Some Guiding Principles for Empirical Production Research in Agriculture

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Constraints on production economic research are examined in three dimensions: problem focus, methodology, and data availability. Data availability has played a large role in the choice of problem focus and explains some misdirected focus. A proprosal is made to address the data availability constraint. The greatest self-imposed constraints are methodological. Production economics has focused on flexible representations of technology at the expense of specificity in preferences. Yet some of the major problems faced by decision makers relate to long-term problems, e.g., the commodity boom and ensuing debt crisis of the 1970s and 1980s where standard short-term profit maximization models are unlikely to capture the essence of decision maker concerns.

The purpose of this paper is to examine the econometric underpinnings and empirical practicality of today's approaches to empirical analysis of agricultural production. I argue that agricultural economists are not fulfilling opportunities to uncover knowledge about agricultural production. Doing so depends upon expanding horizons beyond some of the boxes of tradition and formalism that currently limit thinking. Of course, different individuals have different ideas of what these boxes are with (somewhat) convincing arguments supporting opposing views. Thus, I focus on principles that should guide choices of professional directions.

This paper is divided according to three main dimensions that tend to define the limits of empirical agricultural production research: first, problem focus—the choice of which issues in agricultural production to address; second, the choice of methodology to address those problems—because the potential for meaningful answers is largely limited by the choice of methodology; and third, data availability to address the chosen problems with chosen methodologies. Perhaps many view the choice of methodology as constrained by available data. The choice of data is treated subsequent to the choice of methodology because data availability is endogenous over longer research horizons. Much opportunity will be foregone if agricultural economists do not better influence these choices. Although public data availability is largely determined by policy makers, agricultural economists can both influence the process and generate data directly through their own projects and surveys.

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The Focus of Production Problems

Perhaps a place to start is by asking, "Are the best approaches for agricultural production analysis different than the best approaches for economic analysis of production in general?" In the *Handbook of Agricultural Economics,* the opening chapter by Yair Mundlak (forthcoming) makes the case that the empirical work on agricultural production over the last three decades has not yielded its promised fruits. In the final chapter of about a dozen on agricultural production in the *Handbook,* Rulon Pope and I argue that the main reason for this failure is that the agricultural economics profession has simply imported the methodology of general economics without adapting it to the unique features of agriculture (Pope and Just forthcoming).

Unique Features of Agricultural Production

The dominating unique features of agricultural production include substantial uncertainty due to weather and pests, sequential biological stages of production, temporal allocation of inputs among those stages, limited output observability in the intermediate stages of production, great flexibility in the output mix largely by means of spatial allocation, substantial heterogeneity in farms and farmers, and fragmented technology adoption (Just and Pope forthcoming). While many sectors may

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have some of these features in some degree, agriculture is unique in their extent and combination. Have these unique features been adequately considered in agricultural production analysis? How should empirical practices be adapted to address these features?

If uncertainty due to weather and pests is dominant, how should empirical practices be adapted? First, the structural role of random factors needs to be determined statistically. Depending on the structure with which random factors enter the problem, standard methodologies may be biased even under risk neutrality. Second, preferences of producers toward this randomness and mitigating behavior induced thereby needs to be determined statistically. While many may argue that this has been done, I argue that agricultural production research has failed to address the issue properly due to excessive focus on the short run where, for the most part, important issues are simply assumed away. The lack of focus on these problems in the first case is due to lack of methodology which is just now in development. In the second case lack of focus is due to self-imposed methodological choices discussed below.

If biology dictates stages of production under uncertainty that require temporal allocations of inputs to both preventative and prescriptive uses, then production models need to consider the sequential conditioning of intra-seasonal decisions, the endogeneity bias associated with unobservability and annual aggregation, the need for instrumentation for consistent estimation, and the role of preferences in explaining *ex ante* versus *ex post* decision making. The lack of focus on these problems is largely due to data limitations. While efforts have been made to the extent of data availability, progress depends heavily on whether agricultural production researchers can influence the data generation process.

If the agricultural production problem is characterized by great flexibility in the output mix largely by means of land and technology allocation, then technology representations need to reflect that process and capture the potential econometric efficiency that can be gained thereby. Here the failure in problem focus has been driven largely by the promulgation of reduced-form methodologies that have de-emphasized focus on underlying structure. Expansion of focus to meet potential depends on whether researchers will break out of existing boxes of tradition and formalism.

Finally, if heterogeneity of farms, farmers, and adopted technologies is great, then the effect of that heterogeneity on proper modeling needs to be understood. Instead, many of the methodological advances in agricultural production have been merely demonstrated with a token aggregate data set using a representative producer model. Many such papers, in fact, contain the typical disclaimer which openly admits that the empirical results have only illustrative purposes. For the most part, no comprehensive analysis with disaggregate data has followed. As a result, the empirical results of many of these token applications have come to characterize the extent of empirical knowledge. Again, the lack of appropriate problem focus is due to data availability. Progress depends heavily on whether agricultural production researchers can influence the data generation process.

In reality, heterogeneity alone can explain the common empirical failure of standard theoretical properties such as monotonicity, homogeneity, convexity, and symmetry. While conceptual approaches can and have been developed for adapting and modifying these properties as necessary under heterogeneity, they have not been implemented to date even to the extent of available data (Just and Pope 1999). Local correlations among farm and farmer characteristics can have fundamental implications for agricultural supply and demand and for policy analysis. Similarly, the correlations of farm and farmer characteristics with environmental factors can have fundamental implications for environmental policy analysis (e.g., Just and Antle). Finally, with respect to studying producer perferences, aggregate data wash out such factors as risk faced by local producers preventing their effective study with aggregate data.

Principle 1. *If agricultural production economics is a legitimate sub-discipline, then its study should identify the features of agricultural production that differ from other production problems and determine how methodologies and required data should be adapted accordingly.*

Against this backdrop, the remainder of my discussion on problem focus suggests some principles that should guide problem focus particularly where methodological and data limitations are viewed as endogenous choices over the longer-term horizon of agricultural production research. For convenience of specificity of example in the discussion, research on production risk will often be used as an example of the relevant points.

Identification of Behavior

The study of production in agriculture has come to mean the study of demand and supply as well as the study of technology. The characterization of production thus includes characterization of behavior. Certainly, the important uses and applications of empirical production research include agricultural policy analysis, evaluation of technical change, environmental economic analysis, etc. In each of these applications, knowledge of the technology alone is of little use without knowledge of the behavioral preferences that translate technology into supply and demand.

In reality, agricultural production research has not been able to reach agreement on basic aspects of producer behavior. For example, a number of studies have been able to show that risk response is statistically significant but, for the most part, agricultural production studies continue to ignore risk. With agreement on the importance of risk in agricultural producer behavior, studies that ignore risk would become unacceptable for journal publication. On the contrary, duality has become the most common methodology for studying agricultural production both theoretically and empirically. Although a few papers have attempted to expand dual methodology to the case of risk aversion, the vast majority of studies using duality simply impose the assumption of profit maximization under which the methodology was originally developed.

The reason for lack of agreement seems to be that many of the areas in which risk has been shown to have a statistically significant role in agriculture are subject to identification problems. Perhaps the statistical significance when it has been found has been due to using a too narrow maintained hypothesis. For example, empirical results that show significance of risk in acreage response and diversification often fail to consider alternative explanations for diversification based on the benefits of crop rotation, temporal labor constraints, the need to schedule fixed inputs such as machinery services, etc. Heavy use of pesticides, irrigation, and other inputs that are believed to have risk-reducing effects also have strong effects on expected production and profits that are difficult to sort out empirically. For example, one can hardly be sure that a different specification of technology cannot capture behavior completely in expected profit maximization models if maintained hypotheses are sufficiently broad.

This example raises the issue of whether the agricultural production literature has been sufficiently additive. That is, have new studies contributed evidence against previous hypotheses at the same time they have provided evidence in favor of alternative hypotheses. Alston and Chalfant and Smale, Just, and Leathers show how testing hypotheses against narrow maintained hypotheses that do not represent the breadth of previous literature tends to lead to conflicting research results and inappropriate characterization of statistical significance. The literature thus becomes a maze of conflicting models and empirical results. As a result, knowledge is not additive but rather competing. With sufficiently broad maintained hypotheses, statistical significance becomes meaningful and rejects previous hypotheses if it supports new ones. Such research tends to bring convergence to knowledge.

Principle 2. *In order to contribute to a set of stylized facts that characterize professional knowledge and permit its convergence, hypotheses should be tested against maintained hypotheses sufficiently broad to represent existing literature so that research is additive.*

One of the common deterrents to using maintained hypotheses broad enough to characterize existing literature is that statistical significance is difficult to obtain. This may make journal publication difficult according to our profession's self-imposed limitations for journal acceptance. However, other avenues to statistical clarity remain untapped. In particular, due to failure to develop better data sources, researchers often try to identify certain types of behavior where its detection is not very likely. For example, agricultural risk research has focused too much on risk in problems where risk is less likely to be important and, thus, has failed to be convincing about the importance of risk. Similarly, investigations of investment behavior in agriculture have been performed without crucial vintage, salvage and replacement data and thus have limited statistical discernment.

Principle 3. *Investigations of production and producer preferences should focus on problems where departures from the primary theory are most likely to be important.*

Contrary to this principle, agricultural production research has focused primarily on *short-run* production problems at an inordinate level of *temporal* and *spatial* aggregation whereas many aspects of agricultural production have longer-term considerations and differ substantially among farms and over time. Accordingly, three important choices in problem focus are spatial aggregation, temporal aggregation, and decision problem duration.

Aggregation Over Space

Unfortunately, many of the advances in methodology of agricultural production analysis are demonstrated in the academic journals using only a token aggregate data set. Considering the case of risk preferences for example, studies of the effects of risk on supply response rely on aggregate data, which is a practice I am largely responsible for instituting (Just 1974). Also, most applications and generalizations of the Just-Pope production function, which allows inputs to have risk effects distinct from marginal productivity effects, have been with state and national data (Just and Pope 1979). Even research that attempts to determine the structure of farmers' risk preferences (e.g., whether absolute or relative risk aversion are constant, increasing or decreasing) has been largely based on aggregate data (Antle 1987; Pope and Just 1991; Chavas and Holt). Sadly, the notable exceptions are primarily from non-American agriculture such as Binswanger's lottery experimentation with peasant farmers in India and Bar-Shira, Just and Zilberman's estimation based on farm-level data from Israel.[1]

Just and Weninger find by comparing the results of Nelson and Preckel at the farm level with results of Moss and Shonkwiler at the aggregate level that farm-level yield variance is from 2-10 times greater than implied by aggregate data. Thus, most of the magnitude of the risk problem is overlooked by using aggregate data. A further point is that the averaging over farms distorts the distributional character of farm-level risk.

Principle 4. *To demonstrate production issues more clearly and provide more meaningful answers, agricultural production research must focus on decision making at the farm level rather than continue to demonstrate points and methodology with aggregate data simply because they are available.*

Aggregation Over Time

Biological realities of agricultural production typically involves long time lags (compared to most manufacturing) which are composed of sequential stages during which adjustments can be made in response to evolving crop conditions. Growing seasons are largely determined by climate so that all of a farm's crop is typically in the same stage of production at one time. The resulting annual concentration of production contributes to price risk because all of a farm's production of a particular crop is typically concentrated in a small season in which supply outstrips demand and uncertainties prevail about demands over the following crop year. Also, because all of a farm's crop is typically in the same stage of production, farmers are broadly vulnerable to a single extreme weather or pest event that can cause a crop disaster.

Due to typical annual aggregation as in public data, the problem of intra-seasonal production input timing has been almost totally ignored (see Just and Candler for an exception). Because of the annual seasonality of most agricultural production, economists have been largely content to work with production data aggregated temporally to an annual basis. The problem with this practice, however, is that many of the inputs that might have alternative behavioral motivations are stage-dependent inputs. For example, operator labor may be most constraining in periods where hired labor does not substitute well for it. Similarly, inputs that have distinct risk effects such as pesticides and fertilizers tend to be stage-dependent. For example, insecticides are typically applied only as a prescriptive measure when infestations are observed. They usually occur only after a crop is well into the growing cycle. Similarly, post-emergent herbicides are applied (or applied relatively more) when indications of weed or grass infestations are detected. On the other hand, pre-emergent herbicides may be applied as a precautionary measure either when weed infestations are *expected* or when the *risk* of infestations is great. Similarly, fertilizer can be applied either before or at planting based on expected productivity but some fertilizer is applied as top dressing only after a crop stand has been realized. Post-planting applications are typically not made or are reduced when adequate moisture is not available. How much of this delayed application is a *risk* mitigating behavior and how much is due to the greater *expected* needs of a crop for nitrogen at a particular growing stage is not well understood. The point is that many of the decisions available to the farmer to manage crop production and cope with unexpected dynamic observations of crop conditions are not clearly represented in annual aggregates.

Principle 5. *Understanding the motivation for factor input use calls for temporal (intra-seasonal) disaggregation of the production problem.*

Many production decisions are made in intermediate stages of production based on observed crop conditions. Irrigation is regulated to compensate for lack of moisture and, at least where water must be pumped, will not be applied when rains are adequate. Timing of planting is often based on observed rainfall and soil moisture compared to typi-

[1] The study by Saha, Shumway and Talpaz on Kansas farm-level data is an exception based on American data. Normative programming efforts and simulation models which can focus on individual farms are ignored here because they are often constructed with conjectural data.

cal conditions. Depending on observed crop growth, a producer might decide to use a corn or sorghum plot for grain, silage, or forage. Small grain crops may be used for livestock grazing either before harvest or in lieu of harvest depending on growth and evolving production prospects. If, because of bad weather, a crop stand is sufficiently poor after planting, a farmer may even replant the same or another crop. Each of these *ex post* choices reduce risk from what it would be *a priori* if such responses were not possible during the growing season. However, each of these choices likely also has distinct impacts on expected production and profits that tend to be qualitatively opposite to the effects on risk. Thus, identifying producer preferences and separating risk averse behavior from profit maximizing behavior is not a simple matter. When such decisions are studied without knowledge of information available to farmers at the time of specific decisions, inferred behavior may be severely biased as a result of interpreting the data in inappropriate frameworks.

Principle 6. *Behavior and technology could be more effectively identified econometrically by studying each decision conditioned on the information set available to farmers at the time of the decision.*

As an example of ambiguity, consider characterizing the mid-season efficiency of decisions under either risk neutrality or risk aversion on the basis of *ex post* random draws of output. The impact of any input vector on output is obscured by previous weather occurrences embodied in the state of the crop at the time of the decision, and future weather occurrences that affect the ultimate observed production. If the timing of decisions is due to the unobserved dynamic nature of information coming available to the farmer, then rational behavior can easily appear to be irrational or due to other factors.

Decision Problem Duration

Most agricultural production analysis focuses on the short run. However, longer-run considerations of investment and costs of adjustment can explain why some farms appear to be poorly adjusted in the short run. Many models try to reflect this problem by conditioning the short-run production problem on fixed factors. However, short-run efficiency analyses typically stop short of considerations that might show that short-run inefficient behavior is part of, say, longer-term expected profit maximizing behavior with unanticipated prices, or a longer-term optimal firm growth strategy with an imperfect capital market.

In the case of risk preferences, consideration of longer-run problems may be necessary to uncover concerns of importance. That is, the consequences of risk may not be great in the short-run unless serial correlation is high (which makes it a longer-run problem). Farmers can easily shift major purchases of machinery and equipment and even consumer-durable consumption decisions from one time period to another so that short-run fluctuations in revenue need not cause drastic consequences. Furthermore, many sources of agricultural credit are structured to allow considerable variability in debt repayment as long as solvency is not in question (which is a longer-run problem). So why is almost all risk research in agriculture carried out in the short-run context that focuses on year-to-year variability? Why does risk research not focus on longer-term swings in agricultural production conditions? Certainly, some longer-term swings have been observed and have had serious consequences. For example, the commodity boom of the 1970s with the resulting high investment in land and machinery followed by the high interest rates of the 1980s caused the highest rate of farm failures since the Great Depression. The attempted decoupling and withdrawal of heavy government involvement in the 1990s raises further questions of the implications of a longer-term swing.

Principle 7. *Agricultural production studies should focus on the longer-term variations that can have much stronger consequences for farmers than year-to-year variations because they are sufficiently prolonged to cause farm failure or major re-direction.*

To illustrate, consider the possibilities available to farmers to stabilize the consequences of variable income streams, which thus eliminate or reduce the adverse consequences of risk. That is, if farmers have sufficiently useful approaches to mitigate the effects of short-term risk, then short-term risk problems are less interesting. For example, if farmers can simply borrow against assets when income is low and save funds or repay debt when income is high, then the cost of uncertainty may be low and bounded by the difference in the borrowing and lending interest rate. Similarly, if farmers can purchase assets such as machinery and buildings only when income is high, then income available for consumption can be smoothed to a considerable extent thus mitigating the adverse effects of risk. The risk premium is thus limited, for example, by the additional repair expense incurred in a marginal year of asset ownership.[2]

As an example, suppose production follows a Just-Pope specification with $q_t = x^{\alpha} + x^{\alpha/2}\,\epsilon_t$ where $\epsilon_t \sim \text{iidN}(0,\sigma_\epsilon)$ and $\alpha = .8$, output price is $p = 1$, and input price is $w = .5$. To consider borrowing and saving requires a lifetime model. Suppose the farmer farms for 45 years using 80% of the profit each year for consumption and investing the remaining 20% to accumulate wealth toward retirement. For simplicity, suppose the borrowing and saving interest rate are identical and are equal to the farmer's discount rate (in which case they cancel out) and assume accumulated real wealth after 45 years of farming is used for consumption at a constant real rate during 15 years of retirement. Assume additively separable utility of consumption over time with constant absolute risk aversion ϕ. Suppose $\sigma_\epsilon = .2$, which makes the optimal standard deviation of output approximately 20% of expected output, and absolute risk aversion is $\phi = 1$, which makes relative risk aversion approximately 1.0 in this problem following Arrow's arguments of plausibility. Then the optimal annual risk premium without borrowing and saving is 30.3% of expected consumption. Adding borrowing and saving to smooth consumption at its expectation and considering the residual uncertainty imposed on retirement, total lifetime utility increases by 20.3%, thus effectively eliminating about two-thirds of the cost of risk reflected by standard annual models.[3] If σ_ϵ is increased, then even more of the relative risk premium is recovered by borrowing and saving to smooth consumption.

While this example assumes perfect capital markets and ignores the possibility of encountering insolvency, it demonstrates clearly available approaches to reduce the effects of year-to-year risks imposed on consumption by profit variability. As a result, the risk premium actually borne by a farmer is likely to be considerably smaller than typical annual models imply.

Principle 8. *Possibilities to mitigate the short-run effects of unanticipated variation must be considered to understand both short- and longer-term production problems.*

Intertemporal Preferences

Unlike short-term income fluctuations, longer-term risk associated with asset prices and debt repayment explain most farm failure including the agricultural debt crisis of the 1980s. For such problems, preference representations have not been sufficiently well-developed. For example, typical analytical approaches to multi-period risk problems assume additive separability of utility over time. While additive separability over time yields elegant conceptual results, simulation models with multiple goals have found more use and practical appeal.

A simple example can illustrate. Suppose a farm's profit above normal consumption is represented by $\pi_t \sim N(\bar{\pi},\sigma_\pi)$. If utility is additively separable and with constant absolute risk aversion, $U(\pi_t) = 1 - \exp(-\phi\pi_t)$, then expected utility over a time horizon of T periods is given by

$$(1) \qquad EU = T - \sum_{t=1}^{T} \exp(-\phi\bar{\pi} + \phi^2\sigma_\pi/2).$$

Suppose, however, that the farmers preferences depend on normal consumption and terminal wealth, e.g., retirement income or size of estate left for children. Assuming constant absolute risk aversion with respect to terminal wealth (and identical rates of interest and discounting for simplicity),

$$(2) \qquad U\left(\sum_{t=1}^{T} \pi_t\right) = 1 - \exp\left(-\phi \sum_{t=1}^{T} \pi_t\right).$$

In contrast to (1), expected utility in (2) depends heavily on the correlation of profits over time. Considering two polar cases of serial correlation where

$$V\left(\sum_{t=1}^{T} \pi_t\right) = \sum_{t=1} V(\pi_t) + 2\sum_{t=1}^{T}\sum_{\tau=t+1}^{T} Cov(\pi_t,\pi_\tau) = \begin{cases} T\sigma_\pi \text{ if } Corr(\pi_t,\pi_\tau) = 0 \text{ for } t \neq \tau \\ T^2\sigma_\pi \text{ if } Corr(\pi_t,\pi_\tau) = 1 \text{ for } t \neq \tau, \end{cases}$$

expected utility is

$$EU = \begin{cases} 1 - \exp(-\phi T\bar{\pi} + \phi^2 T\sigma_\pi/2) \text{ if } Corr(\pi_t,\pi_\tau) = 0 \text{ for } t \neq \tau \\ 1 - \exp(-\phi T\bar{\pi} + \phi^2 T^2\sigma_\pi/2) \text{ if } Corr(\pi_t,\pi_\tau) = 1 \text{ for } t \neq \tau. \end{cases}$$

If relative risk aversion at expected wealth is equal

[2] Crop insurance may also be regarded as a risk mitigating vehicle. However, Just, Calvin, and Quiggin show that poor tailoring of crop insurance parameters has made it a poor vehicle for this purpose. They found that (non-)insuring farmers tend to receive positive (negative) expected benefits so that risk is not clearly a motivation for participation.

[3] This overall gain is accomplished by shifting all consumption risk to the retirement years compared to the case with a fixed marginal propensity to consume in which consumption risk at retirement is much lower due to averaging over 45 years of farming. Clearly, other possibilities that better balance the risk between years of farming and retirement are possible. For example, the model can be optimized with respect to the marginal propensity to consume yielding adaptive adjustments in saving or debt repayment when cumulative borrowing or saving turns out to be large. Thus, the example here only establishes an upper bound on the adverse consequences of risk.

to 1 as Arrow argues is reasonable, then $-WU''/U' = \phi W = 1$ where $W = T\overline{\pi}$ so the associated risk premiums reduce to $\sigma_{\pi}/(2T\overline{\pi}^2)$ in the case of no serial correlation and $\sigma_{\pi}/(2\overline{\pi}^2)$ in the case of perfect serial correlation. Thus, the risk premium does not weaken over time with high serial correlation but it approaches zero with a sufficiently long planning horizon with no serial correlation.

As this example demonstrates, multiple-period risk problems can differ substantially from typical short-term representations. In the cases of the 1970s and 1980s when either very favorable conditions prevailed for a number of years or very unfavorable conditions prevailed for a number of years, the magnitude of risk faced by farmers with preferences such as in (2) produces very different results than when outcomes are serially uncorrelated. Furthermore, both of the polar cases following from (2) differ substantially from the case with additive separability in (1). Unfortunately, little empirical information has been compiled about which of these three approaches, if any, represents how farmers approach multi-period risk problems. Given that the most widespread failure of farms in recent times occurred because of serially correlated adverse conditions during the 1980s, I submit that more emphasis needs to be placed on the role of serial correlation of farm income and farmers' related preferences.

Principle 9. *Typical temporal preference assumptions such as additive separability of utility (profits) are inadequate for studying longer-term agricultural production problems. Research should determine what matters to producers, when it matters, and how correlations of outcomes across time matter.*

The major component of the agricultural economics literature that has dealt with multi-period risk problems is the agricultural finance literature. The approaches of finance have not been well integrated with other production research endeavors even where risk preferences are considered. That is, the framework and approaches that have dominated the agricultural finance literature are quite different than what appears in the short-run production literature. The recent review of the agricultural finance literature by Barry and Robison identifies a large number of alternative objective criteria including ending net worth, ending net worth plus annual consumption expenditures, the present value of ending net worth and annual consumption, and the present value of annual income. Some of these have been applied in the context of multiple-goal programming models with goals of solvency, liquidity, and survivability in addition to profitability (e.g., Pflueger and Barry; Candler and Boehlje). Not surprisingly, such models suggest different behavior than successive application of typical short-run expected utility models.

As Barry and Robison conclude, simulation approaches are often found preferable to optimization in multi-period agricultural production applications. Some reasons are that little has been determined empirically about (i) the importance of current income and consumption versus net worth, (ii) how farmers trade off short-run returns and riskiness with long-run security, and (iii) how asset fixity versus flexibility are used as tools for accomplishing these trade offs. Barry and Robison's review emphasizes the remaining need to correctly sort out (i) the role of short-term versus long-run risk aversion, (ii) the role of intertemporal behavior, (iii) the serial correlation of farming outcomes considering cycles due to weather, pests, agricultural policy, and macro policy, and (iv) the flexibility/rigidity of external constraints such as collateral limits or other credit rationing that affect it. For conceptual analysis of multi-period problems to date, outcomes are largely dependent on assumed preference structures. Clearly, much remains to be learned about intertemporal and risk preferences.

In addition to intertemporal and risk preferences, if family labor is viewed qualitatively different than hired labor because of moral hazard and other considerations, farmers may prefer to trade off profit and/or risk for family or operator labor depending on preferences for leisure and the amount of family labor needed to maximize expected utility. Thus, utility functions may need more arguments than expected profit and risk. In summary, when behavioral criteria are imposed rather than estimated, models may be far from robust and results may fall far short of sorting out what is really important.

The Methodologies of Agricultural Production Analysis

Methodologies of agricultural production analysis have constrained problem focus either because alternative methodologies have been unavailable, too cumbersome, or unused because of self-imposed methodological constraints. Because so many methodologies have been applied, this section simply suggests a few ways in which several prominent methodologies fall short.

Dual Approaches

Dual approaches have been common for both theoretical and empirical analysis of agricultural production and are likely to dominate agricultural production analysis for years to come. A relevant question is whether dual methodology can be sufficiently generalized to include major hypotheses in the literature, e.g., to estimate and test preferences regarding uncertainty and intertemporal issues with highly stochastic production. Several advances have been made for this purpose but are not yet sufficiently complete to support implementation on a broad basis. For example, early work by Pope (1980) and Chavas and Pope considered the properties of indirect objective functions and the possibility of deriving supply and demand specifications and welfare implications using Hotelling-like results under risk aversion. However, popular functional forms for the risk case (comparable to the standard second-order flexible forms applicable under profit maximization) have not been developed.[4] One hope is that future risk research can truly generalize flexible functional forms for the purpose of specification of indirect expected utility functions for producers. This could then permit a tractable and flexible parametric system of supplies and demands for estimation. Some progress has been made in representing risk preferences more generally (Pope 1988) and in combining more general technology representations with generalized risk preferences (Saha, Shumway and Talpaz). However, some of the conceptual advantages of duality under profit maximization have not been shown to carry over under risk aversion.

While a few studies have tried to find flexible dual expected utility specifications, applications of duality under risk to date have focused relatively more on cost function estimation (Pope and Just 1996, 1998; O'Donnell and Woodland). However, these advances have come only for restricted cases and the outlook is not entirely positive. For example, O'Donnell and Woodland develop the cost function approach under risk aversion but require multiplicative log-normal production risk and constant returns to scale. Pope and Just (1996) developed the *ex ante* cost function approach for output uncertainty upon noting that cost functions conditioned on *ex post* output do not correspond to the producer's *ex ante* decision problem in this case. *Ex post* cost functions are generally inapplicable when output is risky even under risk neutrality. Pope and Just (1998) generalize this approach for the case of non-constant returns to scale under risk aversion but require that disturbances represent allocative inefficiency rather than technical inefficiency, i.e., disturbances result in behavior on the production frontier.

For the case of stochastic production, unfulfilled expectations raise interesting issues. Results thus far suggest that duality has limits or that its advantages can be lost depending on the form in which disturbances enter the production model. To illustrate, Pope and Just (2000) examine the case where disturbances in input demands transmit to output (as is the case where disturbances represent errors in optimization that flow through the production function). Integrating such input demands obtains a profit function dependent on the input demand disturbances. Further, the corresponding output supplies cannot then be independent of these input disturbances because they flow through the production function. As a result, correct output supply specifications cannot be derived from the profit function used to derive the optimal input demand specifications (which apply to the problem before errors in optimization) nor can they be derived from the pseudo-profit function obtained by integrating the input demands including their disturbances. Apparently, the only way to correctly specify output supplies in this case is to recover the technology and substitute input demands—a cumbersome calculation.[5] Thus, the elegance and convenience of duality appear to fail in this case, which can hardly be ruled out for agriculture.

However, this problem does not occur if disturbances in input demands represent simple errors in measurement (errors in variables). This is the assumption developed by Moschini where he finds that a different estimator than used by Pope and Just (1996) is required to obtain consistent estimation in the case of risk neutrality with stochastic output and no technical or allocative inefficiency. Comparison of his results with Pope and Just

[4] Coyle has extended duality to the case of risk with linear mean-variance expected utility, but these restrictions are widely regarded as too restrictive (Moschini and Hennessy).

[5] To illustrate, suppose the profit function specification under certainty is represented by $\pi(p,w)$ with input price vector w and output price p, and that the corresponding production technology implied by duality is $q = f(x)$ where x is an input vector and q is output. By Hotelling's lemma, demands, supply, and production satisfy $x = -\partial\pi/\partial w$, $q = \partial\pi/\partial p$, and $\partial\pi/\partial p = f(-\partial\pi/\partial w)$. Typical practice is to append random disturbances for purposes of estimation obtaining $x = -\partial\pi/\partial w + \delta$ and $q = \partial\pi/\partial p + \epsilon$. However, if δ is part of the true input quantities rather than errors in observing the true input quantities, then production is $f(-\partial\pi/\partial w + \delta) \neq \partial\pi/\partial p$. Integration of the demand equations used for estimation obtains $\pi = \pi(p,w)\text{-}\delta w$ aside from additive terms not containing w. Integration of the supply equation used for estimation obtains $\pi = \pi(p,w) + \epsilon p$ aside from additive terms not containing p. Combining these results obtains McElroy's AGEM profit function, $\pi = \pi(p,w)\text{-}\delta w + \epsilon p$. Note, however, that this profit function cannot reflect the transmission of input errors to production through the production technology because $f(-\partial\pi/\partial w + \delta)$ does not depend on ϵ. Furthermore, the dual technology relationship is implausible for the case where δ represents actual variation in input levels because $\partial\pi/\partial p$ has output not depending on δ. For further discussion, see Pope and Just (1999, 2000).

(1996) reveals, not surprisingly, that consistency of estimation depends on how stochastic terms enter the production problem. Recognizing this problem, Pope and Just (1999) develop an approach to test for the form in which disturbances enter the production problem. Their empirical results show that errors in optimization are better supported by observed data than errors in measurement, thus raising further doubts about standard dual approaches.

By comparison the McElroy additive general error model (AGEM), the only comprehensive profit function structure that generates congruent disturbance specifications for supplies and demands, cannot represent either of these cases (errors in optimization or errors in variables). If input demand errors are errors in measurement, then the true inputs that determine true profits cannot depend on them and thus cannot appear in the profit function.[6] On the other hand, if input errors are errors in optimization, then they flow through the production function to affect output and, thus, output cannot be independent of the input disturbances as in the McElroy AGEM. These results jointly emphasize the importance of further research on how stochastic variation enters producers' problems and how behavior can be estimated accordingly. In addition, stochastic terms can enter the production problem in other ways including econometrician error that also require investigation. Because these concerns apply even under risk neutrality, the predominance of uncertainty in agricultural production raises concerns regarding typical applications of duality to agriculture.

Principle 10. *The convenience of typical dual approaches is inapplicable under uncertainty with some plausible random disturbance specifications.*

Contrary to this principle, the typical practice is to add disturbances arbitrarily to functional forms derived from duality under certainty. Such arbitrary *ad hoc* error specifications can thus cause integrability conditions to fail implying an incongruity among supply and demand specifications. See Pope and Just (2000).

Approaches with State-Dependent Utility

The state-dependent approach has been used to generalize both dual models and expected utility models. This approach was developed by Machina and Quiggin recognizing typical criticisms of expected utility theory such as the inability to represent behavior associated with extreme probability alternatives. Chambers and Quiggin have explored applications to agricultural production under uncertainty. Their approach characterizes risk by the set of all possible states of nature and the probabilities of each. Each possible decision generates a revenue trajectory, which maps every possible state of nature into a realized revenue for the film. A cost function then specifies the minimum cost of obtaining each revenue trajectory and utility is maximized over possible decisions, i.e., over possible trajectories.

As recognized by Pope (1980), cost functions under stochastic output can be defined holding constant the distribution of output just as conventional cost functions hold deterministic output constant in deterministic duality. Conditioning cost on the output distribution is equivalent either to conditioning cost on all the stochastic moments of the output distribution or on the outcome in every state of nature together with the probabilities of states. While conditioning on all moments is typically regarded as excessively cumbersome, many approaches have tried to condition cost on a small set of moments. The Just-Pope production function was originally proposed as an approach to consider two moments rather than one. The moment-based work of Antle (1983) suggested using additional moments as well. If a finite number of moments captures a decision maker's concerns, then the cost function can be defined in terms of input prices and those moments.

By comparison, the state-dependent approach replaces dependence on stochastic moments with dependence on the outcome in every state of nature and their probabilities. To make the state-dependent approach operational requires a manageable number of states of nature just like the moment-based approach requires a manageable number of moments. If there are truly few states of nature, then fewer pieces of information are required with the state-dependent approach. If there are many states but the distribution can be fully characterized by a few moments, then a cost function conditioned on moments requires fewer pieces of information. This suggests the choice of methodology should be guided by the characteristics of the production problem when utility is not state-dependent.

Principle 11. *If the von Neumann-Morgenstern expected utility axioms apply, then the relative advantages of state-dependent versus moment-dependent representations of risk depend on a*

[6] However, one can define a pseudo-profit function by subtracting from revenue the pseudo-cost obtained by multiplying input prices by the observed input quantities that contain errors in measurement. Pope and Just (2000) show that such a pseudo-profit function may be useful in some caes.

comparison of the number of states of nature versus the number of distributional moments required for adequate representation and the ability to estimate them.

Apparently, farmers face many distributions of prices and yields that have large numbers of potential outcomes (states of nature). For example, most yield distributions (say of bushels per acre) and most price distributions (say of cents per bushel) might be represented well by integers, but scores of such outcomes are required to represent all the states of nature facing a producer. Whether fewer outcomes could appropriately approximate a producer's problem is open to question. Does approximation of a producer's price distribution to the nearest $.25 per bushel or yield distribution to the nearest 10 bushels per acre give up too much precision? On the other hand, using a finite number of moments in a moment-based approach requires, in effect, imposing some parametric distribution. Which provides a better approximation?

With respect to the question of whether state-dependent utility is necessary, several alternatives have been proposed beginning largely with the work of Kahneman and Tversky in 1979 and various applications of experimental economics have attempted to add verification. However, the prominence of the expected utility hypothesis in economic research has hardly been displaced. In fact, the recent work of Buschena and Zilberman (2000) shows that generalized expected utility models lose much of their predictive dominance over expected utility when a heteroscedastic error structure is used. At a practical level, concerns and evidence raised by potential false responses in experimental contexts have prevented widespread adoption of these alternatives. For example, the surveys of Young and Hazell (1982) related to agricultural risk conclude that elicitation is typically unreliable because it fails to represent adequately the preferences or risk applicable to the real decisions with which respondents are familiar. If alternative models are required mainly to represent demand by individuals for lottery tickets and other extreme-probability events, then the alternative models will likely find use only in the narrow ranges of application that require evaluation of extreme-probability events. In contrast, agricultural production appears to be dominated by non-extreme-probability events.

Principle 12. *Agricultural production problems typically have a large number of possible stochastic outcomes with non-extreme probabilities. The methodologies should be selected accordingly.*

Nonparametric Estimation and Data Envelopment Analysis

Nonparametric approaches have been receiving increasing attention and data envelopment analysis (DEA), which is a subset of nonparametric analysis, has been used as a means of quantifying efficient production response. This apprach was popularized by Varian in 1984 and applied in a number of agricultural studies beginning a little over a decade ago (Fawson and Shumway; Featherstone, Moghnieh and Goodwin; Chavas and Cox 1988 and 1994; Cox and Chavas; Tauer). To date, these studies have focused on profit maximization rather than risk aversion.

The frontier of this research has been to generalize results with respect to changing technology. Studies to date have shown that a predominance of observations appear to be inconsistent with profit maximization (e.g., 80 to 90% in Fawson and Shumway). When technical change is incorporated, fewer observations are inconsistent with profit maximization but still many remain inconsistent (see, e.g., Featherstone, Moghnieh and Goodwin). However, more observations are consistent with cost minimization than with profit maximization (Tauer). One explanation for these observed "inefficiencies" is preferences that differ from profit maximization. For example, risk aversion, to the extent it is a monotonic function of wealth and other preference-related variables like farmer age, can be easily incorporated into these analyses, at least in principle. For example, risk aversion likely causes greater departures from profit maximization than from cost minimization. Basic risk differences among outputs cause significant departure from expected profit-maximizing allocation of land among crops whereas more subtle risk effects of inputs cause departure from cost minimization.

Risk explanations for inefficiency will undoubtedly be considered as generalizations continue to be made in the DEA literature. For example, if non-constant risk aversion prevails, then research will show that frontiers must be conditioned on various characteristics of producers that explain risk aversion. This could lead to regressions of standard efficiency measures on wealth and perhaps other factors that are believed to explain risk aversion. Thus, DEA seems to hold a clear potential for considering non-profit-maximization preferences. On the other hand, this literature could well evolve toward research that simply suggests that standard economic efficiency increases, for example, with farm size and skip the explanation for why. The explanation of why may be decreasing risk aversion.

Generalizing the applicability and reliability of DEA faces several obstacles. As Mundlak (forthcoming) points out in his recent review of production and supply, even allowing for technical change one must assume that frontier observations are optimal so that some form of optimality identified by prices is imposed rather than tested (as in the case of duality). Inferring such productivity conclusions based on prices becomes, in effect, an index number problem that he proves cannot differentiate correctly between neutral and differential technical change. Mundlak also criticizes this work for applying a micro theory to macro data (Featherstone, Moghnieh and Goodwin and Tauer are exceptions).

Understandably, economists are attracted by opportunities to avoid imposing parametric forms on data because of the potential for specification bias. Thus, the current interest in DEA and nonparametric approaches is not surprising. Whether this interest represents a temporary fad or a permanent redirection of empirical research is not yet clear. As the limits and practicality of this methodology are investigated, the following principle is worth considering.

Principle 13. *Increased model flexibility may come at the expense of reduced precision for parameters and less useful characterizations of empirical findings, which reduces additivity of research and limits development of stylized facts. In short, the ability of available data to confess reality may be bounded.*

One of the weaknesses of nonparametric analysis has been lack of explanation. Of the many firms that turn out not to lie on the frontier and are thus characterized as inefficient, no integrated comprehensive framework is provided within which to explain the deviations. Using distance function measures, calculations are typically made to determine an inefficiency index for each firm. But when it comes to explaining why the inefficiency occurs across firms (based on individual firm data), such studies are either silent or resort to *ad hoc* regressions (or classifications) of inefficiency measures on various potential explanatory variables (sometimes dichotomous or categorical classification variables related to farmer characteristics and wealth). Some of these variables may represent factors influencing risk aversion or other behavior preferences. Thus, nonparametric approaches face the tradeoff of which variables to include in determining inefficiency versus which variables to use in explaining efficiency variation. For example, should farm size or wealth be used as variables that define the dimensions of efficiency or should these variables be used to explain observed *ex post* efficiency measures calculated in their absence? Implicitly, variables not used in defining the dimensions of efficiency are candidates to use in *ex post* characterization of variation in inefficiency across firms. Using fewer variables suggests inclusion of more variables in the *ex post* characterization of results. On the other hand, using more variables in the efficiency analysis results in a greater share of firms being classified as "efficient," so the results depend on a rather arbitrary choice of the investigator.

Biased Methodology and Imposed versus Revealed Behavior

Although often ignored, the choice of which variables to use in defining efficiency versus explaining it causes an important bias in determination of the role of the various factors. To see this for the DEA case, note that the approach first tries to attribute all variation among firms to efficient behavior according to the specified dimensions of efficiency. Only then are the "inefficiency residuals" regressed on other variables in an *ex post* analysis, whether with formal regression or informal classification analysis. Stepwise regression, which is conceptually identical, was discredited long ago. It produces biased results because it first tries to attribute all of the variation to one set of variables, thus biasing their coefficients away from zero, and then tries to attribute only the remaining variation to the remaining set of variables, thus biasing their coefficients toward zero. The problem is that variables not considered until the *ad hoc ex post* analysis tend to be eliminated from the problem inappropriately by the researcher's choice. Consider, for example, variables that tend to explain risk aversion. If standard aproaches leave them out in measuring firm efficiency (as is typically done), then the analysis is biased toward their exclusion even if they are considered as part of an ex post ad hoc regression explaining variation in efficiency across firms.[7]

Principle 14. *Methodologies should allow behavior to emerge from the data rather than be imposed*

[7] An similarly problematic approach at the other extreme is represented by the parametric MOTAD programming model where the risk aversion coefficient is varied to achieve best fit, thus trying to attribute all remaining variation to risk aversion (Hazell 1971).

on the data. Otherwise, individual studies may conclude against competing frameworks that can explain observed data equally well thus preventing additivity of research.

As an example, the residuals of a nonparametric efficiency analysis may facilitate only low power for detecting the importance of risk averse behavior if the use of risk-reducing inputs are inappropriately characterized as having only expected production effects first. While this principle is similar to Principle 2, it emphasizes statistical power as opposed to statistical significance.

Much of the literature over the last three decades has strived for flexibility by focusing on flexibility in modeling technology. The second-order flexibility of dual approaches and complete parametric flexibility of DEA are examples. Interestingly, this flexibility has been attained by imposing inflexibility on preferences. That is, optimality in the form of profit maximization or cost minimization is often imposed rather than tested. The standard second-order flexible parametric forms of duality impose profit maximization and are developed primarily for the deterministic case and strictly for the risk neutral case. Alternatively, imposing somewhat more structure on the technology based, for example, on knowledge from the production sciences may allow considerably greater flexibility in examining behavioral preferences (Just and Pope, forthcoming). By comparison, producer behavior is primarily an area of economic research about which relatively less is known—because empirical research has tended to give up all flexibility in presenting preferences in order to attain more flexibility in representing technology. Furthermore, the burden of discovery of preferences rests solely on economists unlike the case with technology. Economists as social scientists should focus on social behavior given the often more precise physical and technical relationships that have been or could be uncovered by the production sciences. The approach of assuming complete inflexibility in preferences in order to capture more flexible representations of technology is contrary to natural allocation of scientific missions among the disciplines.

The same criticism applies to nonparametric analysis of production. All deviations from a profit maximizing (or cost-minimizing) frontier are attributed to inefficiency by nonparametric analysis when, in fact, they may be due to different preferences than imposed in determining the frontiers. To some researchers, deviations from "efficient" frontiers are considered inefficient whether due to technically inefficient production or to risk averse behavior. However, these preferences must be taken into account in order to perform analyses of social and policy relevance.

Principle 15. *Lack of focus on the explanation of technical inefficiency, that is, behaviorally- and policy-motivated departures from efficient frontiers, will lead to both social and policy irrelevance of research.*

Studies that have attempted to identify the structure of preferences and how they may depart from profit maximization have been few. For example, studies have not focused on farmers choices to trade off profits for leisure (or operator labor). Relatively few studies have attempted to measure risk preferences with revealed preference data from agriculture (e.g., Pope and Just 1991; Bar-Shira, Just and Zilberman; Chavas and Holt). Some studies have attempted to use generalities of risk perferences that do not yield estimates of the specific structure of risk preferences (Saha, Shumway and Talpaz; Antle 1987). While such studies achieve generality, they do not contribute additively to knowledge about risk preferences or technology because parameters of the two are confounded.

Other Nonparametric Approaches

Given the importance of stochastic variation in agriculture, distributions of prices and yields and preferences for them may be among the most crucial. Two approaches have been used to eliminate the need for parametric specification related to stochastic outcomes: stochastic dominance and nonparametric modeling of distributions.

Unlike the approaches of duality and DEA which focus on generality of technology representations, stochastic dominance focuses on generality of preference representations. Stochastic dominance attempts to order distributions based on principles such as more is better (first-order dominance) and more risk as reflected by a mean-preserving spread is inferior to less risk (second-order dominance). The major problem for empirical research is that only a partial ordering of distributions is obtained.[8] Stochastic dominance can be powerful in theoretical research when the concepts apply. However, partial orderings are not very useful in empirical research with heterogeneity because (i) risk issues are correctly addressed only at the individual firm level and (ii) conditions at the individual firm level vary so widely that

[8] Much of the empirical stochastic dominance literature also has a weakness of merely comparing estimated distributions rather than testing significance. However, statistical tests have been developed over the past dozen years (Tolley and Pope; Anderson).

changes in policy or differences in technology are almost certain not to submit themselves to stochastic dominance orderings for all farmers simultaneously.

Principle 16. *Approaches that yield partial orderings are useful for theoretical research when they apply but are of limited use in empirical research where aggregate data do not reflect the important issues and heterogeneity causes partial orderings to fail for many individuals.*

Another approach is to avoid imposing functional forms on stochastic distributions by estimating them nonparametrically. Such an approach fits conveniently into the state-dependent production model. However, as Moschini and Hennessy (forthcoming) conclude in their survey of risk in agricultural production, "To reconstruct nonparametric stochastic relationships between crop yield and input use would often require volumes of data beyond that usually available to analysts." In the realities of empirical research, time is a critical factor. Policies, technologies, and probably preferences are changing sufficiently over time (and perhaps space) that the volume of data required to facilitate appropriate nonparametric analysis is probably an illusive dream. Perhaps only by imposing some structure and interpreting available data with some imposed smoothness can conclusions be drawn that have relevance to any specific time or location. For example, a useful question is whether the current trend toward nonparametric representations (of technology, stochastic distributions, and behavior) holds more promise than intermediate parametric generalizations using, say 3- or 4-parameter distributions.

Principle 17. *Modeling of stochastic distributions must weigh the data-intensive requirements of nonparametric approaches (that often under-represent the number or dimension of possible outcomes and changes over time and space) against the structure-intensive requirements of parametric approaches (that impose continuous variation across outcomes possibly including time and space).*

If nonparametric approaches are not feasible, the problem is which parametric approach is appropriate. Many proposed forms have been suggested—many with a focus on modeling crop insurance where results are particularly sensitive to correct distributional modeling of the tails. Proposed forms include the gamma, beta, and log-normal distributions in addition to normality and hyperbolic tangent and hyperbolic sine transformations of normality (see Just and Weninger). One problem with this research, which is similar to the problem addressed by Principle 2, is that each study that has considered a new distribution in the literature has not adequately tested its significance against a maintained hypothesis that includes leading previous distributions used in the literature.[9] Thus, the research is not additive and convergence is illusive.

Lessons From the Search for Model Flexibility

Some basic lessons can be learned from the experience with the drive for second-order flexibility in dual models and the drive for even greater flexibility in nonparametric approaches. Apparently, additivity of research has decreased as a result of the drive for technical flexibility. That is, the profession has become less able to characterize its knowledge. Characterizing knowledge refers to representing knowledge in the form of stylized facts that permit policy economists to address various policy issues based on accepted empirical knowledge without having to develop further empirical results. In the 1950s and 1960s, demand and supply studies typically focused sharply on estimated elasticities. Each new study was required to compare its estimates of elasticities with those of previous studies in order to meet the standards for publication. If estimates did not agree, then publication in reputable outlets was generally rejected unless a plausible explanation could be offered in which case the stylized (empirical) knowledge of the profession was altered.

Estimates of elasticities have become less prominent as models have become flexible. Elasticities are estimated at the mean of the data or not reported at all. Rarely are ranges of elasticities across the all observed data reported. One reason is that standard assumptions such as concavity often fail. Futhermore, with the extremities of flexible forms, implausible elasticities are usually generated for plausible cases. For example, Just (1993) found that estimates of elasticities in the literature vary by more than an order of magnitude and that often small changes in exogenous variables are enough to cause signs of elasticities to become implausible. Thus, results are hardly broadly applicable beyond the confines of specific studies.

Principle 18. *More flexible model specifications are desirable if they can be identified by a preponderance of the evidence, or if variations in results among studies can be characterized meaningfully.*

Alternatively, empirical estimates produced by

[9] Another problem with this research is that data must be detrended before distributions can be analyzed appropriately. Just and Weninger show that inadequate methods have caused further problems of comparability.

dual applications of flexible models lack uniformity in signs of cross elasticities as well as magnitudes (Mundlak, forthcoming). Rather each study tends to present a new set of estimates that appear to vary largely randomly from others in the literature thus permitting little additive characterization of technology. Even in the broad categories of monotonicity, concavity, symmetry, homogeneity, and non-jointness, the results are mixed and violations of basic theory are frequent. Just and Pope (1999) suggest a number of approaches to address these problems, many of which are relatively untried.

Principle 19. *To achieve additivity of research and cross-study comparability, models with full flexibility that are not well identified with available data are less useful than models that capture major interactions less perfectly but lend themselves to characterizations that transcend individual studies.*

Use of Multi-Disciplinary Information for Identification

Duality provides a useful tool to incorporate information and verify plausibility of results of both supply/demand implications and technology implications of specifications. As pointed out by Mundlak (forthcoming), however, that ideal was lost immediately after the early studies by Lau and Yotopoulos and Yotopoulos, Lau, and Lin. These early studies estimated a Cobb-Douglas dual model that was then used to compare not only elasticities of supply and demand with previous studies but also the elasticities of production with previous production studies. Rather than providing a seamless relationship between primal and dual representations incorporating information available from both perspectives, the following drive for flexibility caused such "dual" comparisons with accepted stylized facts to vanish because the more general second-order flexible forms did not facilitate closed-form representations of technologies.

Principle 20. *Capturing the full empirical benefits of duality lies in comparing both the primal and dual implications of production estimates to existing literature and the collective wisdom of both economists and production scientists.*

Principle 20 applies regardless of whether relationships are estimated by primal or dual methodology. However, facilitation of communication with the production sciences about technology likely requires primal terminology because non-economists do not typically understand duality or how technology translates into indirect functions. This is an area of pursuit that holds promise for better understanding preferences because it will determine more of the technology with extraneous information and thus allow economic data to be used relatively more to discover preferences and behavior.

Although the potential flexibility of specifications that are tractable with duality has been regarded as a great advantage, an unanswered question is whether these representations have been excessively general. If models of excessive generality are used to analyze production problems, then the ability to communicate about them is reduced. For example, communication becomes difficult among economists in comparing implications from one study to the next (which is necessary for additivity of research results). More seriously, communication becomes difficult between economists and non-economist providers of information as inputs to economic analysis. As a result, production economists' growing empirical flexibility has reduced communication with the very disciplines that can provide scientific information for a priori specification and plausibility evaluation of production studies.

Principle 21. *The choice of methodology affects communication abilities which, in turn, cause a tradeoff between production model generality and the ability of economists (i) to impose prior information from the production sciences in estimation and (ii) to rely on production scientists or farmers to verify plausibility of results.*

Turning to the communication and usefulness of results, estimation of models with excessive generality often leads to estimates that are not congruent with theoretical plausibility (Just and Pope 1999). As a result, empirical studies not only lose their ability to contribute to stylized facts of the profession but production estimates become unusable for standard welfare analyses and other market and policy analyses and other products that serve the clients of the profession.

Principle 22. *Limited availability of data causes a tradeoff between the generality of model specifications and the generality of use of models.*

Just and Pope (forthcoming) argue that a correct description of the structure of technology in absence of imposed behavior usually requires multiple relationships. They show that when these relationships are summarized in a production possibilities frontier as in the typical approach of duality, that the resulting frontier may not possess any of the standard properties of the underlying technologies such as separability or nonjointness. Yet correctly representing properties of the underlying technologies may be crucial in uncovering motivations for behaviors such as diversification. Clearly, when the production possibilities frontier is obtained from profit maximization over a number of subtechnologies, as in the classical Samuelson case (pp. 230–231), the resulting frontier may be far different than when risk-aversion drives the choice of a risk-efficient frontier among the subtechnologies.[10] Thus, more careful investigation of behavior will require more structural specification and estimation of the sub-technologies that define a farmer's choices.

Principle 23. *Production possibilities frontiers alone do not support meaningful investigation of behavioral. Rather, technological possibilities must be described by the feasible mixes of subtechnologies available to decision makers.*

Estimation of Structure Versus Reduced Form

A substantive issue that must be addressed in the comparison of methodologies relates to the lessons of econometrics regarding estimation of structural versus reduced form systems. An important lesson from simultaneous equations estimation is that more econometric efficiency is obtained by structural estimation than by reduced-form estimation (e.g., Dhrymes). If reduced-form estimation is accomplished by aggregating variables and reducing the dimension of observation, this comparison is further strengthened.

These principles are important because the approaches of duality and nonparametric DEA characterize technology by the production possibilities frontier. Mundlak's (1996) *Econometrica* results demonstrate that dual approaches are econometrically inefficient because they, in effect, wash out structure to obtain reduced-form relationships solely in prices. The production possibilities frontier is clearly a reduced form of the production structure when the technology is composed of subtechnologies. A clear indication that dual technologies for agriculture are reduced forms is given by fact that many of the necessary decisions to implement production plans are not specified by dual frameworks. For example, when a dual approach is used to represent a multiple crop technology, the input demands typically do not specify how much land to allocate to each crop nor how much of each variable input to use on the land allocated to each crop (Chambers and Just is seemingly the only exception).

Principle 24. *Structural rather than reduced-form representations can facilitate greater econometric efficiency as well as greater identification, thus contributing to more convergence of knowledge.*

Econometric Analysis of Production Activities and Programming Models

Early farm management efforts focused heavily on activity analysis and programming models. These approaches have largely disappeared from the journals but modern computing power raises new possibilities. If technologies are composed of subtechnologies, then multiple equations are required to describe them just as in programming frameworks. With little doubt, agricultural economists were more successful in communication with production scientists and farmers regarding the description of technologies in this format than any used since. Apparently the decline in programming models was due to (i) inability to test implications statistically, (ii) the practice of judgmental rather than data-based estimation of coefficients, and (iii) the awkward step function decision equations they produced. These problems complicated comparability and additivity across studies at a time when that ability was highly valued. With modern computing power, multiple-equation models including inequality equations and nonlinearities can be readily estimated. Furthermore, bootstrapping approaches have greatly generalized possibilities for statistical testing. Thus, programming and econometric analysis can be merged to address issues such as how sub-technology structures must be modeled explicitly to represent diversification possibilities. With the use of more *a priori* information from the production sciences for sub-technology specification, more degrees of freedom will be available to investigate behavior in the context of a broad maintained behavioral hypothesis.

Conclusions Regarding Methodologies

In conclusion, increasing use of flexible and nonparametric approaches have led away from focusing on the economics of behavior because they have focused only on generality of technology. Because of the way flexibility has been used, investigation of behavior has been de-emphasized and, for the most part, profit maximization has simply

[10] In Samuelson's case, sub-technologies follow $y_i = f_i(x_i)$ where y_i is the ith element of the output vector $\mathbf{y}$ and $\mathbf{x}_i$ is a vector of factor allocations to production activity i. The production possibilities frontier is defined by $F(\mathbf{y},\mathbf{x}) = 0$ where $f^* (y_{-1},x) = \max\{y_1 | y_i = f_i(x_i),\ i = 1,\ldots,n_y;\ x = \sum_{i=1}^{n_y} x_i\}$ and $F(y,x) = y_1 - f^*(y_{-1},x)$. More generally, the outputs of each sub-technology can be defined by vectors of multiple outputs. See Just and Pope (forthcoming) for a definition and further discussion of the role of sub-technologies.

been assumed. This, in turn, has led to emphasis on methodologies that do not allow investigation of alternative behavioral hypotheses. Alternatively, better use of information from the production sciences can help identify technology. Thus, more flexibility will be available to identify behavior given the limited capacity of available data for identification. In effect, on the tradeoff between flexibility of technology and external utility of economic analysis, agricultural production economists have tended to choose the former. An important question for professional debate is whether this choice has been made for internal purposes at the expense of reducing input from the production sciences and reducing the ability of users to understand our products.

Data Limitations and Opportunities

Data availability is often viewed as an exogenous constraint on research. In the short run, this may be a valid view. As a profession, agricultural economists should influence data availability for the public good. Indeed, some important committee efforts of the AAEA are dedicated to work with public agencies to this end. However, as the share of public funds allocated to data production declines, agricultural economists will likely have to carry more of the burden of data production itself as part of grant-funded activities. As a result, an increasing share of meaningful research may have to be addressed with small one-shot data sets collected to investigate specific research questions. Without some overarching coherence, piecemeal data collection will likely further reduce additivity of research. Several major characteristics of agriculture suggest important related considerations.

The Problem of Aggregation Under Heterogeneity

One of the major problems of agricultural data analysis is potential aggregation bias due to heterogeneity (Pope and Just 1999). Clearly, agricultural production is highly heterogeneous. As suggested by Debreu, commodities should be defined by time and location as well as by physical attributes. Accordingly, aggregation can cause bias due to aggregation over time, over location, and over commodities with different physical attributes.

Agriculture is highly heterogeneous even locally. Farms differ in soil quality, climate, access to surface and groundwater, access to markets, and environmental sensitivity. Farmers differ in education, managerial capacity, technical abilities, allocative abilities, and in physical, financial and labor resources. Each of these may be relevant constraints in aggregation of behavior. For example, if wealth determines risk aversion following Arrow, then behavior cannot be meaningfully aggregated without use of wealth data.

Principle 25. *Agricultural production behavior depends on farm and farmer heterogeneity. Accordingly, micro-level data are needed to clarify behavior empirically whereas aggregate data obscures behavior.*

Similarly, aggregation over time within a growing season can have serious effects because agricultural growing seasons are lengthy and involve sequential decision making stages that are strongly tied to seasonality of weather and biological growth constraints. Many decisions apparently depend on intraseasonal observations of stochastic growing conditions. Data sets are needed to characterize weather dependence of planting rates and timing, rainfall dependence of irrigation, dependence of fertilizer and pesticide applications on moisture and pest conditions at the time of decisions, etc. For the most part, modeling of agricultural production has ignored intraseasonal dynamics. Yet these inputs are the ones to which distinct risk effects are usually attributed. With little doubt, single-stage modeling of these problems incurs endogeneity bias because mid-season input quantities are determined simultaneously with some of the random conditions that determine output. Instrumental variable approaches have been used to correct for this bias. However, instrumental variable approaches have low statistical power unless the instruments are well correlated with the farmer's mid-season conditions. Present data availability does not seem to meet this need. To the contrary, available public data typically do not identify whether inputs such as fertilizer and herbicides are applied prior to, at, or after planting.

Principle 26. *Mid-season factor input use depends on information available to farmers at the time of input decisions, which requires mid-season information and input use data for empirical study.*

Behavioral analysis also requires data related to multi-period aspects of risk bearing. Some of the variables that reflect the greatest consequences of risk are asset values (land, buildings, machinery, breeding stock, and perennial stands) and outstanding debt, which are highly heterogeneous. The interaction of these variables determines a farmer's wealth and whether a farm fails, both of which are concerns likely to cause behavior to deviate from simple profit maximization. As mentioned above, the most adverse outcome for agricultural producers in the past half century was the farm debt crisis and related farm failures that occurred with high interest rates in the 1980s following the commodity boom and rapid investment of the 1970s. Without stylized understanding of asset replacement, serious study of this most important phenomenon is difficult or impossible. Unfortunately, data on asset choices are very limited. For related analyses, vintage data are crucial in modeling replacement of perennial crops, machinery, breeding stock and buildings. However, the few micro-level data sets that have been developed typically only include transactions data rather than stock or asset value data. Due to lacking data, few studies of asset replacement are available. For example, the study by French and Matthews is among the last to focus structurally on the asset replacement problem.

Principle 27. *Asset replacement decisions (replacement of buildings, machinery, breeding stock and perennial crops) depend on current characteristics of existing assets. Accordingly, careful analysis requires data reflecting the age distribution, salvage value, and replacement of those assets.*

Application of Microeconomic Theory to Macroeconomic Data

One of the major shortcomings of agricultural production research, and particularly econometric production research, is it has been applied to short-run problems with aggregate data. In the case of risk for example, the risk characteristics not washed out by aggregating data may be substantially misrepresented as a result of averaging (Just and Weninger). While several truly micro level econometric studies have appeared (mostly related to crop insurance), most studies for developed agriculture use two data sets that are only semi-public: the Kansas State University Farm Management Survey and the Agricultural Resource Management Study (formerly the Farm Cost and Returns Survey) of the Economic Research Service. For those without practical access to either of these data sets, short-run applications have been constrained to aggregate data sets. Thus, most of the econometric production literature is presented with the usual caveat that aggregate data are used merely for "illustrative" purposes. What an unfortunate state of affairs!

Principle 28. *Lack of micro-level data that sufficiently describes farmers longer-term and intraseasonal decisions and related conditions misdirects research away from some of the most important agricultural production problems.*

The Role of Information and Expectations

While little has been said to this point regarding expectations, the role of information and its effect through farmer expectations cannot be overlooked in this "age of information." To date, the role of information in agricultural production analysis has hardly risen above determining the operative expectations mechanism, e.g., rational versus naive, adaptive, or extrapolative expectations (see Nerlove and Bessler for a recent review). Production research for the future should focus on the market for information. Realistically, the cost of rational expectations may exceed their benefit in times of stability causing endogenous adjustment in information choices (Just and Rausser). The cost of processing price and market information may imply reliance on a minimal information set by smaller farms or when information costs are higher. Considering the cost of aquiring and processing information on technologies, a profit-maximizing approach may be to follow rules of thumb provided by university extension and input manufacturers (Just, Zilberman, Hochman and Bar-Shira).

At this point, data are generally not available on farmer expectations and the information sources they use. While a few small surveys have been done (e.g., Wolf, Just, and Zilberman), general knowledge is woefully inadequate. Data are needed on alternative sources of information, cost of information sources, costs of processing information, and the choices made by farmers of actual sources of information given their circumstances. In these issues, empirical research has hardly scratched the surface. Again, a major constraint is availability of data.

Principle 29. *With growing and dramatic changes in markets for information, modeling of information markets serving agricultural production will become more crucial, which calls for at least rudimentary data on quantity, quality, and prices of information.*

Needed Investment in a Comprehensive Panel Data Set

To reduce the constraints of data availability on economic analysis of agricultural production, the profession needs broad access to a common micro-level data set. These data should ideally include wealth, assest vintages, debt structure, mid-season weather and pest information affecting input usage, sources of market and technological information and costs, and local attributes of farms and farmers. Given these needs, the profession would do well to invest in a panel data set that can facilitate broad investigation and additive debate on the most serious problems facing agricuture. Such a widely accessible micro-level data base has served the labor economics profession well for this purpose and provides something of a model for the development of stylized facts and additivity of empirical research. The value of such a data set for resolving failure of standard theory due to aggregation was emphasized by Just and Pope (1999). More recently, Just and Pope (forthcoming) have presented a comprehensive critique of agricultural production theory attributing many failures of production economics to the use of aggregate data. They conclude, for example, that "response to risk is unlikely to be measured effectively with secondary aggregate data because it (i) tends to obfuscate individual responses and risk and (ii) offers very poor measurement of wealth on which risk aversion likely depends."

Principle 30. *Additive debate and support for convergence of knowledge can be facilitated by development of a broad and universally accessible data base.*

National significance of an on-going panel data set development effort for agriculture requires that it must go beyond state borders and the proprietary constraints encountered thereby. To be free of survey exposure and right-to-privacy constraints that will cause the effort to fail in some of its most important purposes, and to be free of the *ex post* proprietary interests of bureaucrats, such a data generating effort needs to be funded and developed by a non-governmental organization. Since the data would be primarily used by agricultural economists, a likely sponsoring organization would be the American Agricultural Economics Association or possibly a coalition among the AAEA and the various regional agricultural economics associations. To have adequate concentration in individual areas but yet national implications, it may be appropriate to concentrate the survey in one or two states of each region of the country. Panel data are needed because the more important longer-run issues cannot be studied adequately if different farms are included in the survey each year as in the Economic Research Service's Agricultural Resource Management Study. Use of funds generated, for example, by the AAEA Foundation in this way could genuinely enhance the agricultural economics profession's ability to speak on the important issues facing agriculture. Although this undertaking may appear large for the agricultural economics profession, the ability of the AAEA to solicit private funds to support such an effort is likely substantial—particularly given the benefits that such data may have for private industry.

Conclusions

In conclusion, agricultural production research is, in some important ways, off track. It is failing to achieve additivity and is failing to yield a set of stylized facts that can serve either the profession or users of its research output. Yet many untapped approaches to knowledge remain and the potential research agenda is rich with possibilities that can bring agricultural production research back on track. To fulfill opportunities will require breaking out of some of the ruts and molds that currently constrain thinking and methodologies. Some of these ruts and molds are self-imposed and can be easily left behind. Others are largely externally imposed and can only be escaped by taking a more active and endogenous role in expanding the constraints of the profession.

Data availability is perhaps the greatest contraint. Although largely externally imposed, the days where agricultural economists can be passive in accepting it are past. Prospects are slim for improving public data availability in a comprehensive way that will reveal critical local characteristics and correlations among those characteristics in an on-going way and thus permit evolving and additive research. Non-governmental organizations offer possibilities for avoiding undue survey exposure constraints and bureaucratic control. The natural non-governmental organizations to address these data needs are the agricultural economics professional societies. Developing a comprehensive panel data set is a large task considering the size of our professional societies, but private funds can likely be raised given the benefits that could be directly available to private firms as a result.

Problem focus has been heavily influenced by data availability. Most econometric production research has been applied to short-run data at the aggregate annual level. Accordingly, most production research has focused on problems where the major phenomena affecting the long-term well-being of farmers is de-emphasized and where behavioral departures from profit maximization are unlikely to be discovered. Relatively little research has focused on the multi-period risk problem related to farm failure, restructuring of the agricultural sector, and the underlying issues of investment and asset replacement.

The major methodological constraints of agricultural production analysis are largely self-imposed. The dominating practices of production economics have undergone a major redirection whereby dual methodology has largely replaced primal methodology. Currently another transformation toward nonparametric approaches appears to be in progress. These movements, however, are counterproductive from the standpoint of understanding production behavior because they impose inflexible specifications on preferences. Although some dual approaches can be generalized to handle risk problems, these generalizations have not been fully successful to date. Furthermore, some of the attractive elegance of duality may be lost in the process. Alternatively, primal representations offer greater possibilities for using knowledge generated by the production sciences which, in turn, permits using the identification limits of available data relatively more to understand behavior.

Data availability, problem focus and research methodology are highly interactive inputs determining the overall quality of production research. Clearly, problem focus has been highly influenced by data availability. Also, both problem focus and public data generation efforts have tended to respond to the issues of current political concern. However, methodology can both drive data needs and limit problem focus. With standard dual approaches, some quantity data are not regarded as crucial because dual explanations focus on prices. Disaggregated data on technologies are not regarded as crucial under duality because subtechnologies are assumed to be combined by profit maximization. In short, many of the variables that reflect alternative behaviors are not regarded as important for standard dual approaches. As a result, the effort to build a comprehensive panel data base will have to overcome some of the current thinking about which data are important. This current state of thought is itself a product of previous availability and the methodological choices that have been influenced thereby. Opening possibilities for better understanding of production behavior and better understanding of the underlying structure of production thus depends on breaking the molds of present frameworks that have dominated thought for the last several decades.

References

Alston, J.M., and J.A. Chalfant. 1991. "Unstable Models from Incorrect Forms." *American Journal of Agricultural Economics* 73:1171–1181.

Anderson, G. 1996. "Nonparametric Tests of Stochastic Dominance in Income Distributions." *Econometrica* 64:1183–1193.

Antle, J.M. 1983. "Testing the Structure of Production: A Flexible Moment-Based Approach." *Journal of Business and Economic Statistics* 1:192–201.

Antle, J. 1987. "Econometric Estimation of Producers' Attitudes." *American Journal of Agricultural Economics* 69: 509–522.

Arrow, K.J. 1971. *Essays in the Theory of Risk Bearing.* Chicago: Markham Publishing Company.

Bar-Shira, Z., R.E. Just, and D. Zilberman. 1997. "Estimation of Farmers' Risk Attitude: An Econometric Approach." *Agricultural Economics* 17:211–222.

Barry, P.J., and L.J. Robison. Forthcoming. "Agricultural Finance: Credit, Credit Constraints, and Consequences," in *Handbook of Agricultural Economics,* B.L. Gardner and G.C. Rausser, eds. Amsterdam: Elsevier-North-Holland.

Binswanger, H. 1980. "Attitudes Toward Risk: Experimental Measurement in Rural India." *American Journal of Agricultural Economics* 62:395–407.

Buschena, D., and D. Zilberman. 2000. "Generalized Expected Utility, Heteroscedastic Error, and Path Dependence in Risky Choice." *Journal of Risk and Uncertainty* 20:67–88.

Candler, W., and M. Boehlje. 1971. "The Use of Linear Programming in Capital Budgeting with Multiple Goals." *American Journal of Agricultural Economics* 53:325–30.

Chambers, R.G., and R.E. Just. 1989. "Estimating Multi-output Technologies." *American Journal of Agricultural Economics* 71(4):980–995. November.

Chambers, R.G. and J. Quiggin. 1998. "Cost Functions and Duality for Stochastic Technologies." *American Journal of Agricultural Economics* 80:288–295.

Chavas, J.P., and T.L. Cox. 1988. "A Nonparametric Analysis of Agricultural Technology." *American Journal of Agricultural Economics* 70:303–310.

Chavas, J.P., and T.L. Cox. 1994. "The Primal-Dual Nonparametric Productivity Analysis: The Case of U.S. Agriculture." *The Journal of Productivity Analysis* 5:359–73.

Chavas, J.-P., and M.T. Holt. 1996. "Economic Behavior Under Uncertainty: A Joint Analysis of Risk Preferences and Technology." *Review of Economics and Statistics* 78:329–35.

Chavas, J.-P., and R. Pope. 1985. "Price Uncertainty and Competitive Firm Behavior: Testable Hypotheses from Expected Utility Maximization." *Journal of Economics and Business* 37(19):223–35.

Cox, T.L., and J.P. Chavas. 1990. "A Nonparametric Analysis of Productivity: The Case of U.S. Agriculture." *European Review of Agricultural Economic* 17:449–64.

Coyle, B.T. 1992. "Risk Aversion and Price Risk in Duality Models of Production: A Linear Mean-Variance Approach," *American Journal of Agricultural Economics* 74: 849–59.

Debreu, G. 1959. *Theory of Value.* New York: Wiley.

Dhrymes, P.J. 1973. "Restricted and Unrestricted Reduced Forms: Asymptotic Distribution and Relative Efficiency" *Econometrica* 41:119–134.

Featherstone, A.M., A.G. Moghnieh, and B.K. Goodwin. 1995. "Farm Level Nonparametric Analysis of Cost Minimization and Profit Maximization Behavior." *Agricultural Economics* 13:109–17.

French, B.C., and J.L. Matthews. 1971. "A Supply Response Model for Perennial Crops," *American Journal of Agricultural Economics* 53:478–490.

Hazell, P.B.R. 1982. "Applications of Risk Preference Estimates in Firm-Household and Agricultural Sector Models." *American Journal of Agricultural Economics* 64: 384–90.

Hazell, P.B.R. 1971. "A Linear Alternative to Quadratic and Semivariance Programming for Farm Planning Under Uncertainty." *American Journal of Agricultural Economics* 53:53–62.

Just, R.E. 1974. "An Investigation of the Importance of Risk in Farmers' Decisions." *American Journal of Agricultural Economics* 56(1):14–25. February.

Just, R.E. 1993. "Discovering Production and Supply Relationships: Present Status and Future Opportunities." *Review of Marketing and Agricultural Economics* 61(1):11–40. April.

Just, R.E., and J.M. Antle. 1990. "Interactions Between Agricultural and Environmental Policies: A Conceptual Framework." *American Economic Review* 80(2):197–202. May.

Just, R.E., L. Calvin, and J. Quiggin. 1999. "Adverse Selection in Crop Insurance: Actuarial and Asymmetric Information Incentives." *American Journal of Agricultural Economics* 81(4):834–849. November.

Just, R.E., and W. Candler. 1985. "Production Functions and Rationality of Mixed Cropping: The Nigerian Cas." *European Review of Agricultural Economics* 12(3):207–231.

Just, R.E., and R.D. Pope. 1979. "Production Function Estimation and Related Risk Consideration." *American Journal of Agricultural Economics* 61(2):276–284. May.

Just, R.E., and R.D. Pope. 1999. "Implications of Heterogeneity for Theory and Practice in Production Economics." *American Journal of Agricultural Economics* 81(2):711–718. August.

Just, R.E., and R.D. Pope. Forthcoming. "The Agricultural Producer: Theory and Statistical Measurement." In *Handbook of Agricultural Economics,* B.L. Gardner and G.C. Rausser, eds. Amsterdam: Elsevier-North-Holland.

Just, R.E., and G.C. Rausser. 1983. "Applied Commodity Price Analysis, Forecasting, and Market Risk Management." NCR-134 Conference. Des Moines, IA.

Just, R.E., and Q. Weninger. 1999. "Are Crop Yields Normally Distributed?" *American Journal of Agricultural Economics* 81(2):287–304. May.

Just, R.E., D. Zilberman, E. Hochman, and Z. Bar-Shira. 1990. "Input Allocation in Multicrop Systems." *American Journal of Agricultural Economics* 72(1):200–209. February.

Kahneman, D., and A. Tversky. 1979. "Prospect Theory: An Analysis of Decision Under Risk." *Econometrica* 47:263–91.

Lau, L.J., and P.A. Yotopoulos. 1972. "Profit, Supply, and Factor Demand Functions." *American Journal of Agricultural Economics* 54(1):11–18.

Machina, M.J. 1987. "Choice Under Uncertainty: Problems Solved and Unsolved." *Journal of Economic Perspectives* 1:121–54.

McElroy, M. 1987. "Additive General Error Models for Production, Cost, and Derived Demand or Share Systems." *Journal of Political Economy* 95:737–57.

Moschini, G. 1999. "Production Risk and the Estimation of Ex-Ante Cost Functions." Department of Economics, Iowa State University, Staff Paper #315. March.

Moschini, G., and D.A. Hennessy. Forthcoming. "Uncertainty, Risk Aversion, and Risk Management for Agricultural Producers." In *Handbook of Agricultural Economics,* B.L. Gardner and G.C. Rausser, eds. Amsterdam: Elsevier-North-Holland.

Mundlak, Y. 1996. "Production Function Estimation: Reviving the Primal." *Econometrica* 64(2):431–438.

Mundlak, Y. Forthcoming. "Production and Supply," in *Handbook of Agricultural Economics,* B.L. Gardner and G.C. Rausser, eds. Amsterdam: Elsevier-North-Holland.

Nerlove, M., and D.A. Bessler. "Expectations, Information and Dynamics," in *Handbook of Agricultural Economics,* B.L. Gardner and G.C. Rausser, eds. Amsterdam: Elsevier-North-Holland.

O'Donnell, C.J., and A.D. Woodland. 1995. "Estimation of Australian Wool and Lamb Production Technologies under Uncertainty: An Error Components Approach." *American Journal of Agricultural Economics* 77:552–565.

Quiggin, J. 1993. *Generalized Expected Utility Theory—The Rank-dependent Model.* Boston: Kluwer Academic Publishers.

Pflueger, B.W., and P.J. Barry. 1986. "Crop Insurance and Credit: A Farm Level Simulation Analysis." *Agricultural Finance Review* 46:1–14.

Pope, R.D. 1980. "The Generalized Envelope Theorem and Price Uncertainty." *International Economic Review* 21(1): 75–86.

Pope, R.D. 1988. "A New Parametric Test for the Structure of Risk Preferences." *Economics Letters* 27:117–121.

Pope, R.D., and R.E. Just. 1991. "On Testing the Structure of Risk Preferences in Agricultural Supply Analysis." *American Journal of Agricultural Economics* 7(3):743–748. August.

Pope, R.D., and R.E. Just. 1996. "Empirical Implementation of Ex-ante Cost Functions." *Journal of Econometrics* 72: 231–249.

Pope, R.D., and R.E. Just. 1998. "Cost Functional Estimation Under Risk Aversion." *American Journal of Agricultural Economics* 80(2):296–302. May.

Pope, R.D., and R.E. Just. 1999. "Distinguishing Errors in Measurement from Errors in Optimization." Working Paper, University of Maryland.

Pope, R.D., and R.E. Just. 2000. "Random Profits and Duality." Working Paper, University of Maryland.

Saha, A., C.R. Shumway, and H. Talpaz. 1994. "Joint Estimation of Risk Preference Structure and Technology Using Expo-Power Utility." *American Journal of Agricultural Economics* 76:173–84.

Samuelson, P.A. 1967. *Foundations of Economic Analysis.* New York: Atheneum.

Smale, M., R.E. Just, and H.D. Leathers. 1994. "Land Allocation in HYV Adoption Models: An Investigation of Alternative Explanations." *American Journal of Agricultural Economics* 76(3):535–546. August.

Tauer, L.W. 1995. "Do New York Farmers Maximize Profits or Minimize Costs?" *American Journal of Agricultural Economics* 77:421–29.

Tolley, H.D., and R.D. Pope. 1988. "Testing for Stochastic Dominance," *American Journal of Agricultural Economics* 70:693–700.

Wolf, S., D.R. Just, D. Zilberman. Forthcoming. "Between Data and Decisions: The Organization of Agricultural Economic Information Systems." *Research Policy.*

Yotopoulos, P.A., L.J. Lau, and W.L. Lin. 1976. "Microeconomic Output Supply and Factor Demand Functions in the Agriculture of the Province of Taiwan." *American Journal of Agricultural Economics* 58(2):333–340.

Young, D.L. 1979. "Risk Preferences of Agricultural Producers: Their Use in Extension and Research." *American Journal of Agricultural Economics* 61:1067–1070.