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The Dual Approach to Research Evaluation: A Simplified Empirical Illustration

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In this paper, the dual approach to ex ante research evaluation in a multiple-input, multiple-output industry is explained and demonstrated. A simplified, illustrative model is developed based on a number of fundamental characteristics of the Australian wool industry and output-augmenting technical change. A normalised quadratic restricted profit function of Australian wool production is specified in terms of effective rather than actual prices. The estimated short-run supply elasticities are quite inelastic. The results of the simplified model show that the development and adoption of a 10 per cent yield-increasing wool technology would result in a 19.6 per cent fall in the actual price of wool and a 9.8 per cent increase in the actual quantity of wool produced. The cross-commodity effects of the technology are also allowed for in the model, with actual livestock production falling by 0.6 per cent, actual labour usage increasing by 0.3 per cent and actual crop production increasing by 1.3 per cent. Overall, in the short-run, the introduction of the specified wool yield-increasing technology results in a 17.1 per cent decrease in wool producer profits.

1 Introduction

Technical change is an important source of growth for the Australian agricultural sector (Martin and Alston 1994; Mullen and Cox 1996). Given the limited funds available for research and development in agriculture, measuring the level and distribution of returns to public- and producer-funded research, in a theoretically consistent manner, has become increasingly important. Norton and Davis (1981) provide an early review of the most common approaches used to assess the economic consequences of agricultural research. Since then, the literature on measuring the size and distribution of returns to research has expanded considerably, not only in terms of the number of studies that have been undertaken, but also in terms of the range of procedures used.

Since Schultz (1953) first calculated the change in consumer surplus resulting from the introduction of input-saving technologies in the United States, estimating the returns to technical change within an economic surplus framework has become commonplace in the literature on research evaluation. Over time, various methods have been developed enabling the welfare consequences of research investments to be assessed for a wide range of markets (Alston, Norton and Pardey 1995, Ch.4). Nevertheless, while the economic surplus approach is a useful tool in research evaluation, it does have its limitations. For example, when the market in question is complicated by multiple cross-commodity relationships, while it is possible to measure changes in the total economic surplus areas off general equilibrium supply and demand curves, it is not possible to measure changes in the surplus areas of identifiable groups, such as producers and consumers.

Evaluating returns to technical change within a production economics framework has also been well documented in the literature. Within this broad modelling framework, econometric (primal and dual methods), nonparametric and index-number procedures have been used to relate output, profits, or costs to expenditure on agricultural research and development. The estimated research-induced changes in quantities, profits and

costs have then been translated into measures of returns to research in a number of studies (e.g., Chavas and Cox 1992; Martin and Alston 1994; Mullen and Cox 1995). Dual procedures are of particular interest in this study because they provide a theoretically-consistent means of assessing the economic impact of a technical change in an industry that is characterised by multiple-output, multiple-input production systems (Martin and Alston 1997). As shown by Just, Hueth and Schmitz (1982), if welfare calculations are estimated from demand and supply curves that do not satisfy theoretical restrictions, then the welfare measures are ambiguous. The purpose of this paper is to present a simple, illustrative example based on the Australian wool industry to show how the dual approach can be used to obtain unambiguous estimates of benefits from an *ex ante* technical change in an industry characterised by multiple cross-commodity relationships. With this in mind, the profit function is the chosen dual formulation, primarily because it provides a direct estimate of producer welfare.

Ultimately, the model structure is governed by the question at hand (including factors such as the structure of the industry and the nature of the proposed technical change) and the availability of resources and data for the analysis. Consequently, the format of this paper is as follows. The characteristics of the Australian wool industry and the proposed technical change are summarised in section 2. The profit function is specified and estimated in section 3. To allow for endogenous determination of the research-induced change in the world price for wool, the demand characteristics for wool are presented in section 4. The welfare effect of the proposed technical change on Australian wool producers is evaluated in section 5. This includes estimates of the effect of the technical change on the world price for wool and on the profits of Australian wool producers. In the final section, a summary of the profit function approach to research-evaluation is presented along with the main conclusions.

2 Industry and Technology Overview

The simplified model specified here is based on a number of fundamental characteristics of the Australian wool industry and the illustrative technical change being considered. First, Australia is the world's largest producer and exporter of apparel wool (referred to, hereafter, simply as wool). Therefore, a research-induced change in Australian wool production will affect the world price of wool.

Second, around 97 per cent of Australian wool is exported each year. Around 84 per cent is sold as greasy raw wool while the remaining 16 per cent is sold as semi- (rather than fully-) processed wool (Australian Bureau of Agricultural and Resource Economics (ABARE) 1998). Therefore, given that a large proportion of Australian wool is exported in its raw state, and recognising the predominant overseas ownership in the early-stage processing activities in Australia (Griffith 1993), the focus of this paper is on the effects of the technology on Australian wool producer profits. The research-induced change in consumer welfare is not considered because the vast majority of consumers reside overseas.

Third, purely for illustrative purposes, the technical change assessed in the simple model is assumed to lead to a 10 per cent increase in yield, where yield is measured in kilograms per sheep shorn. This increase in yield will result in an increase in the total supply of Australian wool.

Fourth, the Australian wool industry is characterised by multiple-output, multiple-input firms. In addition to producing wool, a woolgrower may also produce livestock (e.g., cattle and sheep) and crops (e.g., wheat and barley). These competing outputs are related in supply using common inputs, such as livestock, labour, materials and services and capital. For a more accurate estimation of the impact of the technical change on the welfare of wool producers, these cross-commodity relationships should be accounted for in the model (Just, Hueth and Schmitz 1982; Just 1993). Developing a model that consists of netput supply equations for each of the related commodities does this. These equations are related through cross-partial derivatives.

It is acknowledged that a number of other important characteristics of the Australian wool industry exist. They include the regional differences in the type of wool produced, the heterogeneous nature of wool and the dynamic and stochastic nature of livestock production. However, for the sake of simplicity, these characteristics are ignored in this study. Nevertheless, a structured model of the Australian wool industry is developed to show how the economic impact of an *ex ante* technical change can be assessed within a duality-based framework. This model consists of a system of equations in which essential cross-commodity relationships are specified. The mathematical relationships of these equations are consistent with the theoretical restrictions that arise as a result of assuming profit maximisation (i.e., homogeneity, convexity, monotonicity and symmetry). This ensures that the economic welfare calculations are unambiguous.

3 Specification and Estimation of the Profit Function

3.1 Functional Form

Estimation of the welfare consequences of technical change within a dual modelling framework requires that the functional form of the indirect objective function be specified. The chosen specification will, in turn, determine the functional form of the derived netput supply functions. The analyst can choose from a variety of functional forms. For any given research problem, the final decision could depend on a number of criteria, such as being general enough so that not too many *a priori* assumptions need to be imposed and being simple enough so that the estimating equations are tractable.

The normalised quadratic is the chosen representative functional form for the profit function for a number of reasons. First, because the quadratic is a second-order Taylor series expansion, it is a flexible functional form that does not impose as many restrictions on the production technology set as non-flexible functional forms, such as the Cobb-Douglas. Second, the normalised quadratic profit function is relatively simple to estimate because the netput supply equations for the non-numeraire commodities are linear. Third, the normalised quadratic is the only commonly used functional form that is self-dual (i.e., if the profit function is quadratic then so is its primal specification, the production function). Consequently, the respective Hessian matrices are constant (Wall and Fisher 1987, p. 38) and local convexity in prices implies global convexity (Huffman and Evenson 1989). Fourth, convexity can be imposed globally on the normalised quadratic without a loss of flexibility (Wall and Fisher 1987, p.39). Finally, while netput prices are specified as exogenous variables in

the dual modelling framework, profit and cost functions are often fitted to regional, state or national data. As pointed out by Huffman and Evenson (1989, p.765), 'linear aggregation of variables over farms is appropriate when the individual profit functions are normalised quadratic'.

Nevertheless, the analyst needs to be aware that even 'appropriate' aggregation of variables to a national or even regional model can cause specification problems. In the case of a small country trader, agricultural prices are likely to be exogenous to a firm or even to an industry and, therefore, the average farm or industry can be completely modelled within the profit function framework. This is because, even at the national industry level, producers vary inputs and outputs each production period subject to exogenous prices and fixed inputs (Lawrence and Zeitsch 1989). However, in the case of a large-country trader such as Australia with wool, the measured industry-level prices are endogenous, in which case, an estimation procedure such as 2SLS needs to be used (section 3.3).

3.2 Variables and Data

Choice of Supply-side Variables

Modern agricultural production systems are characterised by firms that combine a large number of inputs to produce various outputs. While it may be desirable to include a complete set of variables in the estimation model, this is often not possible because of econometric and data limitations. In the simplified model, only a relatively small set of aggregate outputs and inputs is considered empirically. The variables specified in the simplified profit function include three output prices (wool, livestock outputs and crops), two variable input prices (labour and materials and services) and three non-price exogenous variables (livestock, capital and a time trend). A list of the 'supply-side' variables specified in the normalised quadratic profit function is presented in Table 1.

Table 1: Description of variables specified in the wool producers' profit functions

Abbreviation	Variables
<i>Price/Quantity</i>	<i>Outputs</i>
P_1 / X_1	Wool
P_2 / X_2	Livestock outputs
P_3 / X_3	All crops
<i>Price/Quantity</i>	<i>Variable Inputs</i>
P_4 / X_4	Labour
P_5 / X_5	Materials and services
<i>Quantity</i>	<i>Non-price Exogenous Variables</i>
z_6	Livestock
z_7	Capital
z_8	Time trend variable

A time trend variable has been included in the model to capture the effects of the ongoing change in technical knowledge that is occurring in the Australian wool industry in addition to the specific output-augmenting technical change being analysed in the simplified model. For example, technologies resulting in yield improvements in crops and livestock were developed and adopted continuously over the period being analysed. Despite a number of limitations to this approach (e.g., the underlying assumption that the rate of change in technical knowledge is constant over time), the use of a time trend to reflect the effects of technical change on agriculture production remains the norm in the professional literature (Wall and Fisher 1987; Coelli 1996). The time trend enters the model in the same way as the two quasi-fixed variables, livestock and capital.

Clearly, some of these variables are ‘aggregate’ variables (e.g., crops) in the sense that they comprise two or more individual commodities (e.g., wheat, barley and oats). The decision regarding the composition of the aggregates was based on previous research on modelling Australian agricultural supply response in a multiproduct framework, in particular the work by Coelli (1996). The components of these commodity groups are presented in Table 2.

Once the decision regarding the composite outputs and inputs is made, the next step is to construct price and quantity indices for each of these groups. A number of procedures are covered in the literature. Diewert pointed out that both the Christensen and Jorgenson (C&J) and the Fisher index are exact for flexible aggregator functional forms but that the Fisher index could be preferable to the C&J index ‘because of the way in which it satisfies the tests associated with both the axiomatic and economic approaches to index numbers’ (Mullen and Cox 1996, p.190). In sum, given that the Fisher index is the only index that has the practical advantage of satisfying the factor reversal test (i.e., price * quantity = value), it is the index of choice for this study.

Data from the Australian Agricultural and Grazing Industry Survey (AAGIS) were used to produce Fisher price and/or implicit quantity indices for all the categories of outputs, variable inputs and the quasi-fixed inputs presented in Table 2.

Table 2: Components of commodity groups

Variables
<i>Outputs</i>
Livestock outputs
<ul style="list-style-type: none"> • Sheep sales plus negative operating gains • Lamb sales • Cattle sales plus negative operating gains
Crops
<ul style="list-style-type: none"> • Wheat • Barley • Oats • Sorghum • Oilseeds • Other
<i>Variable Inputs</i>
Labour
<ul style="list-style-type: none"> • Operator and family • Hired labour & contracts • Shearing • Stores and rations
Materials and services
<ul style="list-style-type: none"> • Crop chemicals • Livestock materials • Fodder • Fertiliser • Seed • Fuel • Other materials • Motor vehicle sundry • Rates and taxes • Administration • Miscellaneous livestock items • Total contracts • Other services • Total repairs • Insurance
<i>Non-price Exogenous Variables</i>
Livestock inputs
<ul style="list-style-type: none"> • User cost of sheep capital • Total sheep flock • User cost of beef capital • Total beef herd • User cost of other livestock capital • Movement in other livestock capital
Capital
<ul style="list-style-type: none"> • Land capital • Buildings and other farm improvement capital • Plant (machinery and vehicles) capital

Choice of Demand-side Variables

Given the structure of the market for Australian wool, the price of wool is an endogenous variable on the right-hand side of the profit and netput supply equations. Therefore, it is preferable to estimate the system of structural equations using a simultaneous equation estimator, such as 2SLS. To do this, it is necessary to estimate a reduced-form equation for the price of wool from which the predicted value for the price of wool can be computed. The predicted value then replaces the actual value of wool in the profit function estimation. In the simplified empirical illustration presented here, there are a number of instrumental variables that affect the demand for wool, which are specified in the reduced-form equation, in addition to the exogenous netput prices. They include the price of manufactured fibres, the price of cotton, oil prices and the Gross Domestic Product (GDP) for Japan, which is used as a proxy for consumer income (Table 3). These variables are referred to as ‘demand-side’ variables and, while they are not specified in the profit function, they are used in the estimation procedure.

Table 3: Description of additional variables specified in the reduced-form equation for the price of wool

Abbreviation	Exogenous Variables
P_9	Price of manufactured fibres
P_{10}	Price of cotton
P_{11}	Price of oil
Z_{12}	GDP for Japan

Sources of Supply-side Variables

Data for the variables in the profit function were taken from the AAGIS conducted by ABARE. The survey data includes all farms with more than 200 sheep on a State by zone basis for the 21 years ending 1997/98. The States comprise NSW, Qld, Victoria, WA and SA and the zones are the pastoral zone, the high rainfall zone and the wheat/sheep zone. Data for all three zones are available for NSW and Qld but data are not available for the WA pastoral zone or the QLD high rainfall zone, as the respective sample sizes are too small to be included. In addition, Victoria does not have a pastoral zone. This population of farms produces most of Australia's wool. It also contains many mixed crop-and-livestock farms, which produce a significant part of the Australian grain crop. While it is recognised that output and input mixes are different in each of the three agricultural zones, indicating that each zone should be modelled separately, in the simplified model the specification is for Australia as a whole. Consequently, there are a total of 252 observations for the pooled cross-sectional and time-series data.

Sources of Demand-side Variables

All data used in the reduced-form equation are for the 21 years ending 1997/98. Data for the price of cotton, the price of manufactured fibres, the price of oil and the GDP for Japan were obtained from NSW Agriculture.

6.3.4 Specifying Technical Change

The technical change variable needs to be specified in the profit function in a manner that will represent the nature of the technical change and be consistent with the theoretical requirements of the profit function. In this study, the *ex ante* technical change under review, that is, the staple strength-enhancing technology, is specified as output (or input) augmenting technology. An important aspect of this specification is that a distinction is made between *actual* and *effective* quantities and prices. The actual quantity (price) refers to the observed quantity (price) while the effective quantity (price) refers to the quantity (price) per physical unit, for example, kg/wether (\$/wether).

The relationship between actual (X_i) and effective (X_i^*) output is $X_i = X_i^* \tau_i^e$, where τ_i^e is the level of output or input augmenting technology (Martin and Alston 1997). Under this definition, when X_i is an output, output augmenting technology is represented by an increase in τ_i^e , which raises the actual quantity associated with any given effective quantity. Conversely, when X_i is an input, input augmenting technology is represented by a decrease in τ_i^e , which reduces the actual quantity of an input required to produce a given effective quantity of output, for example, as in the case of the development and adoption of feed-saving management practices by a wool grower.

For illustrative purposes, the technology variable specified in the simplified model is specified as output augmenting. In the base period, the given effective output of wool per unit of physical output is 4 kg per wether equivalent and the technology index is set to unity. Hence, the actual output is also 4 kg for each wether equivalent shorn. The development and adoption of the output augmenting technology in the wool industry is represented by a 10 per cent increase in the technology index, τ_i^e , from 1 to 1.1. Consequently, the actual quantity per effective unit of output increases by 10 per cent to 4.4 kg per wether equivalent.

Further, a technology induced change in the actual quantity of the commodity results in a corresponding change in the effective price of that commodity (associated with the given physical unit). The relationship between the actual (P_i) and effective prices (P_i^*) is given as $P_i = P_i^* / \tau_i^e$ (Martin and Alston 1992, 1994, 1997). When X_i is an output, output augmenting technology is represented by an increase in τ_i^e , which raises the actual quantity associated with any given effective quantity and raises the effective

~~price relative to the actual price. Conversely, when X_i is an input, input-augmenting technology is represented by a decrease in τ_i^e , which reduces the actual quantity of the input required to produce one effective unit and also lowers the effective price of the input relative to the actual price.~~

~~The distinction between actual and effective prices is clear. Returning to the illustrative example given above, if it is assumed that farmer sells wool for \$5/kg then the actual price of the wool is \$5/kg, while the effective (pre-technology) price of the wether equivalent is \$20 (i.e., \$5 times 4 kg). In the post-technology situation, as a result of the technology-induced increase in the actual quantity of wool produced, the effective price of the physical unit increases to \$22 (i.e., \$5 times 4.4 kg), even though the actual \$/kg price of wool hasn't changed.~~

3.3 Estimating Equations

In this model, the technical change is specified as output augmenting. An important aspect of this specification is that a distinction is made between *actual* and *effective* quantities and prices. The actual quantity (price) refers to the observed quantity (price) while the effective quantity (price) refers to the quantity (price) per physical unit which produces the output being studied, for example, kg/sheep (\$/sheep). The relationship between actual (X_i) and effective (X_i^e) quantity is $X_i = X_i^e * \tau_i^e$, where τ_i^e is the level of output-augmenting technology. Under this definition, when X_i is an output, output-augmenting technology is represented by an increase in τ_i^e , which raises the actual quantity associated with any given effective quantity, for example, more wool per sheep. Further, a technology-induced change in the actual quantity of the commodity results in a corresponding change in the effective price of that commodity (associated with the given physical unit). The relationship between effective (P_i^e) and actual prices (P_i) is given as $P_i^e = P_i * \tau_i^e$. When X_i is an output, output-augmenting technology is represented by an increase in τ_i^e , which raises the actual quantity associated with any given effective quantity and raises the effective price relative to the actual price, for example, more dollars per sheep (Martin and Alston 1992, 1994, 1997). In this case, producers are represented as optimising over effective rather than actual netput prices and quantities.

Given that the choices regarding functional form and the variables to be included in the analysis have been made, then in the simplified illustrative example, a normalised quadratic restricted profit specification characterising Australian wool production can be written as follows:

$$\bar{\pi} = \alpha_0 + \sum_{i=1}^4 \alpha_i P_i^e + \sum_{i=6}^8 \beta_i Z_i + 0.5 \sum_{i=1}^4 \sum_{j=1}^4 \alpha_{ij} P_i^e P_j^e + 0.5 \sum_{i=6}^8 \sum_{j=6}^8 \beta_{ij} Z_i Z_j + \sum_{i=1}^4 \sum_{j=6}^8 \chi_{ij} P_i^e Z_j \quad (1)$$

where $\bar{\pi}$ is profit divided by the effective price of materials and services (the numeraire good) P_s^e (i.e., normalised profit); P_i^e is the normalised effective price of the i -th netput (which is positive for outputs, wool = 1, livestock outputs = 2 and crops

= 3, and negative for the variable input, labour = 4) and z_i is the i -th non-price exogenous variable (livestock = 6, capital = 7 and the time trend = 8). In this case, the restricted profit function corresponds to a one-year period, which is long enough for producers to at least partially adjust their composition of outputs and variable inputs but not long enough for adjustments to be made to quasi-fixed inputs such as livestock and capital. In other words, a short-run profit function is specified.

If the normalised quadratic restricted profit function depicted in equation (1) is twice continuously differentiable with respect to normalised netput prices, then applying Hotelling's lemma gives the system of short-run non-numeraire netput supply equations. These netput supply equations (2a) are linear in the normalised prices of the netputs and in the non-price exogenous variables:

$$X_i^e = \alpha_i + \sum_{j=1}^4 \alpha_{ij} P_j^e + \sum_{j=6}^8 \chi_{ij} Z_j \quad i = 1, \dots, 4. \quad (2a)$$

where X_i^e is the effective quantity of the netput (which is positive for outputs and negative for inputs) and all other variables are as previously defined.

The short-run numeraire netput supply equation (X_5^e) can also be derived as the first derivative of the normalised quadratic profit function with respect to the numeraire price, or it can be obtained residually (Huffman and Evenson 1989). Given that $X_5^e = \bar{\pi} - \sum_{i=1}^4 P_i^e X_i^e$, and substituting equation (1) for $\bar{\pi}$ and equation (2a) for X_i^e the numeraire netput supply equation is:

$$X_5^e = \alpha_0 + \sum_{i=6}^8 \beta_i z_i - 0.5 \sum_{i=1}^4 \sum_{j=1}^4 \alpha_{ij} P_i^e P_j^e + 0.5 \sum_{i=6}^8 \sum_{j=6}^8 \beta_{ij} z_i z_j \quad i = 1, \dots, 4. \quad (2b)$$

where all the variables are as previously defined. As shown in equation (2b), the short-run numeraire netput supply equation is quadratic in prices and non-price exogenous variables (Shumway, Jegasothy and Alexander 1987). In addition, the numeraire equation does not include any interaction terms between price and non-price exogenous variables (Martin and Alston 1994).

The system of estimating equations would normally comprise either equations (1) and (2a) or equations (2a) and (2b) with a random error disturbance attached. The chosen system of estimating equations for the simplified illustrative model is the profit function (1) and the four netput supply equations (2a).

Specification of technology in the profit function as output augmenting does not alter any of the parameters in the model. Hence, this specification is consistent with the theoretical requirements of the profit function. Assuming profit maximisation, the estimated normalised quadratic profit function is expected to be symmetric, linearly homogeneous, convex in netput prices and monotonically increasing (decreasing) in variable output (input) prices.

The normalised quadratic profit function is assumed twice continuously differentiable. Therefore, given that the netput supply equations are the first derivatives, the slopes of

these equations are the second derivatives. Because the second partial derivatives of the normalised quadratic profit function are invariant to the order of differentiation, the netput supply equations (2a) and (2b) are symmetric in normalised prices. Without any loss of generality, symmetry is imposed by $\alpha_{ij} = \alpha_{ji}$ for $i \neq j$.

For the normalised quadratic profit function and the derived netput supply functions, homogeneity in prices is maintained and, hence, cannot be tested (Wall and Fisher 1987, p.73). Linear homogeneity of degree one in prices requires that:

$$\sum_{i=1}^4 \alpha_i = 1, \quad \sum_{j=1}^4 \alpha_{ij} = 0, \quad i, j = 1, \dots, 4 \quad (3)$$

For the normalised quadratic profit function (as for all flexible functional forms) the properties of monotonicity and convexity do not necessarily hold and need to be tested after the profit function has been estimated. The normalised quadratic profit function satisfies the monotonicity condition if the estimated values of netput supply are positive (Wall and Fisher 1987, p.74). Convexity of a static profit function requires that the own-price elasticities of the output-supply functions are positive and that the own-price elasticities of the input-demand functions are negative. The cross-price elasticities can be positive, negative or zero (Huffman and Evenson 1989).

3.4 Estimation method

To estimate the parameters of the profit function, a stochastic structure is assumed for the system of five equations (1) and (2a) with random error disturbance terms added to each equation in the system. It is assumed that any deviation in netput supplies from their profit maximising levels is due to random weather conditions or is caused by random errors in optimisation. Furthermore, it is assumed that the disturbance terms are normally distributed with zero means, have constant variances and are uncorrelated.

The coefficients of the equations are estimated by normalising on the index price for material and services, setting the technology index, τ_i^e , to unity (so effective prices equal actual prices) and using the simultaneous regression estimator, 2SLS, in the SHAZAM (version 8.0) econometric package.

In the initial simplified model, not all the own-price elasticities had the expected signs and, therefore, the model did not satisfy curvature conditions. To overcome this problem, it was decided to impose convexity onto the model globally to ensure that the estimated profit function is convex in prices and concave in fixed inputs.

Convexity in prices implies that the matrix of parameters, $A = [\alpha_{ij}]$, is positive semi-definite, while concavity in fixed outputs implies that the matrix of the B parameters, $B = [\beta_{ij}]$, is negative semi-definite. These definite properties can be imposed (e.g., Diewert and Wales 1987; Featherstone and Moss 1994; Coelli 1996). Specifically, to ensure A is positive semi-definite and B is negative semi-definite, the following procedure is undertaken:

$$\begin{aligned}
A &= \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & \alpha_{14} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} \end{bmatrix} \\
&= \begin{bmatrix} h_{11} & 0 & 0 & 0 \\ h_{21} & h_{22} & 0 & 0 \\ h_{31} & h_{32} & h_{33} & 0 \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} h_{11} & h_{21} & h_{31} & h_{41} \\ 0 & h_{22} & h_{32} & h_{42} \\ 0 & 0 & h_{33} & h_{43} \\ 0 & 0 & 0 & h_{44} \end{bmatrix} \\
&= \begin{bmatrix} h_{11}^2 & h_{11}h_{21} & h_{11}h_{31} & h_{11}h_{41} \\ \cdot & h_{21}^2 + h_{22}^2 & h_{21}h_{31} + h_{22}h_{32} & h_{21}h_{41} + h_{22}h_{42} \\ \cdot & \cdot & h_{31}^2 + h_{32}^2 + h_{33}^2 & h_{31}h_{41} + h_{32}h_{42} + h_{33}h_{43} \\ \cdot & \cdot & \cdot & h_{41}^2 + h_{42}^2 + h_{43}^2 + h_{44}^2 \end{bmatrix}, \tag{4}
\end{aligned}$$

$$\begin{aligned}
B &= \begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix} \\
&= \begin{bmatrix} -j_{11}^2 & -j_{11}j_{21} \\ \cdot & -j_{21}^2 - j_{22}^2 \end{bmatrix}, \tag{5}
\end{aligned}$$

and then, after all the cross-equation restrictions have been imposed, the model is estimated in terms of the h_{ij} and j_{ij} parameters.

3.5 Estimated Parameters and Elasticities

The coefficients, standard errors and T-ratios estimated from the normalised quadratic model, after curvature had been imposed, are given in Table 4. In this model, symmetry and homogeneity were maintained. Almost two thirds of the estimated parameters are significant at the 10 per cent level.

For the system of equations (1) to (2b), the own- and cross-price elasticities for the non-numeraire netputs (η_{ij}), the own-price elasticity for the numeraire netput (η_{55}), the cross-price elasticities for the numeraire netput with respect to the non-numeraire netputs (η_{5j}) and the cross-price elasticity for the non-numeraire netputs with respect to the numeraire netput (η_{i5}) can be measured as follows (Huffman and Evenson 1989):

$$\eta_{ij} = \alpha_{ij} \frac{P_i^e}{X_j^e} \quad i, j = 1, \dots, 4, \tag{6a}$$

$$\eta_{55} = -\frac{1}{X_5^e} \sum_{i=1}^4 \sum_{j=1}^4 \alpha_{ij} P_i^e P_j^e \quad i, j = 1, \dots, 4, \quad (6b)$$

$$\eta_{5j} = -(P_j^e / X_5^e) \sum_{i=1}^4 \alpha_{ij} P_i^e \quad i, j = 1, \dots, 4, \quad (6c)$$

$$\eta_{i5} = -\frac{1}{X_i^e} \sum_{j=1}^4 \alpha_{ij} P_j^e \quad i, j = 1, \dots, 4, \quad (6d)$$

The short-run own- and cross-price elasticities were calculated at the mean data values and are presented in Table 5. The own-price elasticities for the five netputs all have the expected signs and they are all inelastic. The signs of the cross-price elasticities for the three outputs indicate that wool and crops, and livestock and crops, are substitutes but that wool and livestock are complements. The signs of the cross-price elasticities for the two inputs, labour and materials and services, indicate that they are substitutes.

Table 4: Estimated coefficients

	Coefficients	Standard Errors	T-ratios
α_0	-0.555	61.032	-0.009
α_1	-7.345	26.168	-0.281
α_2	21.609	19.340	1.117
α_3	41.244	44.667	0.923
α_4	-147.960	19.360	-7.643
β_6	-18.910	7.117	-2.657
β_7	-1.064	0.428	-2.487
β_8	8.103	5.866	1.381
α_{11}	5.104	5.486	0.930
α_{12}	12.649	7.605	1.663
α_{13}	-11.846	7.997	-1.481
α_{14}	5.805	4.565	1.272
α_{22}	40.749	14.074	2.895
α_{23}	-27.153	15.802	-1.718
α_{24}	-11.836	7.543	-1.569
α_{33}	28.016	20.050	1.397
α_{34}	-19.632	10.107	-1.942
α_{44}	79.759	20.565	3.878
β_{77}	-0.750	0.892	-0.840
β_{78}	0.029	0.040	0.733
β_{79}	0.458	0.385	1.191
β_{88}	-0.001	0.003	-0.433
β_{89}	-0.001	0.026	-0.052
β_{99}	-0.089	0.380	-0.235
χ_{17}	39.133	2.491	15.710
χ_{18}	-0.053	0.143	-0.371
χ_{19}	1.635	1.182	1.383
χ_{27}	22.073	1.089	20.262
χ_{28}	-0.143	0.072	-1.995
χ_{29}	4.218	0.660	6.390
χ_{37}	-23.535	4.001	-5.883

χ_{38}	2.625	0.256	10.260
χ_{39}	-9.847	4.303	-2.288
χ_{47}	-12.751	0.961	-13.270
χ_{48}	-0.134	0.057	-2.323
χ_{49}	0.959	0.491	1.952

The relationships between the outputs, crops and livestock, and the variable input, labour, also have the expected signs. For example, an increase in the cost of labour results in a reduction in the quantity of livestock and crops produced. Alternatively, an increase in the price of livestock or crops will not only lead to an increase in its own production but also to an increase in labour usage. In contrast, the relationship between wool and labour is not as one may expect. In this case, an increase in the price of labour results in an increase in wool production while an increase in the price of wool results in a reduction in labour usage. A possible explanation for this seemingly perverse relationship is as follows. If crop production is more labour intensive than wool production, an increase in the cost of labour will result in a decrease in the production of crops, which will, in turn, result in an increase in the production of wool. Conversely, an increase in the price of wool will result in a decrease in the production of crops, which will, in turn, result in a reduction in labour usage.

Table 5: Estimated short-run elasticities for wool, livestock, crops, labour and materials and services

	Wool	Livestock	Crops	Labour	Materials and services
Wool	0.016	0.042	-0.033	0.019	-0.044
Livestock	0.055	0.181	-0.102	-0.052	-0.082
Crops	-0.049	-0.116	0.101	-0.083	0.147
Labour	-0.027	0.057	0.080	-0.379	0.270
Materials and services	0.046	0.065	-0.103	0.195	-0.204

The relationships between the outputs, wool and livestock, and the numeraire input, materials and services, are also as expected. An increase in the price of either wool or livestock will result in an increase in the quantity of materials and services used while an increase in the price of materials and services will result in a decrease in the production of wool and livestock. However, this is not the case with the relationship between crops and materials and services. Here, an increase in the cost of materials and services results in an increase in crop production and, conversely, an increase in the price of crops results in a decrease in material and services usage. Again, this seemingly perverse relationship may be because all the cross-commodity effects are allowed for in this model. In this case, if wool and livestock production are more materials and services intensive than crop production, an increase in the cost of materials and services will lead to a decrease in wool and livestock production which will lead to an increase in crop production. Conversely, an increase in the price of crops will lead to a reduction in the wool and livestock production and, hence, materials and services usage.

A summary of the own-price elasticity estimates from this study and from a number of other duality-based studies on supply response in Australian agriculture is given in

Table 6. In general, the own-price elasticities estimated here are lower than the elasticities given in a number of other studies. These differences in the estimated elasticities could be due of a host of factors such as differences in (a) the chosen functional form of the estimating equations, (b) the agricultural region, (c) the time period or (d) the specification of outputs and inputs. For example, in the Wall and Fisher (1987) study, pooled time-series and cross-sectional data for the years 1967-68 to 1980-82 was used to estimate profit function models for the three major agricultural zones in Australia (i.e., the pastoral zone, the wheat/sheep zone and the high rainfall zone). The three functional forms chosen by Wall and Fisher (1987) were the normalised quadratic, the translog and the generalised Leontief. Outputs included wool, total sheep, total cattle and wheat, except in the high rainfall zone where wheat is not grown. The variable inputs were labour and materials and services, while sheep, cattle, capital and land were specified as fixed inputs. In contrast, Coelli (1996) estimated a generalised McFadden profit function using farm survey data for the Western Australian wheat/sheep zone for the years 1952-53 to 1987-88. The outputs were crops (wheat, barley and oats), sheep products (wool and sheep sales) and other (other crops and cattle) and all the inputs (livestock, materials and services, labour, capital and land) were specified as variable.

4 The Demand Characteristics for Wool

In the small country case, with all commodities tradeable and homogenous across countries, the price of the commodities are determined exogenously and the profit function provides a complete measure of the economic impact of a proposed change in research expenditure for the industry in question. However, in the large country case (or in the case of non-traded goods), prices are endogenously determined on the world (domestic) market.

A common approach to determine technology-induced price changes is to start with a set of partial equilibrium output supply *and* output demand equations and to use the relevant market clearing equations to solve for the price and quantity changes associated with a given technical change. As a second step, the induced price and quantity changes are used to evaluate the technology effects on the welfare of producers and consumers.

As Australia is a large-country trader in wool, the adoption of an output-augmenting technology in the Australian wool industry will effect the world price for wool. In turn, the induced price change will affect wool producer and consumer welfare and so the price change needs to be estimated. As stated earlier, if supply and demand curves are not theoretically consistent then the welfare evaluations will be ambiguous. However, as the majority of Australian wool consumers reside overseas, the focus of this study is on the technology-induced change to Australian wool producer welfare. The change in consumer welfare is not considered. Therefore, it is not necessary to fully specify a theoretically consistent demand curve; all that is required is enough information that will, when combined with information on the supply of wool and on the market clearing conditions, enable the research-induced change in price to be calculated. In short, knowledge of the own-price total elasticity of the demand for Australian wool by the Rest-of-world and the equilibrium price and quantity of wool is sufficient 'demand-side' information.

5 Evaluating the Welfare Impact

5.1 Impact on the World Price of Wool

When some or all of the prices in equation (1) are endogenous, the first step to research evaluation is to calculate the research-induced change in the price of the endogenous variable. In the simplified model, it is assumed that the only endogenous price is the price of wool. In this case, knowledge of (a) the base equilibrium price and quantity values for wool, (b) the output supply equation for wool, (c) the total elasticity of demand for Australian wool by the Rest-of-world and (d) the technology variable is sufficient to solve for the induced price change.

The base (that is, the ‘without-technology’) values for the actual normalised price indexes (hereafter, simply referred to as actual prices) and the actual predicted quantities (hereafter, simply referred to as actual quantities) for each of the netputs, the technology index, τ_i^e , and the total elasticity of demand are presented in Table 7. While the technology index is set to unity in the base period, in the simplified model, the development and adoption of the output-augmenting technology in the wool industry is represented by a 10 per cent increase in the technology index from 1 to 1.1. Consequently, there is a 10 per cent technology-induced increase in Australian wool supply measured at the initial equilibrium quantity. Assuming that in the short-run, the elasticity of demand for Australian wool by the Rest-of-World is -0.5 (Connolly 1992; authors judgement), the 10 percent increase in the supply of Australian wool results in a 19.6 per cent decrease in the normalised price (index) for wool from 0.88 c/kg to 0.71 c/kg. This change in the actual price of wool, together with the specified change in the technology index, is used to estimate the research-induced change in wool producer profits.

5.2 Impact on Australian Wool Producer Profits

Base and new values for the actual and effective prices and quantities for the four netputs are presented in Table 7. The base and new values for the normalised prices are used to estimate the profit levels corresponding to the ‘with- and without-technology’ scenarios. In this simplified model, the base values for the actual normalised price indexes for each of the non-numeraire netputs are the average normalised price indexes for the 21 years ending 1997/98. Similarly, the base values for the non-price exogenous variables are the average values for the same 21-year period.

To calculate the technology-induced change in wool producer profits, the base (‘without-technology’) and new (‘with-technology’) profit solutions need to be obtained. Following from equation (1), the base profit, π^{-0} , is:

$$\begin{aligned} \bar{\pi}^0 = & \alpha_0 + \sum_{i=1}^4 \alpha_i P_i^{e0} + \sum_{i=6}^8 \beta_i z_i^0 + 0.5 \sum_{i=1}^4 \sum_{j=1}^4 \alpha_{ij} P_i^{e0} P_j^{e0} \\ & + 0.5 \sum_{i=6}^8 \sum_{j=6}^8 \beta_{ij} z_i^0 z_j^0 + \sum_{i=1}^4 \sum_{j=6}^8 \chi_{ij} P_i^{e0} z_j^0 \end{aligned} \quad (7a)$$

where P_i^{e0} is the base effective normalised price of the i -th netput and z_i^0 is the base value for the i -th non-exogenous variable. The relationship between the base effective price (P_i^{e0}) and base actual price (P_i^0) for the i -th netput is $P_i^{e0} = P_i^0 * \tau_i^{e0}$, where τ_i^{e0} is the base technology index. Therefore, given that the base technology index is set to unity, the base actual and effective prices are equal.

The new profit, $\bar{\pi}^1$, is given by:

$$\begin{aligned} \bar{\pi}^1 = & \alpha_0 + \sum_{i=1}^4 \alpha_i P_i^{e1} + \sum_{i=6}^8 \beta_i z_i^0 + 0.5 \sum_{i=1}^4 \sum_{j=1}^4 \alpha_{ij} P_i^{e1} P_j^{e1} \\ & + 0.5 \sum_{i=6}^8 \sum_{j=6}^8 \beta_{ij} z_i^0 z_j^0 + \sum_{i=1}^4 \sum_{j=6}^8 \chi_{ij} P_i^{e1} z_j^0 \end{aligned} \quad (7b)$$

where P_i^{e1} is the new effective normalised price of the i -th netput and the relationship between the new effective price (P_i^{e1}) and new actual price (P_i^1) for the i -th netput is $P_i^{e1} = P_i^1 * \tau_i^{e1}$, where τ_i^{e1} is the new technology index. In the simplified illustration, only the technology index for wool is assumed to change (by 10 per cent to 1.1); the technology indexes for the other netputs are not altered. Therefore, the new actual and effective prices for wool vary from their original base values and they are no longer equal. In contrast, the new actual and effective prices for the other netputs are not affected by the technology and, therefore, the 'new' effective and actual prices for livestock, crops and labour are equal to their respective base actual and effective prices (see Table 7).

Equations (7a) and (7b) can be readily solved given that the base values for the exogenously determined netput prices and the technology variable are known, the value of the coefficients have been estimated (section 3.6), the research-induced change in the price of the endogenous variable (in this case the price of wool) has been calculated and the value of the new technology index has been determined. The effect of the wool technology on producer profits, $\Delta\bar{\pi}$, is the difference between equations (7b) and (7a):

$$\Delta\bar{\pi} = \bar{\pi}^1 - \bar{\pi}^0. \quad (8)$$

In addition to being able to calculate the base and new values for actual and effective prices and for producer profits, it is also possible to estimate the base and new values for actual and effective quantities for the non-numeraire netputs.

Following from equation (2a), the base effective quantity for the i -th netput, X_i^{e0} , is:

$$X_i^{e0} = \alpha_i + \sum_{j=1}^4 \alpha_{ij} P_j^{e0} + \sum_{j=6}^8 \chi_{ij} Z_j^0. \quad i = 1, \dots, 4 \quad (9a)$$

Given that the relationship between the base actual quantity (X_i^0) and base effective quantity (X_i^{e0}) for the i -th netput is $X_i^0 = X_i^{e0} * \tau_i^{e0}$ and substituting the definitions of X_i^{e0} and P_j^{e0} into equation (9a), the base actual quantity for the i -th netput is:

$$X_i^0 = \tau_i^{e0} (\alpha_i + \sum_{j=1}^4 \alpha_{ij} (P_j^0 \tau_j^{e0}) + \sum_{j=6}^8 \chi_{ij} Z_j^0). \quad i = 1, \dots, 4 \quad (9b)$$

Similarly, the new effective quantity for the i -th netput, X_i^{e1} , is:

$$X_i^{e1} = \alpha_i + \sum_{j=1}^4 \alpha_{ij} P_j^{e1} + \sum_{j=6}^8 \chi_{ij} Z_j^0 \quad i = 1, \dots, 4 \quad (9c)$$

and, given that the relationship between the new actual quantity (X_i^1) and new effective quantity (X_i^{e1}) for the i -th netput is $X_i^1 = X_i^{e1} * \tau_i^{e1}$, substituting the definitions of X_i^{e1} and P_j^{e1} into equation (9c) gives the new actual quantity for the i -th netput:

$$X_i^1 = \tau_i^{e1} (\alpha_i + \sum_{j=1}^4 \alpha_{ij} (P_j^1 \tau_j^{e1}) + \sum_{j=6}^8 \chi_{ij} Z_j^0). \quad i = 1, \dots, 4 \quad (9d)$$

As evident from equation (9d), output-augmenting technical change involves two proportional shifts in the netput supply equation: one in the price direction (from the multiplication of some or all of the prices by the technology index), and one in the quantity direction (from the multiplication of the whole term in the parenthesis by τ_i^e). Hence, unless the supply curve passes through the origin, the intersection of the supply curve with the price axis, as well as its slope, will be affected (Martin and Alston 1997).

The base value data and the solutions to equations (7a), (7b), (9a), (9b), and (9d) are presented in Table 7. Because the prices of the netputs are normalised indexed prices, and the netput quantities and normalised profit are calculated using these prices and the imputed quantity indexes for the quasi-fixed inputs, it is the percentage change in the values, rather than the values themselves, that are of interest. The technology-induced percentage changes for the technology index, the actual and effective prices, the actual quantities and profit are given in the last column of the table.

A 10 per cent increase in the technology index results in an 19.6 per cent change in the actual price for wool from 0.88 to 0.71. The corresponding new effective wool price is 0.78, which is 11.5 percent below the base effective price. In this case, the 10 per cent wool output-augmenting technical change yields a less than 10 per cent (9.8 per cent) increase in the actual quantity of wool produced, with the difference depending on the elasticities of supply and demand. The cross-commodity relationships between the each of the outputs, wool, livestock and crops, and between the outputs and the input,

labour, are allowed for in the model. A fall in the effective price of wool results in a 0.6 per cent fall in the actual quantity of livestock produced, a 0.3 per cent increase in actual labour usage and a 1.3 per cent increase in actual crop production. Overall, because of the technology-induced fall in the price of wool, in the short-run, wool producer profit falls by 17.1 per cent.

Table 7: Effect of technical change on producer profit

	Base values	New values	Actual change	Percentage change
Technology variable				
Wool	1.00	1.10	0.10	10.00
Total demand elasticity				
Wool	-0.5	na	na	na
Actual normalised prices				
Wool	0.88	0.71	-0.17	-19.56
Livestock	0.91	0.91	0.00	0.00
Crops	0.76	0.76	0.00	0.00
Labour	0.89	0.89	0.00	0.00
Effective normalised prices				
Wool	0.88	0.78	-0.10	-11.51
Livestock	0.91	0.91	0.00	0.000
Crops	0.76	0.76	0.00	0.000
Labour	0.89	0.89	0.00	0.000
Actual predicted quantities				
Wool	257.88	283.10	25.22	9.78
Livestock	202.97	201.68	-1.29	-0.63
Crops	89.86	91.07	1.20	1.34
Labour	-182.54	-183.13	0.59	0.32
Profit	152.94	126.77	-26.17	-17.11

6 Summary and Conclusions

In this paper, a simplified, illustrative model was used to show how the dual approach could be used to model the economic impact of *ex ante* research in a multiple-input, multiple-output industry. The simplified model was based on a number of fundamental characteristics of the Australian wool industry and output-augmenting technical change. A normalised quadratic restricted profit function of Australian wool production was specified in terms of effective rather than actual prices. The profit and netput supply functions were fitted to ABARE and NSW Agriculture data and estimated using the simultaneous regression estimator, 2SLS, to allow for the endogenous determination of the technology-induced change in the world price for wool. The welfare effects of the illustrative technical change on Australian wool producers were then evaluated. The results of the illustrative example show that, in the short-run, the development and full adoption of a 10 per cent yield-increasing wool technology by the Australian wool industry would result in a 19.6 per cent fall in the actual price of wool and a 9.8 per cent

increase in the actual quantity of wool produced. The cross-commodity effects of the technology are also allowed for in the model, with actual livestock production falling by 0.6 per cent, and actual labour usage increasing by 0.3 percent and actual crop production increasing by 1.3 per cent. Overall, in the short-run, the introduction of the specified wool yield-increasing technology results in a 17.1 per cent decrease in wool producer profits.

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Table 6: Summary of estimated own-price elasticities

Study	Time period	Functional form	Region	Outputs						Variable Inputs			
				Wool	Livestock		Crops	Labour	M & S	Live-stock	Capital	Land	
					Total	Cattle							Sheep
This study	1977/78-1997/98	Normalised Quadratic	Australia ^a	0.02	0.18			0.10	-0.38	-0.20			
McKay Lawrence & Vlastuin 1983	1952/53-1976/77	Translog	Wheat/sheep zone	0.72 ^b		0.12 ^c		0.12 ^d	-0.47		-0.10		
Lawrence & Zeitsch 1989	1972/73-1986/87	Generalised McFadden	Australia ^e		0.19			0.20	-0.78 ^f	-0.33	-0.33	-0.83	-0.03
Low & Hinchy 1990	1978 to 1987	Generalised McFadden	Australia ^a	0.94 ^g		0.161 ^h		0.262 ^{ij}					
Wall & Fisher 1987	1967/68 - 1980/81	Normalised quadratic	Pastoral zone	0.10		0.43	0.39	2.67 ^j				Σ	
			Wheat/sheep zone	0.04		0.11	0.36	0.72 ^k	0.62 ^j				
			High rainfall zone	0.04		0.14	0.28	0.76 ^k					

Table 6: Summary of estimated own-price elasticities (continued)

Study	Time period	Functional form	Region	Outputs				Variable Inputs					
				Wool	Livestock		Crops	Labour	M & S	Live-stock	Capital	Land	
					Total	Cattle	Sheep						
Wall & Fisher 1987	1967/68 - 1980/81	Translog	Pastoral zone	0.26		0.27	0.46	1.66 ^j			-0.64		
			Wheat/sheep zone	0.19		0.22	0.49	0.47 ^j			-0.10		
			High rainfall zone	0.19		0.116	0.46						
Wall & Fisher 1987	1967/68 - 1980/81	Generalised Leontief	Pastoral zone	0.16		0.35	0.42	1.42 ^j 0.85 ^k	-0.33	-0.33	-0.83	-0.03	
			Wheat/sheep zone	0.10		0.11	0.22	0.75 ^j 1.51 ^k					
			High rainfall zone	0.05		0.12	0.30						
Coelli 1996	1952/53-1987/88	Generalised McFadden	WA Wheat/sheep zone	0.04 ^b	0.03 ^l			0.49 ^m	-0.32	-0.24	-0.17	-0.20	-0.521

a Five mainland states; b Wool and sheep; c Cattle and other livestock; d Wheat and other crops; e Six states; f Hired labour; g Wool price lagged two years; h Cattle price lagged three years; i Wheat only; j Wheat price lagged one year; k Other crops; l Cattle and other crops; m Wheat, barley and oats.