempt to characterize how risk affects farmer output and input choices, a number of studies have instead focused on quantifying the effects of various inputs and production practices on risk. For example, Shankar et al. (2007, 2008), Di Falco et al. (2007), and Di Falco and Chavas (2009) explored how crop variety choice affected risk; Rosegrant and

Roumasset (1985), Smith and Umali (1985), and Pandey and Pandey (2004) explored how fertilizer use affected risk; Antle and Crissman (1990) explored how fertilizer, labor, and irrigation affected risk; Villano and Fleming (2006) explored how pesticide, fertilizer, and labor affected risk; Barrett et al. (2004) explored the effect of the System of Rice Intensification (SIR) on risk; and Kurosaki (1997) explored the effect of enterprise choice on risk.

The effect of genetically modified crop varieties on risk in South Africa explored by Shankar et al. (2007, 2008) used two different methodologies to essentially reach the same conclusion. Shankar et al. (2007) estimated a Just - Pope production function with three years of farm survey data and showed that Bt cotton varieties were FOSD over conventional varieties in terms of output for all three years. Net returns for Bt cotton were also FOSD over net returns for conventional varieties in two of the three years, but were not even SOSD over conventional varieties in the third year. Additionally, the results indicated that pesticides and Bt cotton increased output and output variance. Using two years from the same data, Shankar et al. (2007) reports similar conclusions based on crop damage, rather than production function, estimates.

The effect of crop variety diversity on risk explored by Di Falco et al. (2007) and Di Falco and Chavas (2009) also used different methodologies, though for two different crops. Di Falco et al. estimated a Just - Pope production function with a quadratic mean and linear variance using data collected from Ethiopian wheat farmers. The inputs used in the analysis included fertilizer, labor, whether seed was an improved variety, a variety richness index, land degradation, land degradation interacted with the variety richness, and a number of other farm characteristics. The authors found that variety richness increased mean yields at a decreasing rate, though land degradation reduced this positive effect. Variety richness initially increased, but then decreased variability, though variability was lower in general on more degraded land.

Fertilizer increased variability, while more fragmented production lead to lower and less varied production. Di Falco and Chavas obtained generalized method of moment estimates for a stochastic production function using data collected from Ethiopian barley farmers. The production function estimates controlled variety biodiversity as well as differences in inputs, environmental factors, managerial factors, and other crops. The moments of the distribution of output that were estimated included the mean, variance, and skewness. The authors found that increased variety biodiversity increased output and the variance of output, though downside skew was reduced. Using a CARA utility function, the authors also found that the benefits of variety biodiversity were larger on more degraded soils.

The effect of using nitrogen fertilizer on risk in Philippine rice production was evaluated by Rosegrant and Roumasset (1985) by estimating a Just - Pope production function that included a variety of stochastic inputs (e.g., moisture stress, solar radiation, and typhoon occurrence) as well as nitrogen. The authors found that nitrogen increased the variability of output. The authors determined that risk aversion would decrease the optimal nitrogen rate relative to the risk neutral optimum by 13.3 to 30.8 percent based on the CRRA coefficients estimates reported in previous literature.

Experimental data collected by the IRRI in the Philippines was used by Smith and Umali (1985) to evaluate the effect of risk on optimal nitrogen application rates. The authors used this experimental data and generalized least squares to estimate a quadratic production function with random coefficients. They then used this production function to evaluate the optimal nitrogen rates for a risk averse and risk neutral farmer assuming constant PRRA. The authors found a risk averse optimum of 32 to 35 kg per hectare, which was lower than the 42 kg per hectare optimum

found for risk neutral attitudes. These estimates were consistent with observations that 50% of farmers in the Philippines used between 30 to 40 kg per hectare.

Pandey and Pandey (2004) used pooled time series and cross-sectional data collected from Philippine rice farmers to estimate a Just - Pope production function where the inputs included labor, fertilizer, rainfall, and a dummy variable for the use of modern rice varieties. Both the mean and variance of output were specified using a Cobb-Douglas function. They found that all inputs positively affected average output. While modern rice varieties reduced output variability, fertilizer and rainfall increased it. Given alternative assumptions about the degree of risk aversion, the authors found that risk would reduce fertilizer use by 5 to 10 percent.

While many studies have found that fertilizer increases variability and presumably risk, Antle and Crissman (1990) found that it could be risk increasing or decreasing for Philippine rice farmers when casting risk in terms of the variability profit rather than yields. Similarly, they found that irrigation could be risk increasing or decreasing. Alternatively, labor was found to be both productivity enhancing and risk decreasing.

Villano and Fleming's (2006) stochastic frontier analysis with a Just - Pope production function explored the technical efficiency of Philippine rice farmers. The inputs included in the analysis were the area farmed, fertilizer use, herbicide use, labor, and a time trend (to capture technological innovation over the seven years of data). Inefficiencies were then related to a farmer's age and education; the ratio of adults in the household; non-farm income; and time. The results indicated that area farmed, fertilizer, and labor increased output variability, while herbicide use decreased it, though none of the effects were statistically significant.

Barrett et al. (2004) assessed how the System of Rice Intensification (SIR) affected production risk in Madagascar. SIR was developed in the 1980s by a French missionary priest as

a way for farmers to improve rice production. To see if the production method was indeed superior, the authors developed an econometric method for decomposing changes in average yield and yield variance into plot, farmer, and technology effects. The authors found that SIR production substantially increased yields, though unobservable farmer skill also helped explain higher yields. They also found that SIR production substantially increased yield variance, which they concluded was an important reason for why many farmers started and then stopped using it.

The effect of enterprise diversification on risk was explored by Kurosaki (1997). Specifically, the author considered farm households that produced rice, wheat, fodder, and milk. The authors estimated price, yield, and profit risk using farm household survey data from Pakistan. They found that profit from fodder production was negatively correlated with profit from milk production. This occurred because fodder prices were low when fodder yields were high, which lowered fodder profit. But this made fodder, an important input for milk production, a relatively cheap input which boosted milk profit. Wheat profit was also found to be positively correlated with milk profit, but negatively correlated with fodder profit. Rice profit was positively correlated with wheat profit. The author used these results to argue that enterprise diversification in the region was consistent with the notion that farmers diversify their enterprises to reduce risk.

Several studies have focused on evaluating farmer perceptions of yield distribution to better understand the effect of risk on new technology adoption. For example, Herath et al. (1982) elicited the yield distribution for both local and modern rice varieties from Sri Lankan farmers. They then used these yield distributions to ascertain the optimal amount of land that farmers should have allocated to local and modern varieties based on assumptions of risk neutrality and risk aversion. Comparing the optimal to actual allocations made by farmers, the

authors conclude that the optimal allocations assuming risk aversion were more closely aligned with the actual allocations, which suggested that risk attitudes were an important factor in determining farmer adoption of new rice varieties.

For maize farmers in Malawi, Smale and Heisey (1993) and Smale et al. (1994) elicited yield distributions in order to assess the effect of risk on the adoption of hybrid maize and fertilizer. They found that farmers with a higher subsistence requirements planted less hybrid maize and used less fertilizer on it, though they used more fertilizer on local maize varieties. Holding the mean of yields constant, an increase in yield variability was related to decreased adoption of hybrid maize and decreased fertilizer use on hybrid maize, a result that again supports the notion that risk can slow the adoption of new technologies.

Nkonya et al. (1997) considered how risk perceptions affected Tanzanian farmers' adoption of improved maize varieties. Contrary to Herath et al., Smale and Heisey, and Smale et al., the authors did not find that risk perceptions affected adoption, either positively or negatively. Instead, the authors found that farm size, education, extension visits, and fertilizer use were important factors related to adoption. While the qualitative difference in the authors' results from other authors could be related to a difference in their sampling frame (e.g., Tanzanian versus Malawian or Sri Lankan farmers), it is more likely attributable differences in how risk perceptions were measured. Instead of eliciting yield distributions, the authors elicited the difference in yield between a normal and drought year.

Several other studies have focused on the relationship between risk and new technology adoption by eliciting farmers risk attitudes rather than risk perceptions. For example, Knight et al. (2003) used Ethiopian farmer's choices between a hypothetical certain prospect and a risky prospect with a higher average return (contextualized in terms of livestock and crop production)

to estimate risk attitudes. The authors then relate these risk attitudes to education and technology adoption where technology adoption was defined in terms of a farmer's use of at least one innovative input and one innovative crop. They found that risk aversion was negatively related to the farmer's level of education. Technology adoption was positively related to a farmer's education and negatively related to increased risk aversion, which led the authors to conclude that risk does have a negative influence on technology adoption, but increased education can foster technology adoption both directly and indirectly through a decrease in risk aversion.

While Knight et al.'s analysis was guided by expected utility theory, Liu's (2008) analysis was guided by prospect theory. Following Tanaka et al., Liu estimated farmers' risk attitudes, degree of loss aversion, and propensity to under-weight low and over-weight high probability events and uses these estimates to try to explain how rapidly farmers adopted Bt cotton in China. Farmers who exhibited a higher degree of risk and loss aversion took longer to adopt Bt cotton, while those who tended to over-weight low probability events adopted Bt cotton sooner.

Still others have relied on field experiments to better understand the relationship between risk and new technology adoption. Byerlee and de Polanco (1986) used experimental field data to characterize the risk of adopting improved barley varieties, fertilizer, and herbicide in Mexico. They then related these experimental results to actual adoption behavior. They found that adoption was sequential and lagging for low return and high risk innovations.

Drawing succinct general conclusions for the developing world from this broad literature is a challenge because studies vary markedly in terms of the sample populations, crops, and inputs of interest. Studies also vary notably in terms of methodology. The most robust conclusion that can be drawn is that fertilizer tends to increase yield variability, though Antle and

Crissman suggests this result need not translate into increased risk if farmers are interested in profit rather than yield. The bulk of the evidence also suggests that risk slows the adoption of improved seed varieties, depresses the use of fertilizer, and results in farmers choosing production activities that lead to lower, though less variable, returns, which are all decisions that can exacerbate poverty.

6. Conclusions

Many of the poor in developing countries rely on agriculture for their livelihood. Unfortunately, agricultural production worldwide is inherently risky, which puts these poor farmers at risk of failing to meet subsistence needs. To understand what types of interventions can help these farmers lead more secure and productive lives, it is important to understand their attitudes toward and responses to risk. A large literature now exists to enhance our understanding, though important gaps remain.

This literature review provides insight into the breadth and depth of the knowledge gained to date regarding the attitudes toward, responses to, and implications of agricultural production risk in the developing world. The studies reviewed encompass 25 countries across four continents, though our efforts focused most heavily on crop production in Africa and Asia (see Table 1 for a summary). The factors of production encompassed by these studies are wide ranging, with fertilizer, labor, land, and seed being the most broadly represented (Table 2). While a vast majority of these studies considered multiple factors of production, surprisingly few (e.g., DiFalco et al. and Difalco and Chavas) explicitly considered the degree of complementarity and substitutability of these factors, which theory suggests is important for fully understanding the implications of risk. The crops covered by the studies are also wide ranging, with rice garnering the most attention by far followed by corn, cotton, and wheat (Table 3). The majority

of studies focus on a single crop, with little concern for the potential effect of crop diversification on risk.

From a more topical perspective, three decades of lottery experiments with villagers in the developing world have been valuable for understanding attitudes toward risk. This research shows that most individuals are risk averse when it comes to the prospect of gains, though risk attitudes are heterogeneous across individuals and time. There are substantial cultural differences; indeed, in a few cultures risk preferring appears to be the norm. Risk aversion tends to be negatively related to age, education, risk pooling, luck, household size, and liquidity, and positively related with the size of the gamble, proportion of children in the household, age of the household head, and perceived vulnerability. While expected utility theory has served as the primary tool for evaluating a farmers' risk attitudes and response to risk, there is emerging evidence of its shortcomings in the developing world that mirror those found in developed-country studies. Recent evidence suggests that farmers in the developing world may be risk averse over gains, risk preferring over losses, loss averse, and ambiguity averse. They may also over- or under-weight the likelihood of chance outcomes. Given this emerging evidence, further research into the potential for alternatives to expected utility theory to better organize farmer choices in lottery experiments seems warranted.

Efforts to identify risk attitudes using household survey data have also been important for corroborating the findings of lottery experiments. These studies are important because an individual's response to risk over simple monetary gambles need not reflect their response to the more salient risks that can result from poor decisions in the context of agricultural production realities (e.g., not growing enough to eat or feed ones family). With that said, one of the advantages of studies that have employed lottery experiments is that the methods have been more

consistent among studies, making it easier to draw comparisons. Methodological consistency has not been as common for studies using household survey data, which could be remedied in future work. There also remain opportunities to learn more about the consistency of experimental lottery and household survey results because most evidence to date has been anecdotal. Combining both methodologies in a single study that is designed to formally test systematic differences would be insightful.

With inadequate access to savings, credit, and insurance, as is typical in most developing countries, theory suggests risk averse farmers will devote resources to reducing risk and tend to produce less, a result that is corroborated by many of the empirical studies reviewed. For example, there is ample evidence that more risk averse farmers choose less-productive crops, devote too much labor to less-productive farm activities, too little labor to more-productive farm activities, and use fewer productivity-enhancing inputs like fertilizer. Sacrificing productivity to manage risk makes it more difficult to accumulate wealth, which can further exacerbate poverty. While these studies of the effect of risk on production have been insightful, there remain opportunities to further our knowledge. As mentioned previously, few studies carefully explore how the complementarity and substitutability of various factors of production can be used to reduce risk or the potential for crop diversification to reduce risk. Additionally, significant methodological differences among studies often make it difficult to identify consistent trends or understand apparently contradictory results. For example, while some studies find that the increased use of labor reduces risk, others find no effect or that labor increases risk. With emerging evidence of the weaknesses of the expected utility hypothesis, opportunities exist to explore what new insights other paradigms, like prospect or cumulative prospect theory, might offer in terms of better understanding how farmers respond to risk. Both prospect and

cumulative prospect theory, provide alternatives to the safety-first models employed in the literature in terms of understanding why subsistence concerns are commonly found to influence farmers' risk attitudes and response to risk.

Much has been learned from the study of farmer risk attitudes and response to risk, and the affect of alternative production decisions on risk in the developing world, but much more remains to be learned. As our knowledge of agricultural production risk in the developing world continues to grow, so will our ability to identify strategies that can effect real change.

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Table 1: Summary of review by region and country.

Region	Country	Studies
Africa	Burkino Faso	Carter (1997) & Reardon and Taylor (1996)
	Ethiopia	Bezabih (2009), Dercon et al. (2007), DiFalco and Chavas (2009), DiFalco et al (2007), Harrison et al. (2010), Knight et al. (2003), Mosley and Verschoor (2005), Wale and Yalew (2007), & Yesuf and Bluffstone (2009)
	Kenya	Batz et al. (2003)
	Madagascar	Barret (1996) & Barret et al. (2004)
	Malawi	Gine and Yang (2009), Smale and Heisey (1993), & Smale et al. (1994)
	Mozambique	Heltberg and Tarp (2002)
	South Africa	Shankar et al. (2007) & Shankar et al. (2008)
	Tanzania	Dercon (1996), Dercon (1998), Henrich and McElreath (2002), & Nkonya et al. (1997)
	Uganda	Harrison et al. (2010) Mosley and Verschoor (2005) Vargas Hill (2009)
	Zambia	Wik et al. (2004)
	Zimbabwe	Barr (2003)
Asia	Bangladesh	Shahabuddin et al. (1986)
	China	Ghatak and Seale (2001) & Liu (2008)
	India	Antle (1987), Antle (1989), Binswanger (1980), Binswanger (1981), Fafchamps and Pender (1997), Harrison et al. (2010), Kanwar (1999), Mosley and Verschoor (2005), Rose (2001), Rosenzweig and Binswanger (1993), Rosenzweig and Wolpin (1993), & Townsend (1994)
	Indonesia	Miyata (2003)
	Nepal	Dhungana et al. (2004)
	Pakistan	Kurosaki (1997) & Kurosaki and Fafchamps (2002)
	Philippines	Antle and Crissman (1990), Kumbhakar and Tsionas (2008), Pandey and Pandey (2004), Rosegrant and Roumasset (1985), Smith and Umali (1985), Villano and Fleming (2006), & Villano et al. (2005)
	Sri Lanka	Herath et al. (1982)
	Thailand	Grisley and Kellog (1987)
	Vietnam	Tanaka et al. (2009)
North America	Mexico	Byerlee and de Polanco (1986) & Moscardi and de Janvry (1977)
South America	Brazil	Dillon and Scandizzo (1978)
	Chile	Henrich and McElreath (2002)
	Peru	Engle-Warnick et al. (2007)

Table 2: Summary of review by production inputs evaluated.

Study	Animal Holdings/ Power	Climate/ Rainfall	Fertilizer	Herbicides/ Fungicides	Labor	Land Holding/ Quality	Improved Seed/Variety Selection	Irrigation	Insecticides/ Insect Control	Tractor/ Machinery
Antle (1987)	X		X		X	X				
Antle and Crissman (1990)			X		X			X		
Barret (1996)					X	X				
Barret et al. (2004)		X	X		X	X				
Byerlee and de Polanco (1986)			X	X			X			
Carter (1997)		X								
Dercon (1996)					X	X				
Dercon (1998)	X									
Dercon et al. (2007)		X	X			X				
Dhungana et al. (2004)			X		X	X				
DiFalco and Chavas (2009)	X		X		X	X	X			
DiFalco et al (2007)			X		X	X	X			
Engle-Warnick et al. (2007)							X			
Herath et al. (1982)							X			
Fafchamps and Pender (1997)								X		
Gine and Yang (2009)			X				X			
Kanwar (1999)					X					
Knight et al. (2003)			X	X					X	
Kumbhakar and Tsionas (2008)			X		X	X				
Kurosaki (1997)						X		X		X
Kurosaki and Fafchamps (2002)						X		X		X
Liu (2008)							X		X	
Morris et al (2007)			X							
Moscardi and de Janvry (1977)			X			X				
Nkonya et al. (1997)			X				X			
Pandey and Pandey (2004)		X	X							
Reardon and Taylor (1996)		X								
Rose (2001)		X			X					
Rosegrant and Roumasset (1985)		X	X			X			X	
Rosenzweig and Binswanger (1993)	X	X						X		X
Rosenzweig and Wolpin (1993)	X							X		
Shankar et al. (2007)					X		X		X	
Shankar et al. (2008)					X	X	X		X	
Smale and Heisey (1993)			X				X			
Smale et al. (1994)			X				X			
Smith and Umali (1985)			X							
Vargas Hill (2009)					X					
Villano and Fleming (2006)			X	X	X					
Villano et al. (2005)			X	X	X					
Wale and Yalew (2007)							X			

Table 3: Summary of review by crops evaluated.

Study	Barley	Basmati	Coffee	Cotton	Fodder	Livestock	Maize	Milk	Potato/ Sweet Potato	Rice	Sorghum	Wheat	Other[a]
Antle (1987)										X			
Antle and Crissman (1990)										X			
Barret (1996)										X			
Barret et al. (2004)										X			
Byerlee and de Polanco (1986)	X												
Carter (1997)											X	X	X
Dercon (1996)						X			X				
Dercon (1998)				X		X	X		X		X		X
Dhungana et al. (2004)										X			
DiFalco and Chavas (2009)	X												
DiFalco et al (2007)												X	
Gine and Yang (2009)							X						X
Herath et al. (1982)										X			
Knight et al. (2003)			X						X				X
Kumbhakar and Tsionas (2008)										X			
Kurosaki (1997)		X			X			X				X	
Kurosaki and Fafchamps (2002)		X			X			X				X	
Liu (2008)				X									
Moscardi and de Janvry (1977)							X						
Nkonya et al. (1997)							X						
Pandey and Pandey (2004)										X			
Rosegrant and Roumasset (1985)										X			
Shankar et al. (2007)				X									
Shankar et al. (2008)				X									
Smale and Heisey (1993)							X						
Smith and Umali (1985)							X						
Smith and Umali (1985)										X			
Vargas Hill (2009)			X										
Villano and Fleming (2006)										X			
Villano et al. (2005)										X			
Wale and Yalew (2007)			X										

[a] For example, Avacado, Chat, Groundnut, Millet, Paddy, Sugarcane, and Vegetables.