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Abstract

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 an input-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% labour-reducing technology results in a 10% fall in the 'effective' price paid for labour and a 6.3% decrease in the actual quantity of labour used. The cross-commodity effects of the technology are also allowed for in the model, with wool production falling by 0.07%, livestock production increasing by 0.7% and actual crop production increasing by 1.4%. Overall, in the short-run, the introduction of the specified wool labour-reducing technology results in a 10.6% increase 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 et al. 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 (Thurman 1991).

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), 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 et al. (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 that is characterised by multiple interrelationships between the commodities. With this in mind, the profit function is the chosen dual formulation, primarily because it provides a direct estimate of producer welfare. As far as the authors are aware, there are no other empirical examples of this method in the literature.

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% of Australian wool is exported each year. Around 84% is sold as greasy raw wool while the remaining 16% is sold as semi- (rather than fully-) processed wool (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 live overseas.

Third, purely for illustrative purposes, the technical change assessed in the simple model is assumed to be labour saving.

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 interrelationships should be accounted for in the model (Just et al. 1982; Just 1993). Developing a model that consists of netput[1] 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 interrelationships between the netputs 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,

1. A netput is either an output or a variable input, where the variable input is entered as a negative value.

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 the choice of a specific functional form of the indirect objective function. 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 that not too many a priori assumptions need to be imposed and being simple enough that the estimating equations are tractable.

The normalised quadratic is selected for this study 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 during 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 a two-stage least squares (2SLS) simultaneous equation estimator 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 this 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
Price/quantity	*Outputs*
P_1 / X_1	Wool
P_2 / X_2	Livestock outputs
P_3 / X_3	All crops
Price/quantity	*Variable inputs*
P_4 / X_4	Labour
P_5 / X_5	Materials and services
Quantity	*Non-price exogenous variables*
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 in the Australian wool industry in addition to the specific input-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 several 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 multi-product 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. Several procedures are covered in the literature. Diewert is quoted (in Mullen and Cox 1996, p. 190) as pointing 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'. 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) (available from ABARE) 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.

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.

Table 2. Components of commodity groups

Variables
Outputs
Livestock outputs
• Sheep sales plus positive operating gains
• Lamb sales
• Cattle sales plus positive operating gains
Crops
• Wheat
• Barley
• Oats
• Sorghum
• Oilseeds
• Other
Variable inputs
Labour
• Operator and family
• Hired labour and contracts
• Shearing costs
• Stores and rations
Materials and services
• Crop chemicals
• Fertiliser
• Fodder
• Fuel
• Livestock materials
• Motor vehicle sundry
• Seed
• Other materials
• Administration
• Contracts
• Insurance
• Miscellaneous livestock items
• Rates and taxes
• Total repairs
• Other services
Non-price exogenous variables
Livestock inputs
• 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
• Land
• Buildings and other farm improvement (structures)
• Machinery and vehicles (plant)

In the simplified empirical illustration presented here, there are several instrumental variables that affect the demand for wool. They are specified in the reduced-form equation, in addition to the exogenous netput prices, and 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 include all farms with more than 200 sheep on a State and zone basis for the 21 years ending 1997/98. The States comprise New South Wales, Queensland, Victoria, Western Australia and South Australia, and the zones are the pastoral zone, the high rainfall zone and the wheat/sheep zone. Data for all three zones are available for New South Wales and South Australia but not for the Western Australia pastoral zone or the Queensland 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 is 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 New South Wales Agriculture.

3.3 Estimating Equations

In this model, the technical change is specified as input augmenting. An important aspect of this specification is that a distinction is made between actual and effective input 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 that produces the output being studied, for example, hours (of labour) per sheep ($(cost) per 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 input-augmenting technology. Under this definition, when X_i is an input, input-augmenting technology is represented by a decrease in τ_i^e, which lowers the actual quantity associated with any given effective quantity, for example, less labour per sheep. Further, a technology-induced change in the actual quantity of the input results in a corresponding change in the effective price of that input (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 input, input-augmenting technology lowers the effective price relative to the actual price, for example, less dollars (reduced cost) 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 in equation (1) (see next page), in which $\bar{\pi}$ is profit divided by the effective price of materials and services (the numeraire good) P_5^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. In equation (2a), 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

$$X_5^e = \overline{\pi} + \sum_{i=1}^{4} P_i^e X_i^e$$

and substituting equation (1) for $\overline{\pi}$ and equation (2a) for X_i^e the numeraire netput supply equation is equation (2b), in which 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 et al. 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 empirical model is the profit function (1) and the four netput supply equations (2a).

Specification of technology in the profit function as input 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 the condition described by equation (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

Equations 1–3

$$\overline{\pi} = \alpha_0 + \sum_{i=1}^{4} \alpha_i P_i^e + \sum_{i=6}^{8} \beta_i z_i + 0.5 \sum_{i=1}^{4}\sum_{j=1}^{4} \alpha_{ij} P_i^e P_j^e + 0.5 \sum_{i=6}^{8}\sum_{j=6}^{8} \beta_{ij} z_i z_j + \sum_{i=1}^{4}\sum_{j=6}^{8} \chi_{ij} P_i^e z_j \qquad (1)$$

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

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

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

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 the model therefore did not satisfy curvature conditions. To overcome this problem, global convexity was imposed 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 inputs 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 procedure shown in equations (4) and (5) is undertaken.

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% level.

For the system of equations (1) to (2b), the own- and cross-price elasticities for the non-numeraire netputs (ε_{ij}), the own-price elasticity for the numeraire netput (ε_{55}), the cross-price elasticities for the numeraire netput with respect to the non-numeraire netputs (ε_{5j}) and the cross-price elasticity for the non-numeraire netputs with respect to the numeraire netput (ε_{i5}) can be specified as shown in equations (6a–d) (Huffman and Evenson 1989).

Equations 4–5

$$A = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & \alpha_{14} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} \end{bmatrix}$$

$$= \begin{bmatrix} h_{11} & 0 & 0 & 0 \\ h_{21} & h_{22} & 0 & 0 \\ h_{31} & h_{32} & h_{33} & 0 \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} h_{11} & h_{21} & h_{31} & h_{41} \\ 0 & h_{22} & h_{32} & h_{42} \\ 0 & 0 & h_{33} & h_{43} \\ 0 & 0 & 0 & h_{44} \end{bmatrix} \quad (4)$$

$$= \begin{bmatrix} h_{11}^2 & h_{11}h_{21} & h_{11}h_{31} & h_{11}h_{41} \\ . & h_{21}^2 + h_{22}^2 & h_{21}h_{31} + h_{22}h_{32} & h_{21}h_{41} + h_{22}h_{42} \\ . & . & h_{31}^2 + h_{32}^2 + h_{33}^2 & h_{31}h_{41} + h_{32}h_{42} + h_{33}h_{43} \\ . & . & . & h_{41}^2 + h_{42}^2 + h_{43}^2 + h_{44}^2 \end{bmatrix}$$

$$B = \begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix}$$

$$= \begin{bmatrix} -j_{11}^2 & -j_{11}j_{21} \\ . & -j_{21}^2 - j_{22}^2 \end{bmatrix} \quad (5)$$

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 all are inelastic. The signs of the cross-price elasticities for the three outputs indicate that wool, livestock and crops are complements. The positive cross-price elasticities for wool with respect to livestock and for livestock with respect to wool are significant and counter-intuitive. One possible explanation for the complementarity between wool and livestock is that, in the short run, an increase in the price of wool would lead to an increase in the quantity of livestock (fat lambs and cattle) sold as farmers move out of livestock production and into wool production. Conversely, an increase in the price of livestock would lead not only to an increase in livestock production but also to an increase in wool production because wool and sheep-meat are joint products. The cross-price elasticities for wool (livestock) with respect to crops and for crops with respect to wool (livestock) crops are also counter-intuitive, although insignificant.

The relationships between the outputs, crops and livestock, and the variable input, labour, 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 lead not only 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 might 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. This counter-intuitive result can also be found in the agricultural supply studies undertaken by Coelli (1996) and Agbola (1999). A possible explanation for this relationship is as follows: if crop production is more labour intensive than wool production, then a decrease in the cost of labour will result in an increase in the production of crops at the expense of wool production. Conversely, an increase in the cost of labour will result in a fall in crop production resulting in a increase in the quantity of wool produced.

The relationships between the outputs, wool, livestock and crops and the numeraire input, materials and services, are as expected. An increase in the price of any of the outputs 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, livestock and crops. Finally, the cross-price elasticities for the two inputs, labour and materials and services, indicate that these two inputs are complements.

Table 4. Estimated coefficients

	Coefficients	Standard errors	t-ratios
α_0	89.245	65.639	1.360
α_1	–34.745	30.615	–1.135
α_2	10.998	23.363	0.471
α_3	–104.950	83.565	–1.256
α_4	–125.100	22.289	–5.613
β_6	–13.514	6.961	–1.941
β_7	–0.990	0.373	–2.656
β_8	–10.664	6.055	–1.761
α_{11}	9.699	8.133	1.193
α_{12}	13.103	6.696	1.957
α_{13}	6.266	15.865	0.395
α_{14}	2.235	5.253	0.426
α_{22}	24.239	13.659	1.775
α_{23}	10.751	23.259	0.462
α_{24}	–15.214	6.720	–2.264
α_{33}	27.722	80.221	0.346
α_{34}	–31.758	12.747	–2.491
α_{44}	82.831	20.666	4.008
β_{66}	–0.899	0.849	–1.059
β_{67}	0.030	0.039	0.769
β_{68}	0.281	0.357	0.786
β_{77}	–0.001	0.002	–0.432
β_{78}	–0.014	0.024	–0.602
β_{88}	0.684	0.402	1.703
χ_{16}	37.803	2.473	15.284
χ_{17}	–0.062	0.139	–0.442
χ_{18}	3.442	1.294	2.660
χ_{26}	22.227	1.089	20.414
χ_{27}	–0.163	0.071	–2.309
χ_{28}	4.284	0.779	5.498
χ_{36}	–30.036	4.105	–7.318
χ_{37}	2.624	0.248	10.567
χ_{38}	13.920	2.790	4.989
χ_{46}	–11.994	0.970	–12.369
χ_{47}	–0.128	0.058	–2.221
χ_{48}	–0.381	0.587	–0.648

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

	Wool (P1)	Livestock (P2)	Crops (P3)	Labour (P4)	Materials and services (P5)
Wool (X1)	**0.031**	0.043	0.017	0.007	–0.099
Livestock (X2)	0.057	**0.108**	0.040	–0.067	–0.138
Crops (X3)	0.026	0.046	**0.100**	–0.134	–0.038
Labour (X4)	–0.011	0.073	0.129	**–0.394**	0.202
Materials and services (X5)	0.103	0.110	0.026	0.146	**–0.386**

A summary of the own-price elasticity estimates from the simplified model 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 several other studies. These differences in the estimated elasticities could be the result 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 were 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.

Another possible explanation for the relatively low elasticities estimated in this study is to do with the changing structure of farms in Australia. Over time, Australian farms have become larger and more specialised. For example, in 1960–61 the total area of Australian farms was 468.1 million hectares and the number of agricultural establishments 202,800. By 1997–98, the number of agricultural establishments had fallen to 115,285 while the area of farm land remained relatively constant at 466.4 million hectares (ABARE 1999). Increased specialisation means that farmers cannot readily respond to changes in the relative prices of alternative outputs because the specialised inputs are output specific (e.g. a wheat harvester can not be used for wool production). Consequently, the elasticities for the outputs and inputs would be lower now than they were in earlier times.

Equation 6

$$\varepsilon_{ij} = \alpha_{ij}\frac{P_i^e}{X_j^e} \qquad i, j = 1,..., 4. \qquad (6a)$$

$$\varepsilon_{55} = -\frac{1}{X_5^e}\sum_{i=1}^{4}\sum_{j=1}^{4}\alpha_{ij}P_i^eP_j^e \qquad i, j = 1,..., 4. \qquad (6b)$$

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

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

Table 6. Summary of estimated own-price elasticities

Study	Period	Functional form	Region	Outputs: Wool	Outputs: Livestock Total	Outputs: Livestock Cattle	Outputs: Livestock Sheep	Outputs: Crops	Variable Inputs: Labour	Variable Inputs: M & S	Variable Inputs: Live-stock	Variable Inputs: Capital	Variable Inputs: Land
This study	1977/78–1997/98	Normalised Quadratic	Australia[a]	0.03	0.11			0.10	–0.39	–0.39			
McKay et al. (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[i] [j]					
Wall & Fisher (1987)	1967/68 – 1980/81	Normalised quadratic	Pastoral zone	0.10		0.43	0.39	2.67[j] 0.72[k]					
			Wheat/ sheep zone	0.04		0.11	0.36	0.62[j] 0.76[k]					
			High rainfall zone	0.04		0.14	0.28						
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.

It is difficult to make comparisons of the cross-price elasticity estimates from other studies because of the large number of estimates and the significant differences between each of the analyses (as mentioned above). However, it is interesting to note that, as is the case with this study, some of the cross-price elasticities for one output with respect to another output that were reported in earlier studies are also counter-intuitive. In other words, the signs of the cross-price elasticities are not as one would expect (e.g. McKay et al. 1983; Lawrence and Zeitch 1989; Wall and Fisher 1990; Low and Hinchy 1990; Agbola 1999). For example, a considerable number of the cross-price elasticities estimated by Wall and Fisher (1990) for the normalised quadratic profit function, which are presented in Table 7, are positive, indicating that these outputs are complements rather than substitutes, which is contrary to a priori expectations. For instance, for the pastoral zone, all the following cross-price elasticities are positive: wool with respect to other crops; cattle with respect to wheat and other crops; wheat with respect to sheep, cattle and other crops; and other crops with respect to wool, cattle and wheat. Possible reasons for the counter-intuitive signs were in general not provided in the earlier studies.

In contrast, the cross-price elasticities for the three composite outputs—wool and sheep; wheat, barley and oats; and cattle and other crops—reported in the study by Coelli (1996) all have the expected signs. That is, the signs of the respective cross-price elasticities indicate that these composite outputs are substitutes. This may be because the model was specified as a long-run profit function with all inputs variable. Nevertheless, some of the cross-price elasticities for an output with respect to an input are counter-intuitive (e.g. the cross-price elasticities for wool with respect to labour and the cross-price elasticities for land with respect to the three outputs). Examples of other studies in which counter-intuitive relationships between the outputs and inputs were reported include McKay et al. (1983), Lawrence and Zeitch (1989) and Agbola (1999).

4 The Demand Characteristics for Wool

In the small country case, with all commodities tradeable and homogeneous across countries, the prices 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.

Table 7. Estimated cross-price elasticities for the normalised quadratic profit function: Wall and Fisher 1990

Outputs	Pastoral zone	Wheat–sheep zone	High rainfall zone
Wool–sheep	–0.05	0.00	–0.10
Wool–cattle	–0.01	–0.03	0.03
Wool–wheat	0.00	–0.04	na
Wool–other crops	0.03	–0.05	na
Sheep–wool	–0.02	0.01	–0.14
Sheep–cattle	–0.25	0.02	–0.10
Sheep–wheat	0.00	0.24	na
Sheep–other	–0.04	–0.03	na
Cattle–wool	0.00	–0.09	0.05
Cattle–sheep	–0.28	0.03	–0.14
Cattle–wheat	0.02	–0.14	na
Cattle–other crops	0.03	0.10	na
Wheat–wool	0.00	–0.17	na
Wheat–sheep	0.03	0.50	na
Wheat–cattle	0.22	–0.19	na
Wheat–other crops	0.42	–0.33	na
Other crops–wool	0.39	–0.55	na
Other crops–sheep	–1.44	–0.18	na
Other crops–cattle	0.94	0.34	na
Other crops–wheat	1.72	–0.86	na

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 input-augmenting technology in the Australian wool industry will affect the supply of wool, and hence its world price. 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 live 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. In this case, information on the own-price elasticity of the demand for Australian wool by the rest-of-the-world and on the equilibrium price and quantity of wool is sufficient 'demand-side' information for wool.

The prices of all the other netputs (livestock, crops, labour, and materials and services) are assumed to be exogenously determined in the model. Hence, the demand curve for each of these netputs is not required to estimate the research-induced change in netput prices and quantities. Simply, combining information on (a) the demand and market clearing conditions for Australian wool, (b) the base equilibrium price and quantity values for all the netputs and (c) the new technology variables with the system of netput supply curves specified in equation (9d), and then solving this system of equations simultaneously, gives estimates of the 'with-technology' price and quantity values for each netput. These estimates can then be used to estimate the change in producer profits as described below.

5 Impact on Australian Wool Producer Profits

The base (that is the 'without-technology') and the new ('with-technology') values for the actual and effective prices and quantities for the four netputs are presented in Table 8. 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, $\overline{\pi}^0$, is as shown in equation (7a), in which 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-price exogenous variable. Given that the base

Table 8. Effect of technical change on producer profit

	Base values	New values	Actual change	Percentage change
Technology variable				
Labour	1.000	0.900	0.100	–10.000
Total demand elasticity				
Wool	–0.670	na	na	na
Actual normalised prices				
Wool	0.882	0.883	0.001	0.111
Livestock	0.905	0.905	0.000	0.000
Crops	0.763	0.763	0.000	0.000
Labour	0.893	0.893	0.000	0.000
Effective normalised prices				
Wool	0.882	0.883	0.001	0.111
Livestock	0.905	0.905	0.000	0.000
Crops	0.763	0.763	0.000	0.000
Labour	0.893	0.804	–0.089	–10.00
Actual predicted quantities				
Wool	256.157	255.967	–0.190	–0.074
Livestock	202.889	204.261	1.372	0.676
Crops	204.020	206.862	2.842	1.393
Labour	–181.744	–170.225	–11.519	–6.338
Profit	159.355	176.167	16.812	10.550

na: not applicable

technology index is set to unity, the base actual and effective prices are equal.

The new profit, $\overline{\pi}_i$, is given by equation (7b), in which 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 $P_i^{e0} = P_i^{0} * \tau_i^{e1}$, where τ_i^{e1} is the new technology index. In the simplified illustration, only the technology index for labour is assumed to change (by 10% to 0.9); the technology indexes for the other netputs are not altered. Therefore, the new actual and effective prices for labour vary from their original base values and are no longer equal. In addition, because the price of wool is determined endogenously in the system of netput supply curves specified in equation (9d), the new actual and effective prices for wool are not equal to their base values. In contrast, the new actual and effective prices for livestock and crops are determined exogenously and are therefore equal to their respective base values (see Table 8).

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 values of the coefficients have been estimated (section 3.5) and the value of the new technology index has been determined. The effect of the labour-saving technology on producer profits, $\Delta\overline{\pi}$, is the difference between equations (7b) and (7a), as depicted in equation (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 as shown in equation (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_i^{e0} into equation (9a), the base actual quantity for the i^{th} netput is as shown in equation (9b).

Similarly, the new effective quantity for the i^{th} netput, X_i^{e1}, is as shown in equation (9c), and, given

Equations 7–9

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

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

$$\Delta\overline{\pi} = \overline{\pi}^1 - \overline{\pi}^0 \qquad (8)$$

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

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

$$X_i^{e1} = \alpha_i + \mathop{}_{j=1}^{4}\alpha_{ij}P_j^{e1} + \sum_{j=6}^{8}\chi_{ij}z_j^0 \qquad i = 1,..., 4. \qquad (9c)$$

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

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 and into equation (9c) gives the new actual quantity for the i[th] netput (equation (9d)).

As evident from equation (9d), input-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 8. 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 that are of interest, rather than the values themselves. 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% decrease in the labour technology index results in a corresponding 10% fall in the effective price of labour from 0.893 to 0.804. The corresponding new actual quantity of labour is 6.3% below the base value. In addition, the interrelationships between each of the outputs—wool, livestock and crops—and between the outputs and labour input, are allowed for in the model. As shown in Table 8, a fall in the effective price of labour results in a 0.07% fall in the actual quantity of wool produced and a 0.1% increase in the price of wool, the latter because the price of wool is determined endogenously and assuming that the elasticity of demand for Australian wool is by the rest-of-world –0.67 (Connolly 1992). The fall in the quantity of Australian wool produced is in line with the positive cross-price elasticity for labour with respect to wool (Table 5). A fall in the effective price of labour also results 0.7% increase in actual livestock production and a 1.4% increase in actual crop production. Overall, because of the technology-induced fall in the price paid for labour, in the short-run, wool producer profit increases by 10.6%.

6 Summary and Conclusions

In this paper, a simplified, illustrative model of the Australian wool industry 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 an illustrative input-augmenting technical change. The normalised quadratic restricted profit function was specified in terms of effective rather than actual prices. This model consisted of a system of equations in which essential interrelationships between the netputs were specified. The mathematical relationships of these equations were consistent with the theoretical restrictions that arise as a result of assuming profit maximisation (i.e., homogeneity, convexity, monotonicity and symmetry), ensuring that the economic welfare calculations were unambiguous.

The profit and netput supply functions were fitted to ABARE data and estimated using 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 producer profits were then evaluated. The results of the illustrative example show that, in the short-run, the development and full adoption of a 10% labour cost-reducing technology by the Australian wool industry results in a 10% fall in the effective price paid for labour and a 6.3% decrease in the quantity of labour used by the industry. In addition, the cross-commodity effects of the technology are also allowed for in the model, with a 0.07% fall in the actual wool production (and a corresponding 0.1% increase in the price of wool), a 0.7% increase in livestock production and a 1.4% increase in crop production. Overall, in the short-run, the introduction of the specified labour-reducing technology results in a 10.6% increase in wool producer profits.

It is acknowledged that the omission of a number of important characteristics of the Australian wool industry could have influenced the estimated parameters and hence the results presented here. These characteristics include the regional differences in the type of wool produced, the heterogeneous nature of wool, and the dynamic and stochastic nature of livestock production. Further research is currently being undertaken by the authors to extend the simplified model to include at least some, if not all, of the previously omitted aspects of the Australian wool industry. This will not only enhance the work done in this study but also result in the development and implementation of a theoretically consistent modelling framework for estimating the impact of research aimed at improving the quality of a commodity.

Notwithstanding the simplified model, this study clearly shows that the dual approach to research evaluation provides a theoretically consistent measure of the economic effects of multiple sources of technical change, even when the market being analysed is complicated by multiple sources of cross-commodity impacts. It also provides great flexibility in the specification of technology. Finally, measures of research-induced changes in consumer and producer welfare can be obtained from the dual model. However, the data requirements are significant compared with the economic surplus approach to research evaluation. Being aware of the advantages and drawbacks of alternative approaches to research evaluation enables the analyst to choose the most appropriate method in light of the question at hand and the availability of resources and data. In general, the economic surplus approach is likely to remain the method of choice because it is intuitively appealing, relatively easy to compute and the data requirements are minimal. However, the analyst needs to be aware that errors in welfare measurement could occur if important cross-commodity impacts are ignored. Further empirical analysis is needed to give an indication of the likely magnitude of these errors.

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