A comparative breakeven net return threshold to guide development of conservation technologies with application to perennial wheat

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Abstract

In recent decades, public research into agricultural technology development has shifted is primary focus from farm profitability to environmental stewardship. While the orientation of technologies coming from the public sector has changed, the factors motivating adoption by farm businesses remain focused on profitability. This paper develops a comparative breakeven net return threshold for new conservation technologies that requires net returns to the farm enterprise *after* adoption of the new technology to at least equal their net returns *before* adoption.

The framework is applied to the case study of perennial wheat, a wheat-grass hybrid that can survive and yield grain for multiple seasons. Its perenniality generates environmental benefits over annual wheat via improved soil conservation, water quality, and greenhouse gas sequestration. The framework is illustrated using data from the evaluation of a small set of perennial wheat breeding lines in Australia during 2009-11. We calculate a net return threshold and a potential environmental subsidy and evaluate the potential for changes in yield, price, and perenniality to enhance the commercial viability of PW. Increasing absolute grain yields seems to be the most promising option for further research and development. In all cases, increasing the price of PW through increasing grain quality without making additional improvements to other PW traits would require grain prices that exceed the range of currently feasible market levels.

This paper generates a simple but versatile framework for the *ex ante* economic evaluation of new conservation technologies. The framework can be used to estimate a benchmark level of economic performance that must be achieved in order for a practice to be deemed economically attractive and ultimately adopted by producers. This framework can be used to inform technology developers of the most economically productive avenues for further refinement of their nascent technologies, thereby increasing the potential for their adoption by farmers.

Keywords: technology development, conservation, comparative breakeven, perennial wheat

1. Introduction

Agricultural conservation has a long history in the United States. Many of the first efforts at conservation in production agriculture were kindled in the 1920s and 1930s. Soil conservation was of particular interest during this period as the Dust Bowl brought into sharp focus the need for farm management techniques that reduced rates of erosion of valuable topsoil from farm fields. During this time, agricultural technology developers focused largely on new methods of tillage which could achieve dual goals of decreasing soil loss and maintaining – or even enhancing – crop yields (Nelson, 1997). Although the environmental consequences of erosion exerted some influence on the push for conservation efforts, soil conservation was pursued during this period primarily as a means of enhancing and sustaining farmer incomes. The Soil Conservation and Domestic Allotment Act of 1936 "enabled farmers to receive soil conservation payments for reducing 'soil depleting' crops" (Batie 1985). The law supported farm incomes both directly (via payments) and indirectly (via reducing crop supply that raised prices). It happened that these "soil depleting" crops were in surplus, so idling land in the name of soil conservation served the primary purpose of increasing commodity prices – thereby enhancing farmer incomes – while nominally enhancing the sustainability of agricultural production.

Although environmentalists have recognized the benefits of agricultural conservation as early as the 1920s (Nelson, 1997), it was not until after the environmental movement of the 1960s and 1970s that conservation efforts began to be pursued more explicitly for their resultant environmental benefits. One of the needs addressed by the Resources Conservation Act of 1977, for instance, was an accounting of the reduction in soil losses and improvements in water quality that resulted from federal conservation payments to farmers (Batie, 1985). This increased

concern over environmental outcomes, coupled with diminishing concern over farmer incomes – which have typically been higher than non-farm households in recent years (U.S. Department of Agriculture 2012) – has led to a greater emphasis on enhancing environmental benefits from agricultural conservation technologies.

As the orientation of the development of conservation technologies has evolved, so has social scientists' understanding of the factors that drive their adoption. Reams of literature have explored various components of farmers' decisions on whether or not to adopt a new agricultural conservation technology. A significant portion of this literature explores the role of farm and farmer characteristics on the decision to adopt, including: socioeconomic descriptors such as age and education; structural characteristics like farm size and financial strength; institutional characteristics such as the availability of government programs that support adoption of new technologies; and environmental characteristics, which may take the form of environmental attitudes or awareness of environmental degradation that results from agricultural production (*e.g.* Ervin and Ervin, 1982; D'Souza *et al.*, 1993; Featherstone and Goodwin, 1993). While these studies generally find correlations between various farm and farmer characteristics and adoption behavior, there is little, if any, evidence that there exists a universal set of factors that can be considered reliable drivers of conservation technology adoption (Knowler and Bradshaw, 2007; Prokopy *et al.*, 2008). Other approaches have taken into account characteristics of the technologies themselves. Adesina and Zinnah (1993) and Adesina and Baidu-Forson (1995), for example, investigate how farmer perceptions of technology-specific characteristics affect their decision of whether or not to ultimately adopt novel crop varieties. Still other approaches argue for a more refined framework that incorporates both of the aforementioned strands of the

literature (Pannell *et al.*, 2006) or the integration of microeconomic behavior models of adoption with technology diffusion models (Feder and Umali, 1993).

The relevant insight from the adoption literature is that new technologies must be privately attractive to farmers, even if the motive for their development is to provide public benefits (National Research Council, 1989; Feather and Cooper, 1995; Lichtenberg, 2004; Pannell *et al.*, 2006; National Research Council, 2010). The purpose of this paper is to identify minimum standards of economic performance to guide the development of new conservation technologies that farmers will adopt. The objectives of this study are: 1) develop a framework to identify the threshold needed to make a new technology at least as attractive as the prevailing standard; 2) use that framework to evaluate alternative technology development strategies; 3) illustrate the framework with an application to the development of perennial wheat.

We begin by outlining a conceptual framework in Section 2 where producers focusing on private utility maximization reach socially inefficient technology adoption decisions in the presence of environmental externalities. Using this framework, we argue that more socially efficient technology choices can be incentivized through enhancing the commercial viability of conservation technologies relative to conventional technologies. In Section 3, we use the conceptual framework to derive a "net return threshold," a level of profitability beyond which a new conservation technology returns more than the best available alternative. We apply this threshold to the case study of perennial wheat, a nascent conservation technology. In particular, we apply the threshold using comparative breakeven budgeting to evaluate three alternative technology development strategies with and without socially justifiable environmental subsidies. Results from the case of perennial wheat illustrate the potential for *ex ante* farmer adoptability of environmentally beneficial (EB) technologies in general.

2. Conceptual model

a. The producer's problem

Our discussion begins with deriving a model of farmers' unilateral utility maximization decisions. Assume that there exist J farmers. Farmer $j \in J$ faces the problem of optimizing their own payoff from farming. This optimization is achieved by maximizing their private utility function, $u_j(C_j, E)$, where C_j denotes the farmer's own consumption of a composite consumption good and E denotes environmental quality. For simplicity, assume that utility is defined over these two arguments alone. Note that E is a public good; a subscript is therefore omitted since all members of society are able to enjoy its provision. It is assumed that producers have lexicographic preferences with the consumption good C_j preferred to E – that is, for two consumption bundles $x_i^1 = (C_i^1, E^1)$ and $x_i^2 = (C_i^2, E^2)$ in $\mathbb{R}_+^2$, $x_i^1 \succcurlyeq x_i^2$ if $C_i^1 > C_i^2$ or $C_i^1 = C_i^2$ and $E^1 > E^2$. Thus, we assume that the farmer will choose the feasible consumption bundle that maximizes his utility from the composite good C_j. If two or more bundles allow the farmer to attain the same level of C_j, then the farmer will choose that which yields the highest level of environmental quality.

Lexicographic preferences cannot be represented using a continuous and differentiable utility function, thus eliminating the possibility of analytically deriving demand functions for C_j and E from first-order conditions. That said, producer j's consumption of the composite good C_j can be written as a function of the wealth y_j he earns from farming. If we assume that farmer wealth is equivalent to his profits from farming, then the producer's utility maximization problem is equivalent to a profit-maximization problem (PMP). We may write profit π as a function of the price vector $\boldsymbol{p}$ as well as the farmer's production technology choice, represented

by transformation function $\{\mathrm{T}_{j\ell}(\boldsymbol{z}) : \mathrm{T}_{j\ell}(\boldsymbol{z}) \in \{\mathrm{T}_{j1}(\boldsymbol{z}), \mathrm{T}_{j2}(\boldsymbol{z}), \dots, \mathrm{T}_{jL}(\boldsymbol{z})\}, \mathrm{T}_{j\ell}(\boldsymbol{z}) \leq 0\}$. Note that here, $\boldsymbol{z}$ represents a netput vector of both inputs and outputs. This notation allows for the production of multiple outputs as well as the use of multiple inputs. Vector $\boldsymbol{p}$ represents both output and input prices.

Typically, the PMP is solved by selecting the optimal combination of netputs given exogenous netput price vector $\boldsymbol{p}$. Here, we are interested in modeling the decision by the farmer to adopt a new conservation technology. Thus, we assume that the producer solves a variation of the PMP in which he chooses the *technology* $\mathrm{T}_{j\ell}(\boldsymbol{z})$ that maximizes his profit. Let $\mathrm{Z}_j^* = \{\boldsymbol{z}_{j1}^*, \boldsymbol{z}_{j2}^*, \dots, \boldsymbol{z}_{jL}^*\}$ denote the set of input combinations that maximize profit for each technology $\ell = 1, 2, \dots, L$, i.e., $\boldsymbol{z}_\ell^* = \arg\max_{\boldsymbol{z}_{j\ell}}(\boldsymbol{p} \cdot \boldsymbol{z}_{j\ell} \;\; s.t. \;\; \mathrm{T}_{j\ell}(\boldsymbol{z}_{j\ell}) \leq 0)$. Then, the farmer's PMP becomes

$$\max_{\{\mathrm{T}_{j\ell}(\boldsymbol{z}_{j\ell}^*) \in T\}} \pi_j = \boldsymbol{p} \cdot \boldsymbol{z}_{j\ell}^*$$
$$\text{s.t. } \mathrm{T}_{j\ell}(\boldsymbol{z}_{j\ell}^*) \leq 0 \qquad [1]$$

When the above problem is maximized by two or more different technology choices $\mathrm{T}_{j\ell}^*$ and T_{jk}^*, $\ell \neq k$ that offer equal profitability, the producer will choose the one that generates the highest level of environmental quality.

b. The social planner's problem

In contrast to the producer's problem, the social planner's problem is to choose the technology that maximizes total social surplus from farming. Let the I individuals have preferences defined over the composite consumption good $C_i(\mathrm{T})$ – which includes the consumption of farmer output (and therefore makes consumption a function of farmers' technology choice T) – and environmental quality $E(\mathrm{T})$. In the consumer's case, the levels of

environmental quality and consumption they enjoy are a function of the profit-maximizing technology choice made by farmers $E(\mathrm{T}^*)$, where $\mathrm{T}^* = \{\mathrm{T}_1^*, \dots, \mathrm{T}_J^*\}$. This choice of technology is exogenous to the consumer. A simple representation of preferences that facilitates demand aggregation is a quasilinear utility function such that the consumer's utility maximization problem is

$$\max_{E(\mathrm{T}^*),\, C_i(\mathrm{T}^*)} u_i\big(C_i(\mathrm{T}^*), E(\mathrm{T}^*)\big) = \eta_i\big(E(\mathrm{T}^*)\big) + C_i(\mathrm{T}^*)$$
$$\text{s.t. } C(\mathrm{T}^*) + p_E E(\mathrm{T}^*) = y_i$$

where p_E is the price of environmental quality and y_i is the wealth of the consumer. Without loss of generality, p_E may equal zero. Note that consumer utility depends upon all environmental outcomes of the production technology, including ones that may be external to the decisions of the producer. Indirect utility can then be written as

$$v_i\big(y_i, E(\mathrm{T}^*)\big) = \phi_i\big(E(\mathrm{T}^*)\big) + y_i$$

(Mas-Collel, *et al*. 1995). Given that each producer's surplus is equal to their profits from farming, as described above, and that the production set satisfies addititivity, the social planner's problem is then

$$\max_{\{\mathrm{T}_{j\ell} \in \mathrm{T}_j\}} \sum_i \phi_i \left(E\big(\mathrm{T}_{1\ell}, \dots, \mathrm{T}_{J\ell}\big)\right) + \sum_j \boldsymbol{p} \cdot \boldsymbol{z}_{j\ell}^*$$
$$s.t. \, \mathrm{T}_{j\ell}\big(\boldsymbol{z}_{j\ell}^*\big) \leq 0 \; \forall \, j \in J \qquad [2]$$

Except by coincidence, it is unlikely that the choice of technology $\mathrm{T}_{j\ell}$ that maximizes Equation 1 for each producer individually and Equation 2 will be the same. As a result, unilateral maximization of lexicographic preferences by producers is likely to generate a socially inefficient level of environmental quality E. However, efficiency can be restored through various means. One alternative would be to subsidize the implementation of the socially optimal technology through payments for environmental services. Further, enhancing the economic

performance of EB technologies through continued research and development may lead to greater adoption of socially efficient technologies by producers. Indeed, given our assumption of lexicographic preferences on the part of producers, increasing the profitability of EB technologies to levels equal to or greater than those of conventional technologies will result in utility-maximizing producers choosing socially efficient production technologies.

3. Empirical framework for evaluating profitability of conservation technologies applied to perennial wheat

a. Empirical framework

To determine the conditions for the adoption of a new conservation technology when private profitability dominates producer objectives, the empirical framework compares the profitability of the new conservation technology to a current benchmark agricultural technology that represents the opportunity cost that a producer would give up in adopting the new technology. Off-site environmental benefits E are external to the grower's adoption decisions and would only be internalized if they had a direct impact on the profit produced by the technology, such as through subsidy payments. The empirical framework in this section thus identifies conditions for a grower to maximize profit upon switching from a current benchmark technology to a new conservation technology.

The empirical framework for technology comparison builds upon the assumptions that: 1) the grower's utility function is lexicographic in profit, making profit maximization the foremost objective; 2) the new conservation technology and the benchmark production technology are separable from all other farm practices; 3) yields of the EB technology and the conventional technology come from two separate production functions T_j^{EB} and T_j^{C}, respectively; 4) the profit-

maximizing netput combinations $\boldsymbol{z}_{j\ell}^{*}$ for each of the two technologies are known; 5) prices are constant, though price vectors $\boldsymbol{p}_{EB}$ and $\boldsymbol{p}_{C}$ do not have to be equal.

Given these assumptions, the empirical model of the producer's profit-maximization problem is:

$$\max_{\mathrm{T}_{j\ell}\in\{T_j^C,T_j^{EB}\}} \pi_j(\mathrm{T}_{j\ell}) = \boldsymbol{p}_{\boldsymbol{\ell}}\left(q(\mathrm{T}_{j\ell})\right)\cdot \boldsymbol{z}_{j\ell}^{*} + \sigma_j\left(E(\mathrm{T}_{j\ell})\right)$$

where $\pi_j(\mathrm{T}_{j\ell})$ is profit as a function of technology choice $\mathrm{T}_{j\ell}$, $\boldsymbol{p}_{\boldsymbol{\ell}}\left(q(\mathrm{T}_{j\ell})\right)$ is the price vector as a function of output quality q, itself a function of technology choice $\mathrm{T}_{j\ell}$, and $\sigma_j\left(E(\mathrm{T}_{j\ell})\right)$ is a payment for environmental services or benefits that result from the producer's technology choice.

Since the EB technology must have net returns that are greater than or equal to those of the current technology in order to prove attractive for adoption, we may define a net return threshold that must be met in order for the EB technology to become commercially viable. For simplicity, we assume a single-output technology represented by production function $\tau_\ell(\boldsymbol{z}_\ell^{*})$ where $\boldsymbol{z}_\ell^{*}$ now represents the profit-maximizing *input* vector. If farmers are to adopt an EB technology τ_{EB} in lieu of a conventional technology τ_C, it must satisfy the following breakeven condition:

$$\pi_j\left(\tau_C(\boldsymbol{z}_\ell^{*})\right) \leq p\left(q\left(\tau_{EB}(\boldsymbol{z}_\ell^{*})\right)\right)\cdot \tau_{EB}(\boldsymbol{z}_\ell^{*}) - c_j(\tau_{EB}(\boldsymbol{z}_\ell^{*}),\boldsymbol{w}) + \sigma_j\left(E\left(\tau_{EB}(\boldsymbol{z}_\ell^{*})\right)\right) \quad [3]$$

where p is output price as a function of quality q and $c_j(\cdot)$ is the producer's cost function given output generated from technology τ_{EB}[1] and input price vector $\boldsymbol{w}$. The net return threshold thus provides the comparative breakeven net return that the new EB technology must produce in order

[1] We abuse notation slightly by using $\tau_{EB}(\boldsymbol{z}_\ell^{*})$ to represent both the choice of technology *and* the output level/yield.

to be commercially competitive with the conventional benchmark technology. The net return threshold from Equation 3 is represented by the solid horizontal line in Figure 1a-d.

(FIGURE 1)

The net return threshold illustrates how the profitability threshold relates to marketable yield of the EB technology. The vertical intercept of the net return threshold represents the total revenue of the conventional technology. The black dashed line represents the locus of points that associate the yields of the EB technologies with their associated net returns, assuming variable costs are identical for all of them. As traits of these technologies change, the shape points may move along or with the dotted line to reflect these changes. The dotted line intersects the vertical axis at the level of net revenue the farmer would earn with a yield of zero; i.e., the vertical intercept represents the sum of variable costs from the EB technology. The solid line intersects the net return threshold at the level of yield at which the EB technology breaks even with the conventional technology. The three shape points shown in Figure 1a represent three EB technologies that fall below below the net return threshold, meaning that they generate net returns that are not commercially competitive with the conventional technology.

This framework can illustrate four distinct changes to the technology's traits that can be modified by technology developers: 1) changes in unit cost; 2) changes in subsidized external benefits; 3) changes in product quality; and 4) changes in the quantity of marketable product produced (i.e., yield). A decrease in the unit cost of production or an increase in subsidized environmental benefits would shift the dotted line upward (Figure 1b); conversely, higher costs or a lower subsidy would shift the dotted line downward. An increase in product quality would increase the market price received, which would rotate the dotted line toward the origin, thus decreasing the minimum crop yield necessary for the new EB technology to reach the net return

threshold (Figure 1c). Finally, an increase in the yield of marketable product from a specific technology would shift the shape point representing that technology upward along the dotted line, because accompanying profit would also rise. Figure 1d demonstrates this change for three initial technologies represented by the black shape points. As their yields increase, the shape points move along the dotted line, becoming the white shape points.

b. Application to perennial wheat

The empirical framework from Equation 3 and Figure 1 is applied to perennial wheat (PW), a conservation technology that is currently under development. The profitability of PW is compared to that of annual wheat (AW), the conventional benchmark technology. The framework is applied first to identify the net return threshold for adoptability of the new PW varieties. Then, that threshold is used to evaluate four strategies for plant breeding to make PW more readily adoptable.

PW was first created by crossing varieties of AW, *Triticum aestivum*, with a perennial grass from the *Thinopyrum* genus (Scheinost *et al*. 2001). PW plants can survive up to five years without needing to be replanted, and therefore require lower levels of tillage than AW (Lammer *et al*. 2004). PW has the potential to provide a number of environmental benefits – including carbon sequestration, reduced soil erosion and decreased nitrate leaching – largely due to its complex root system and perennial nature (Glover *et al*. 2010). Additionally, the biomass produced by PW has the possibility of being grazed by livestock, while also producing a grain yield each year, offering increased flexibility to adapt cereal production systems in a variable climate (Bell *et al*. 2008).

The data for comparing PW and AW come from research trials in Cowra, New South Wales, Australia, where 28 lines of PW were grown from 2009 through 2011 and one line of AW – Wedgetail – was sown during the 2008 growing season (Hayes *et al*, 2012).

The net return threshold was developed using the following steps: 1) identify a suitable time horizon for comparison; 2) measure annual variable costs and returns (cash flows); 3) aggregate annual costs and returns over the planning horizon; 4) convert the aggregate total value into a readily understood profitability measure. The time horizon for comparing PW with AW was dictated by the longer expected survival of PW. Hence, cash flow budgets were developed for three year periods, the maximum length of PW grown in the Cowra experiment.

The annual variable costs of inputs and the revenues produced by the lines under comparison were combined using enterprise budgets into gross margins above fixed costs, which captured annual cash flows. Fixed costs (such as land) that would not differ between crop enterprises were omitted from calculations. Pesticides and fertilizer costs were calculated as quantity times price, while labor and equipment costs were captured by commercial charges for custom production operations (Weir 2012). Hayes *et al.* (2012) provided the grain yields generated by each wheat line in grams per plot, and these amounts were aggregated to tons per hectare. Due to uneven grain milling quality, PW was priced at its 2010 value as a livestock feed (AUS \$297 mt^{-1} [Australian Bureau of Statistics 2011]). AW grain was priced at the mean 2010 Australian price of food wheat grain (AUS \$372 mt^{-1}).

The annual gross margin for each wheat line was aggregated over the three-year time horizon to calculate its net present value using a discount rate of 8% (the average interest rate on three-year fixed-term small business loans in Australia over the past 20 years [Reserve Bank of

Australia 2011]). Finally, for profitability comparison with AW, the three-year net present values were converted to annualized net returns using a standard financial annuity formula.

c. Results and discussion

Comparison of the 28 PW lines with one widely-grown cultivar of AW showed that none of the PW lines had an annualized net return that was greater than or equal to the net return of AW (Table 1). The AW line had an annualized net return of AUS \$1,124 ha^{-1}. Out of the 28 lines of PW, only four had positive annualized net returns. These four lines and their respective net returns were: AUS \$13 ha^{-1} for C47b and O42; AUS \$49 ha^{-1} for C39b; and AUS \$207 ha^{-1} for C64a. Note that the line numbers refer to the final digits of the lines citied in Hayes, *et al.* (2012). Since C47b and O42 exhibit the same economic performance, we refer only to O42 for the rest of the analysis. The three PW breeding lines with positive returns are shown in Table 1 and represent the shape points illustrated in Figure 1a. Since none of the annualized net returns of the PW lines were equal to or greater than the net return of the AW line, the PW lines would not be adopted by growers with lexicographic preferences for profitability over environmental benefits.

For EB technologies that are under development, like PW lines, the question of interest is how these lines might be developed further to reach the net return threshold. We approach this by first estimating potential environmental subsidies, followed by calculating breakeven targets for breeding traits that could reach the net return threshold with and without environmental subsidies.

(TABLE 1)

i. Potential for subsidies from external environmental benefits

PW is expected to generate external environmental benefits for which a subsidy could potentially be paid to compensate the grower for the production of those benefits. We estimate potential subsidy levels using benefit transfer methods to value reduced soil erosion, one of the most significant environmental benefits that is expected to be provided by PW (Weir 2012). Although soil conservation would have a number of off-site environmental benefits, values were only placed on the reservoir dredging costs that would be avoided through a reduction in erosion.

To calculate the avoided reservoir dredging costs, estimates for the amounts of soil erosion that would be reduced by the growth of PW were developed using the universal soil loss equation (USLE). Crop cover parameters for PW were developed by combining values for AW and pasture from Canada (Stone and Hilborn 2000). These were combined with slope length, rainfall and erodibility factors from Bathurst in northern New South Wales (Mahmoudzadeh *et al.* 2002) to estimate reduced soil erosion in the region from growing PW. PW was estimated to reduce erosion by 13.3 m^3 ha^{-1} yr^{-1} on soils that are highly erodible, 7.8 m^3 ha^{-1} yr^{-1} at medium erodibility, and 5.1 m^3 ha^{-1} yr^{-1} at low erodibility (Weir 2012). These estimates were then adjusted downward by one third because not all soil eroded from cropland ends up in a waterway (Pimentel 2006). The adjusted erosion amounts were multiplied by the 2010 Australian price of dredging sediment from a reservoir (AUS \$7 m^{-3} [Bruun and Willekes 1992; ABS 2011]). These values were applied to calculate the avoided reservoir dredging costs due to growing PW instead of AW. The potential subsidy values were estimated at AUS \$59 ha^{-1} at high erodibility, AUS \$35 ha^{-1} at medium erodibility, and AUS \$23 ha^{-1} at low erodibility. As demonstrated in Figure 1b, these values would have the effect of shifting the dotted line upward by the corresponding subsidy amount.

ii. Comparative breakeven analysis of target technology traits, with and without subsidies

We consider three traits of PW that could potentially be manipulated by plant breeders to reach a net return threshold. These traits are annual grain yield, years of survival, and grain quality.[2] Each of these is evaluated using comparative breakeven analysis (Hilker *et al.*, 1987; James *et al.*, 2010). Comparative breakeven values are computed by rearranging Equation 3 to isolate threshold levels of specific traits of interest. For example, the comparative breakeven yield $\tau_{EB}^{CB}(\boldsymbol{z}_\ell^*)$ for an EB crop like PW is the grain yield threshold at which yield is sufficient to cover both the net return from the conventional benchmark technology (AW) and the variable costs of the EB technology (PW), given the expected price of the EB technology (i.e., the Australian feed grain wheat price). Adapted from Equation 3, the formula for comparative breakeven yield of PW is

$$\tau_{EB}^{CB}(\boldsymbol{z}_\ell^*) = \frac{\pi_j\left(\tau_C(\boldsymbol{z}_\ell^*)\right)+c_j\left(\tau_{EB}(\boldsymbol{z}_\ell^*),\boldsymbol{w}\right)}{p\left(q\left(\tau_{EB}(\boldsymbol{z}_\ell^*)\right)\right)} \qquad [4]$$

Converting comparative breakeven grain yields into percentage increases above current norms offers a clear measure of how much yield increase is required. Using each PW line's experimental mean yield as its basis for percentage gains needed, Table 1 reports results of the breakeven yield analysis with and without the mean AUS \$35 ha^{-1} potential soil conservation subsidy for the three most promising lines of PW grown in the Cowra 2009-11 trial (details including target yield changes in kg ha^{-1} available in Weir 2012). Of note is that even the most promising PW line, C64a, could only reach comparative breakeven yield with a gain of 201% without or 193% with a AUS \$35 ha^{-1} soil conservation subsidy. By contrast, PW line O42 would require a 424% yield gain without or a 410% yield gain with the subsidy. These

[2] We omit three other possibilities: 1) reducing production costs (discussed in Weir 2012), 2) adding or enhancing a joint product (like grazing forage yield of early season wheat; Moore 2009; Mokany *et al*., 2008) and 3) enhanced environmental benefits to increase potential subsidies.

relationships are illustrated in Figure 2, which shows how the dotted line from Figure 1 shifts upward with the subsidy and how much the individual varieties would have to move right and upward to reach the new threshold. The grey dotted line and grey vertical solid line demonstrate the effects of the subsidy. The grey dotted line shifts up by the amount of the subsidy (AUS $35) and the solid vertical lines, which represent the level of yield necessary for a PW line to break even with AW, shifts from the black line to the grey line, representing a decrease in the comparative breakeven yield resulting from the subsidy.

(FIGURE 2)

iii. Comparative breakeven prices, with and without subsidies

By increasing the quality of the PW grain, plant breeders could increase the price it fetches. Wheat is used for a variety of purposes, including bread, pastries, pasta, and livestock feed. Prices of the various market classes of AW reflect the respective values of specialized wheat types that have been developed for these purposes. At present, PW lacks a clear market niche. Grown in large quantities, it would have to be sold as a feed grain (as assumed for the comparative breakeven yield analysis). But grain quality improvements could translate into higher grain prices. Comparative breakeven prices are thus the grain prices that would allow the net returns of the PW lines to equal the net return of the AW line. The formula is similar to the comparative breakeven yield formula in Equation 4, except that the denominator is the expected *yield* of the wheat line in question.

As with the yields, the comparative breakeven price increases are reported as percentage gains needed in Table 1. Note that the base price of feed grain wheat was AUS $297 mt^{-1}. Given that the mean price of food quality AW grain was AUS $372 mt^{-1}, a 25% quality-based price increase would be needed to reach the ordinary food quality price level. The analysis

shows PW comparative breakeven price increases for these three promising varieties range from a minimum of 140% (PW line C64a) to 267% in line O42. These results indicate that, on their own, price increases brought on by improvements in PW grain quality would be insufficient to make PW commercially competitive with AW as the highest possible increase in price one might expect to generate by increasing grain quality is 25% -- i.e., the percentage difference between feed-quality and food-quality grain. The medium subsidy payment of AUS $35 per hectare per year would decrease the comparative breakeven prices of the PW lines, but even this subsidy will not be sufficient to make price increases from grain quality improvement an effective change, at least in isolation from other improvements (Table 1).

iv. Impacts of perenniality on profitability

A critically important driver of both production costs and environmental benefits in PW is the duration of its life cycle before it requires replanting. Sometimes called degree of "perenniality," this trait underpins the environmental benefits of PW. By avoiding the need for replanting, increased perenniality of the PW lines could increase their profitability and encourage adoption. In practice, the Cowra 2009-11 wheat trial showed no relationship between perenniality and annualized net returns. Indeed, only five of the 28 PW lines evaluated survived for three years. Moreover, all five of the PW lines that lived for three years had negative annualized net returns. So, the PW lines that were more perennial were actually less profitable than the subset of PW lines referred to here as "promising" due to positive net returns, which survived only two years, suggesting some level of trade-off between higher grain yield and increased longevity.

Profitability aside, maintaining perenniality is essential to the environmental benefits of PW. Perenniality prevents the soil from being disturbed, which generates the benefits of soil

conservation as well as other benefits not valued in this analysis (e.g., carbon sequestration, surface water quality). Hence, in a broader analysis, maintaining perenniality is necessary to justify subsidies for perenniality-associated environmental benefits.

4. Conclusion

The framework introduced here offers an *ex-ante* way to evaluate agricultural technologies while they are under development with an eye to enhancing their adoptability by commercial farmers. The framework was motivated by the increasing number of public sector agricultural technologies being developed with the objective of achieving environmental benefits. These technologies face adoption decisions by private managers who typically compare new technologies to conventional benchmarks using profitability as the primary decision criterion. Our framework develops a comparative breakeven net return threshold and then analyzes the potential to manipulate alternative technology traits that affect profitability, such as quantity of marketable product, quality (and thereby price) of marketable product, unit cost of production, and subsidized environmental benefits. A graphical image shows how improvements in these traits affect movement toward the comparative breakeven threshold.

The framework is illustrated using data from the evaluation of a small set of PW breeding lines in Cowra, New South Wales, during 2009-11. We calculate a net return threshold and a potential environmental subsidy and evaluate the potential for changes in yield, price, and perenniality to enhance the commercial viability of PW. Increasing absolute grain yields seems to be the most promising option for further research and development. In all cases, increasing the price of PW through increasing grain quality without making additional improvements to other PW traits would require grain prices that exceed the range of currently feasible market levels. Increasing the perenniality of PW does not appear to increase the profitability of the crop

based on this data set, so achieving gains by that mechanism would require fundamental breakthroughs in plant breeding to maintain good grain yields while enhancing the longevity of the crop. However difficult, maintaining perenniality is fundamental to justifying the environmental benefits that motivate public interest in PW.

The net return threshold framework developed here can easily be adapted to assess other nascent technologies to inform technology developers of research directions that will contribute to farmer acceptance. As such, this framework offers a form of *ex-ante* economic evaluation that is oriented toward early-stage technology developers, rather than the downstream technology adoption evaluations that have been characteristic of most farming systems research studies (Nagy and Sanders 1990).

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Figure 1: Net return threshold for an environmentally beneficial technology under a) the baseline case; b) subsidy or cost reduction; c) output price increase; and d) improvement in yield

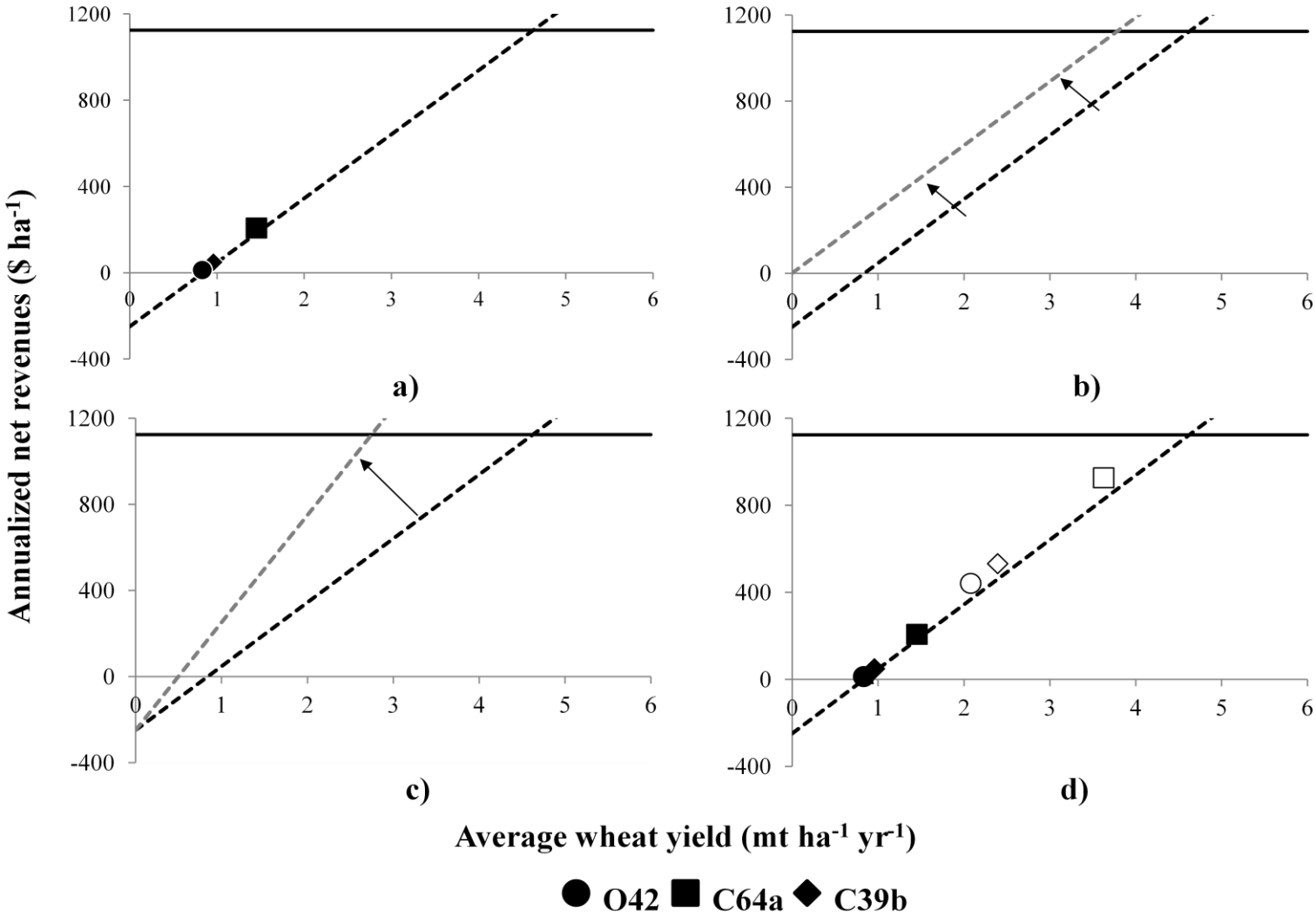

Figure 2: The effect of a subsidy on breakeven perennial wheat yield

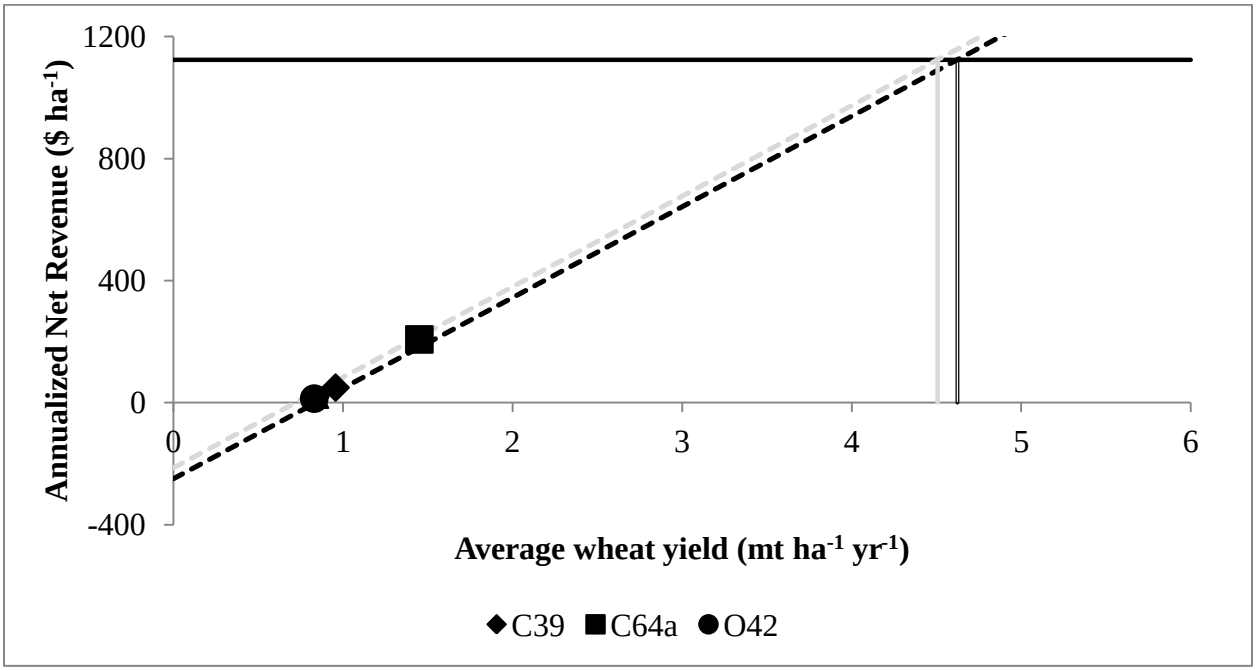

Table 1: Percent increases in yield and price needed to achieve comparative breakeven profitability with annual wheat for the highest-performing varieties of the 2009-11 Cowra trial

Line	Annualized net return (AUS $/ha)	No subsidy (%)		AUS $35/ha subsidy (%)	
		Yield	Price	Yield	Price
C39b	49	360	267	348	257
O42	13	424	318	410	307
C64a	207	201	140	193	134
Annual wheat	1,124	--	--	--	--