The opportunity costs of enhancing legume-based sustainable agricultural intensification practices in Malawi

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Abstract

Determining the value of legumes as soil-fertility amendments can be challenging, yet this information is required to guide public policy and to incentivise prescribed land-management practices such as conservation agriculture. We apply a directional distance function to data from Malawi, to estimate shadow prices for symbiotic nitrogen and the technical efficiency for mixed maize-legume production systems. The shadow prices reflect the trade-off between fertiliser-nitrogen and symbiotic-nitrogen required to achieve a given quantity of output. Our results reveal considerable technical inefficiency in the production system. The estimated shadow prices vary across farms and are, on average, higher than the reference price for commercial nitrogen. Our results suggest that it would be beneficial to redesign the current price-support programs that subsidise chemical fertilisers and indirectly crowd-out organic soil amendments such as legumes.

Key words: conservation economics, efficiency and productivity, shadow price, sustainable agricultural intensification practices

1. Introduction

Legumes are an important component of smallholder farming systems in sub-Saharan Africa (Sanginga, 2003; Giller et al., 2009). Besides crop outputs, legume-based cropping systems (henceforth LBCS) supply a variety of indirect benefits that are essential for sustainable agricultural intensification (Giller et al., 2009; Jensen et al., 2012; Preissel et al., 2015). For example, LBCS can help to suppress parasitic weeds and pest/disease-incidence recurring from a monoculture practice. In addition to breaking the weed or disease cycle, LBCS maintain soil fertility through nutrient recycling and prevention of soil erosion (Giller et al., 2009; Preissel et al., 2015). Thus, the organic soil amendments supplied through LBCS or other forms can reduce the need, at least partly, for commercial fertiliser application and can lower farm investment costs (Pannell and Falconer, 1988; Sanginga, 2003; Mafongoya et al., 2007). Furthermore, as part of a soil-nitrogen management plan, LBCS represent a cheap form of abatement to reduce nitrogen leachates associated with excessive fertiliser use (Jensen et al., 2012). However, the values of LBCS's benefits, particularly the nutrient-recycling function, have not been adequately studied. This lack in studies is partly due to the fact that the nitrogen derived from legume-association is an intermediate resource which is not directly observable or traded in the commodity market, and thus difficult to value through direct market prices. Instead, valuing biological nitrogen derived from legume-based symbiotic nitrogen fixation (SNF) requires the application of indirect methods, such as shadow pricing.

Valuing soil-fertility benefits can help ascertain the economic importance of LBCS, and justify the role of legumes in conservation agriculture and sustainable environmental management. Currently, legume intensification is being promoted in sub-Saharan Africa as one of the strategies under conservation agriculture (Giller et al., 2009; Thierfelder et al., 2013). For example, in Malawi, the Government has included legume seed as part of the targeted farm input support program. The farm-subsidy program promotes both chemical and biological (legumes) fertilisers. Coincidentally, the impact of conservation agriculture practices is not well researched in the case of Malawi and other African countries (Giller et al., 2009; Thierfelder et al., 2013). Therefore, accurate information on the economic benefit of SNF will be useful for policy interventions that promote conservation agriculture across Africa.

A few studies have attempted to value SNF (Pannell and Falconer, 1988; Döbereiner, 1997; Smil, 1999; Herridge et al., 2008; Chianu et al., 2011). Apart from Pannell and Falconer (1988) and Schilizzi and Pannell (2001) who use bioeconomic modelling to value SNF, previous studies have mainly applied the replacement cost method to estimate the value of SNF (Smil, 1999; Herridge et al., 2008; Chianu et al., 2011). The replacement cost method, for example, assumes that two alternative inputs are perfectly substitutable; and thus, the estimates from this method do not capture changes in the degree of input substitutability. We address this limitation by adopting an econometric approach, and use the ratio of marginal products to determine the degree of input substitutability for alternative inputs. In our approach, we apply the directional distance function (DDF) technique to estimate shadow prices for SNF. The shadow price reflects the trade-off between commercial nitrogen from fertilisers and symbiotic nitrogen from LBCS required to produce a given quantity of output. Thus, shadow prices represent the benefit of using SNF as a production input.

The paper makes a contribution to the literature in two ways. First, we demonstrate the application of DDF, as an alternative technique, to value the contribution of SNF as a factor of production. To the best of our knowledge, this is the first study to apply DDF to value SNF.

Second, we apply bootstrapping technique to the DDF as a robustness check (Canty, 2002; Canty and Ripley, 2015). Compared to other frontier-based approaches, the DDF represents a flexible technique that can derive an inefficiency measure that accounts for possible input reductions and output enhancements, simultaneously. In other words, with the DDF it is possible to set an appropriate scaling vector that evaluates the extent to which the technology can achieve input-savings, output-expansion, or both. This scaling would not be possible if the Shephard (radial) distance function approach were estimated (Färe et al., 2008). The other advantage of using the DDF is that the individual firm's inefficiencies can be summed over into an aggregate measure of industry inefficiency (Färe et al., 2009). Further, the DDF, like its radial counterpart, can be used to represent multi-input, multi-output production technologies. Finally, by using the bootstrapping technique, we are able to get a sense of the variability surrounding shadow price and technical efficiency estimates. Although a non-frontier production function could be used to determine shadow prices, as in Barbier (1994) and Magnan et al. (2012), such an approach does not account for firm inefficiencies. Given the extent of inefficiency routinely reported in studies evaluating the performance of smallholder agriculture, it is more appropriate to use frameworks that allow for the estimation of inefficiency and shadow prices.

The rest of the paper is organised as follows. In the next section we present a theoretical representation of the DDF, followed by empirical estimation procedures. We describe the study site and data in Section 4. Finally, empirical results are discussed in Section 5 and conclusions are presented in Section 6.

2. Theoretical representation

The productive efficiency of a firm is determined by comparing its inputs and outputs against the boundaries of the best-practice frontier. A firm's measure of inefficiency is given by how far that firm is, relative to the frontier boundary. Denote production inputs by $x=\left(x_1,x_2,.....,x_N\right)\in\mathbb{R}_+^N$ and outputs by $y=\left(y_1,y_2,.....,y_M\right)\in\mathbb{R}_+^M$. Then a production technology can be defined as the set of feasible input-output combinations or $T=\{(x,y):x\in\Re_+^N,\ y\in\Re_+^M,\ x\ can\ produce\ y\}$.

The DDF inherits the standard properties imposed on the production technology set, T (Chambers et al., 1996; Färe et al., 2008). We assume that T is a closed, convex, nonempty set with inputs and outputs freely disposable (Färe et al., 2006; Färe et al., 2008). Other important properties of the DDF technology include: 1) representation or that all technologically feasible input-output combinations have non-negative directional distance function value, and vice-versa; 2) translation or that adding a multiple of the direction vector to the input-output bundle reduces the distance function by that multiple; 3) monotonocity in the sense that the function is non-decreasing in inputs and non-increasing in outputs; and 4) the function is concave in the input-output vector (Chambers et al., 1996; Färe et al., 2008).

The directional distance function, $DDF(x,y;\ g_x,g_y)=\sup_{\beta}\left\{\beta\!:\ (x-\beta g_x,\ y+\beta g_y)\in T\right\}$, represents the technology and helps to measure a firm's level of inefficiency. The vector, $g(g_x\in\Re_+^N, g_y\in\Re_+^M)$, is the translation metric which maps the directions in which inputs and outputs are scaled. Thus, the translation vector seeks to achieve maximum (desirable) output expansion in the g_y-direction and input contraction in the g_x-direction. For any firm on the frontier boundary $DDF(x, y; g_x, g_y) = 0$, indicating that it is technically infeasible to translate the input-output bundle in any direction. Conversely, any firm below the technology frontier has a positive distance value, $DDF(x, y; g_x, g_y) > 0$, such that the observed input and output bundles can be translated in the direction given by $g(g_x, g_y)$. The alternative distance function specification is the radial approach, where the analyst has no control over the projection path to the frontier (Färe et al., 2008), as the direction depends on the mix of inputs or outputs in the observation. The radial input (output) distance function values reflect the highest (smallest) possible proportionate reduction in inputs (outputs).

We derive shadow prices of SNF exploiting the duality relationship between the DDF and the cost function. Let $w = \left(w_1, w_2, \ldots.., w_N\right) \in \mathbb{R}_+^N$ denote the vector of input prices for which the shadow cost function is given by:

$$C(y, w) = \underset{x}{i\,nf} \left\{wx : x \in T\right\} \tag{1}$$

It follows from the principle of cost minimisation that $C(y, x) \leq wx \quad \forall x \in T$. That is, the minimum cost cannot exceed the actual cost of producing $y \in \Re_+^M$. Achieving input-efficiency implies that $x - \left(DDF(y, x : g_x).g_x\right) \in T$. Thus, for any production situation where technical inefficiency can be reduced or eliminated, the minimum cost ought to be lower than the actual costs as follows:

$$C(y, x) \leq w(x - \left(DDF(y, x : g_x).g_x\right) = wx - wg_x DDF(y, x : g_x) \tag{2}$$

By rearranging equation (2), the duality relationship between the cost function and the DDF can be expressed as (Chambers et al., 1996; Färe et al., 2009):

$$DDF(y,x:g_x)=\min_{w}\left\{\frac{wx-C(y,x)}{wg_x}\right\} \tag{3}$$

Applying the envelope theorem to equation (3), yields the following normalised input price vector:

$$w_n = wg_x\frac{\partial DDF(x,y;g)}{\partial x_n} \qquad n=1,2,.......N \tag{4}$$

Provided that the DDF is differentiable, one can estimate partial derivatives and use these to derive shadow prices. For any two different inputs, n and n', it follows that their price ratio equals the corresponding ratio of distance function derivatives. The ratio of distance function derivatives indicates the marginal rate of technical substitution as expressed in equation (5) below (Chambers et al., 1996):

$$\frac{w_n}{w_{n'}}=\frac{\partial DDF(x,y;g_x,g_y)/\partial x_n}{\partial DDF(x,y;g_x,g_y)/\partial x_{n'}}=\frac{MPx_n}{MPx_{n'}} \qquad \forall\ n,\ n' \tag{5}$$

where w_n is the price for the n^{th} production factor (x_n), and MP is the marginal product with respect to x_n.

In addition to the marginal products, one can also obtain technical (in)efficiency measures, if a frontier-based technical relationship is specified. For a directional distance measure of inefficiency, zero distance indicates that a firm is fully efficient, and a positive distance-function value shows the level of inefficiency as follows:

$$TI(x,y)=DDF(x,y;g_x,g_y) \tag{6}$$

3. Empirical estimation

Nonparametric approaches [e.g. data envelopment analysis (DEA)] and parametric methods can be used to estimate the DDF parameters. However, DEA generates a piece-wise frontier and it is not easy to recover shadow prices from it. Therefore, parametric approaches have dominated empirical applications. Applications that have used deterministic parametric frontiers (e.g. Piot-Lepetit and Vermersch, 1998; Hailu and Veeman, 2000; Bond and Farzin, 2007; Bostian and Herlihy, 2014) tend to employ mathematical-programming methods. Besides the deterministic approach, the parametric distance function can be specified as a stochastic-frontier model. These stochastic frontiers can be estimated using maximum likelihood methods (e.g. Coelli and Perelman, 2000) or using Bayesian methods (e.g. O'Donnell and Coelli, 2005; Hailu and Chambers, 2012). Although one could easily impose monotonicity conditions using Bayesian methods, the choice of proper priors on the parameters of frontier models is not straightforward. Use of improper priors in stochastic frontier models can affect the accuracy of the posterior estimates (Fernández et al., 1997; Fernández et al., 2000). Apart from Bayesian stochastic methods, theoretical regularity restrictions can be imposed using a deterministic frontier approach (Hailu and Chambers, 2012). We therefore estimate the DDF as a deterministic frontier using mathematical-programming technique to impose representation, montonicity and translation conditions.

The quadratic functional form is used because it is the flexible form that allows for the global imposition of the translation property (Hailu and Chambers, 2012). We choose the unit directional vectors, with positive elements for output and negative elements for inputs, so that the projection to the frontier of an observed point seeks to expand output and contract inputs concurrently. Since the data are normalised by mean values, the use of the unit vector for direction is equivalent to the use of the average sample direction for the translation. The quadratic DDF is specified as follows:

$$DDF(x,y;\ \text{-1},\ 1) = \beta_0 + \sum_{n=1}^{N}\beta_n x_n + \sum_{m=1}^{M}\beta_m y_m + 0.5\sum_{n=1}^{N}\sum_{n'=1}^{N}\beta_{nn'}x_n..x_{n'} \\ +0.5\sum_{m=1}^{M}\sum_{m'=1}^{M}\beta_{mm'}y_m.y_{m'} + \sum_{m=1}^{M}\sum_{n=1}^{N}\beta_{mn}y_m.x_n + u \qquad (7)$$

where y_m represents the production output under consideration, x_n is a vector of inputs, and u represents the inefficiency term. Equation (7) is estimated using the APEAR software (Hailu, 2013).

The underlying distance function and parameter values (β_s and u) are based on a true, but unobserved technology frontier. Typically, the estimated frontier and parameters depend on a sample of observations, usually believed to be representative of the true population. Thus, one empirical challenge is to mitigate the potential bias that could result from small samples and sampling variability. Therefore, we apply nonparametric bootstrapping techniques to explore the variability of our sample estimates. Using the bootstrapping procedure explained in Canty (2002) and Canty and Ripley (2015), the estimation of the function in equation (7) was bootstrapped a thousand times, whereby each pseudo (bootstrap) sample was drawn with replacement from the original sample.

4. Study area and data description

4.1 Study area

We use survey data collected from Kasungu and Mzimba districts in Malawi. The survey was conducted in the 2013/14 crop season. These districts fall under the medium altitude agro-ecological zone of the country. A subdivision of this agro-ecological zone is the Kasungu–Lilongwe plain. This zone is one of the areas where the LBCS are most dominant in the country.

The survey followed a three-stage random sampling approach: first, the study zones were selected based on Ministry of Agriculture administrative demarcations, known as extension planning areas (EPAs). The EPAs are district-level administrative units established to coordinate and oversee the execution of extension services across the country. The second step involved the choice of an EPA section. An EPA section is the lowest unit of administration in the Ministry of Agriculture hierarchy. Finally, after the selection of EPAs and sections was completed, face-to-face interviews were conducted with a set of randomly chosen respondents (household heads).

4.2 Data description

The survey collected information on farm and household characteristics. We use primary data from a sample of 135 plots, representing the mixed maize-legume cropping system. Typically, farmers intercropped maize with common beans (*Phaseolus vulgaris*), groundnuts (*Arachis hypogaea*) or soybean (*Glycine max*). Table 1 summarises the data. The total crop value is an aggregate of maize and legume grain produced jointly on a farm, in the same season. There is wide variation in the amount of output ranging from MWK[1]1,200/acre (US$3.5/acre) to over

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[1] The crop value is measured in local currency unit, Malawi Kwacha (MWK). Exchange rate at the time of the survey was 1US$ = MWK350

MWK170,000/acre (US$492/acre). On average, maize output represents the greatest share, accounting for about 70 per cent of total crop value.

Table 1 Descriptive statistics for the variables used in the estimation (*n* = 135)

Variable name	Mean	SD	Min.	Max.
Output				
Crop value (MWK/acre)	41 962	32 283	1211	172 346
Inputs				
Fertiliser nitrogen (kg N /acre)	27.3	19.8	0	109.0
Symbiotic nitrogen (kg N/acre)	0.7	1.1	0	11.1
Labour (AEU/acre)	1.9	1.3	0.2	8.1
Other input costs (MWK/acre)	4,088	6,753	0	53,275

Note: MWK=Malawi Kwacha (1US$ = MWK350); AEU = adult-equivalent units

Four production inputs are included in the estimation of the distance function. These inputs are quantity of commercial fertilizer, expressed in kilograms of total nitrogen as the major active ingredient[2]; family labour, converted to adult-equivalent-units (AEU/acre)[3]; symbiotic nitrogen (kg N/acre); and farm expenses, represented by cost of seeds, manure, herbicides and other variable expenses. Symbiotic nitrogen is included as an additional source of nitrogen available for the component crops.

SNF values are not directly observable. However, the literature currently contains abundant SNF estimates that are obtained using reliable measurement methods, such as ^{15}N-based

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[2] The main mineral fertilisers used in the maize-based production systems are Urea, Calcium Ammonium Nitrate and 23:21:0+4S. These three fertilisers, respectively, contain 46%, 27% and 23% nitrogen (N).

[3] Adult equivalent unit (AEU) refers to full-time equivalent of farm labour supply computed on the basis of the following conversion factors: adult male ($\geq$ 15 years of age) = 1 AEU; adult female = 0.8 AEU; and children, male or female (5-14 years) = 0.5 AEU.

techniques (Peoples et al., 2009; Ronner and Franke, 2012). We use published SNF estimates to compute the amount of symbiotic N fixed on agricultural land. The quantity of symbiotic nitrogen is computed based on the harvest index method, which relates plant biomass, nitrogen concentrations and the proportion of atmospheric nitrogen fixed (Høgh-Jensen et al., 2004; Herridge et al., 2008; Peoples et al., 2009). Computation details are provided in the appendix and summarised in Table A1.

SNF is estimated for intercropping and rotation cropping practices. SNF benefits from intercropping are estimated using the harvest index method (see Table A1). We also account for rotational effects on SNF using coefficients obtained from fitting a crop-response model (Stauber and Burt, 1973; Stauber et al., 1975; Frank et al., 1990) estimated as a quadratic function (8) to allow for diminishing marginal productivity:

$$y_t = \alpha_0 + \alpha_n N_t + \alpha_i x_{it} + \alpha_{nn} N_t^2 + \alpha_{ii} x_{it}^2 + \alpha_{ni} N_t . x_{it} + \alpha_{n'} N_{t-1} + \varepsilon_t \qquad i = 1, 2, ..., I \qquad (8)$$

where y_t is output in the current season *t*, N_t is the quantity of nitrogen applied in the current season, N_{t-1} is the carry-over nitrogen from the previous season, x represents other factors of production, and ε is the random error term. Table A2 shows the results of the crop-response model.

In our sample, crop rotations had been adopted on 61 farms (45 per cent). Out of these 61 farms, 72 per cent were legume-maize rotations and most of the remaining (23 per cent) were tobacco-maize rotations. Further, 52 per cent of the sample (135 farms) practiced crop residue retention, a practice aimed at enhancing soil productivity through residue mineralisation. We use this plot-history data to test whether crop rotation has significant effects on land productivity (i.e. crop yield) and the evidence suggests positive incremental effects (Table A2).

The net residual nitrogen is then estimated implicitly as a ratio of input elasticities for the intercropped SNF and the rotation variables.

5. Results and discussion

The coefficient estimates of the directional distance function are reported in Table A3. The estimated first-order coefficients have the expected signs: they are positive for inputs and negative for output variables, with generally small standard errors.

5.1 Estimated measure of technical efficiency

Recall that technical inefficiency is given by the relative distance to the frontier, and the shorter the distance the more efficient the production unit is. Table 2 presents the results of the DDF measure of technical inefficiency (TI). The DDF estimates reveal a considerable level of inefficiency for the sample farms. Only 24 farms (representing 18 per cent of the total sample) were operating at maximum efficiency. The mean TI obtained from the bootstrap model is 0.37 compared to 0.33 from the the base model. The TI obtained using the base (non-bootstrap) model is significantly lower than that obtained using the bootstrap model ($p<0.1$). Therefore, the base model underestimates technical inefficiency. Generally, it is the bootstrap estimates that are considered plausible and robust (Mugera and Ojede, 2014). Thus, the TI estimate of 0.37 implies that each farmer could reduce its current level of input use by 37 per cent of the average input bundle, while at the same time increasing its output level by the same margin (i.e. 37 per cent of the mean crop value).

Table 2 Estimated directional distance measure of technical inefficiency (TI)

	Mean inefficiency	SE	[95 per cent confidence interval]
Base model	0.33	0.02	[0.28-0.37]
Bootstrap model	0.37	0.04	[0.28-0.45]

Our findings are comparable with previous studies conducted in the region, although few studies have applied directional distance functions on African agriculture. For example, using a directional distance function, Singbo and Lansink (2010) reported mean inefficiency of 0.20 for the Beninese rice and vegetable production system. In another study, Singbo et al. (2014) evaluated the performance of vegetable-production in Benin and reported TI of 0.14 and marketing inefficiency of 0.25. Mulwa and Emrouznejad (2013) evaluated the performance of sugarcane production in Kenya and estimated TI to be 0.14. The evidence from previous studies and the present one shows that there is room for performance improvement in the studied production systems and African agriculture in general.

5.2 Morishima elasticity of input substitution

The Morishima elasticity of substitution (MES) provides complete information about input substitutability in cases where a production technology has more than two inputs (Blacorby and Russell, 1989). The MES measures the degree of curvature of the isoquant or the relative change in shadow prices associated with a unit change in the ratio of the corresponding inputs (Grosskopf et al., 1995). We calculate the indirect Morishima elasticities to get a sense of the ease with which one input can be substituted for another in the production process. Equation

(9) shows the MES derived from the distance function approach (Blacorby and Russell, 1989; Grosskopf et al., 1995):

$$MES_{nn'} = x^{*}_{n'} \left[\frac{DDF_{nn'}}{DDF_{n}} - \frac{DDF_{n'n'}}{DDF_{n'}} \right] \tag{9}$$

where x^{*}_{n} is the frontier value of input (input level adjusted for inefficiency), DDF_n and DDF_{nn} are the first-order and second-order derivatives of the directional distance function, respectively. The MES estimates are reported in Table 3.

Table 3 Estimates of the indirect Morishima elasticity of substitution

	f	*s*	*l*	*o*
f	-1.183	1.469	2.523	0.988
s	0.019	-0.061	0.105	0.041
l	0.619	0.672	-0.004	-0.322
o	0.922	0.909	0.898	-0.929

Note: *f* = fertiliser nitrogen, *s* = symbiotic nitrogen, *l* = family labor; *o* = other input costs

The sign and size of the MES are important: the elasticity sign helps to classify inputs as substitutes or complements, whereas the size of the elasticity indicates the degree of substitutability or complementarity. Inputs n and n' are considered to be Morishima substitutes if $MES_{nn'} > 0$, or complements if $MES_{nn'} < 0$. The high MES values show a low degree of substitution and low values indicate relative ease of substitution (Grosskopf et al., 1995). As can be noted in Table 3, MES elasticities are generally asymmetric ($MES_{nn'} \neq MES_{n'n}$). For example, the substitution of commercial fertiliser for symbiotic nitrogen gives an elasticity value 1.45, whereas the reverse yields 0.02. The size and sign of the elasticities suggest that the two inputs are partially substitutable; thus, increasing fertiliser nitrogen to replace symbiotic nitrogen is relatively difficult but the reverse is relatively easy.

5.3 Estimates of SNF shadow prices

We apply equation (5) to obtain shadow prices for SNF. The value of SNF is estimated to be a fraction of the average market price for fertilizer nitrogen (US$2.11/kg N)[4]. The estimated shadow values can be interpreted as the opportunity cost of biological nitrogen in terms of foregone commercial nitrogen, keeping output constant. An alternative interpretation of shadow price values is to regard them as surrogate or implicit prices for a nonmarket good (SNF). In this regard, the commercial fertiliser market serves as a proxy market for its SNF substitutes or complements. Table 4 gives a summary of shadow prices for the base and bootstrap models. The shadow price values are positive and range from 0.18 to 6.34 US$/kg, when evaluated at the 95 percent confidence interval. The mean shadow price for SNF is estimated to be US$2.53/kg for the bootstrap model, and US$5.17/kg for the base model. The difference between the two mean shadow prices is statistically significant ($p<0.01$). We note that both the base and the bootstrap models yield average shadow prices that are higher than the reference market price of $2.11 $/kg N. The mean shadow price of US$2.53/kg could serve as an appropriate accounting value for fertiliser cost-savings, achieved as a result of substituting SNF for fertiliser N. This price represents the per-unit benefit that a producer would gain by using organic nitrogen as a substitute for fertiliser nitrogen (Bond and Farzin,

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[4] The average of $2.11 is based on the market price of fertiliser nitrogen (UREA). In the 2013/14 crop season, the average commercial price for Urea fertilizer (46% N) was MWK17000 per 50kg bag, which is equivalent to US$2.11/kg N. Exchange rate: 1 US$ = MWK 350

2007). For example, a farm operating without any unit of SNF would increase crop output-value by $2.53 if an extra kilogram of SNF were available in the soil.

Table 4 Estimated shadow prices for symbiotic nitrogen (US$/kg N)

	Mean	SE	[95 percent confidence interval]
Base model	5.17	0.59	[4.00-6.34]
Bootstrap model	2.53	1.19	[0.18-4.87]

Because shadow prices for SNF are not readily available in the literature, we compare our estimates against somewhat related environmental services. Table 5 presents these studies. The analysis of sustainable intensification or best management practice most closely related to ours is an application by Bond and Farzin (2007), which deals with the effect of low input production system using legume cover-crops, herbicides, and air pollution in California, USA. Unfortunately, due to limitations in their soil quality data, the study did not include shadow prices for non-marketable inputs (legume-fertiliser effects). Other studies that have treated nitrogen leachate from agricultural sources as a bad output are Shaik et al. (2002), who studied the effect of organic and inorganic fertilisers in the USA, Reinhard et al. (1999), who assessed the Dutch dairy industry, and Piot-Lepetit and Vermersch (1998), who analysed the French pig sector. From these studies, the estimated shadow prices for excess nitrogen are reported to be in the range of US$2.00-4.77/kg for the US study, $1.86/kg for The Netherlands and $0.14-1.02/kg for the French pig sector. Recently, Hou et al. (2015) estimated the cost of soil erosion and nitrogen loss in the Chinese Ansai region. Form this study, the cost of soil erosion and nitrogen loss are estimated to be $0.02/kg/ha and $0.06/kg/ha, respectively. The reviewed studies show variations in the estimated shadow price values. The variation in the shadow price estimates in the above studies is not surprising because each study dealt with a different sub-sector that could differ in a number of ways, including operational scale and local environmental conditions at the study locations. Our results are closer to the estimates for the US and the Netherlands.

Table 5 Selected studies using production and distance functions to value environmental goods and services

Environmental good/service	**Shadow price/value**	**Reference price/ market**	**Estimation method**	**Efficiency score**	**Study region**	**Reference**
Organic N (hog slurry)	\$0.14-1.02/kg	Commercial fertiliser	RDF/DEA	0.94-0.96	France	Piot-Lepetit and Vermersch (1998)
Organic N (dairy slurry)	\$1.86/kg	Dairy output	SFA	0.89	Netherlands	Reinhard et al. (1999)
Conservation land	\$2236/acre	County income	DDF	0.05	Missouri, USA	Färe et al. (2001)
Soil N (N pollution)	\$2.00-\$4.77/kg	Desirable output (crop and livestock products)	RDF	-	Nebraska, USA	Shaik et al. (2002)
Soil N (N pollution)	\$3.81-\$4.30/kg	Input cost (crop and livestock production)	RDF	-	Nebraska, USA	Shaik et al. (2002)
Ground water	\$0.02/m^3	Crop revenue	RDF/SFA	0.47-0.94	Kiti region, Cyprus	Koundouri and Xepapadeas (2004)
Pesticide leaching	0.051	Crop price	DDF	0.09	USA	Färe et al. (2006)
Pesticide run-off	0.002	Crop price	DDF	0.09	USA	Färe et al. (2006)
Pesticide pollution	\$37/pint	Corn and tomato	DDF	0.79	California Davis, USA	Bond and Farzin (2007)
Fishing licence	\$37906/licence	Fish feed	DDF	0.74	Norway	Färe et al. (2009)

Table 5 continued

Environmental good/service	**Shadow price/value**	**Reference price/ market**	**Estimation method**	**Efficiency score**	**Study region**	**Reference**
Crop stubble	\$1.00-3.20/day	Straw and feed price	PF	-	Morocco	Magnan et al. (2012)
Wetland quality	\$18.77(\$19.83)/acre	Crop value	DDF (bootstrap)	0.36 (0.36)	Nanticoke, USA	Bostian and Herlihy (2014)
Fertiliser N	\$1.38 x 10^{-3} -\$2.17 x 10^{-3}	1	DEA (bootstrap)	0.64-0.88 (0.31-0.78)	Benin	Singbo et al. (2015)
Insecticides	\$1.21 x 10^{-6} - \$8.70 x 10^{-4}	1	DEA (bootstrap)		Benin	Singbo et al. (2015)
Other pesticides	\$6.07 x 10^{-6} -\$9.51 x 10^{-4}	1	DEA (bootstrap)		Benin	Singbo et al. (2015)
Soil erosion	\$0.02/kg/ha	Crop revenue	DDF	-	Ansai County, China	Hou et al. (2015)
Soil N loss	\$0.06/kg/ha	Crop revenue	DDF	-	Ansai County, China	Hou et al. (2015)
Symbiotic N	\$5.17/kg	Commercial fertiliser price	DDF	0.33	Malawi	This study
Symbiotic N	\$2.53/kg	Commercial fertiliser price	DDF (bootstrap)	0.37	Malawi	This study

Note: DDF = directional distance function; DEA = data envelopment analysis; PF = production function; RDF = radial distance function; SFA = stochastic frontier analysis

Conclusions

The challenge of maintaining or improving agricultural productivity in sub-Saharan Africa is enormous. As such, agricultural researchers and policy makers are constantly looking for technologies that are economically attractive and environmentally sound. The best strategy to improve productivity and maintain soil fertility in sub-Saharan Africa should focus on a combination of both inorganic and organic fertilizers for maximum complementary benefits (Mafongoya et al., 2007). However, research evidence shows low adoption of integrated soil fertility management practices, which includes legume cultivation (Giller et al., 2009). A better understanding of the value of these legume systems is needed to develop more effective economic incentives that would facilitate the adoption of best management practices and reward soil conservation efforts.

Using the directional distance function approach, this study appraised the value of symbiotic nitrogen and estimated the technical efficiency of legume-based cropping systems (LBCS) in Malawi. Our results reveal two major findings. First, the results show that smallholder farmers exhibit substantial production inefficiency, with a mean directional inefficiency value of 37% relative to the average farm in the sample. By addressing this production inefficiency, input use could be reduced by more than a third while output is simultaneously increased by the same proportion. Second, the average shadow price for symbiotic nitrogen is higher than the observed market price for commercial nitrogen fertiliser. The shadow price values of symbiotic nitrogen (and LBCS) reflect only productivity benefits. The total value of LBCS could be greater if other environmental services and socio-economic benefits, such as disease break and soil erosion control effects, are accounted for.

In the interest of maintaining a productive stock of soil capital, market-based mechanisms could be used to help enhance legume production and promotion of conservation agriculture. One of the possible policy options is to facilitate price premiums for organic produce. For example, a recent study has shown that consumers in Tanzania are willing to pay higher prices for organic tomatoes than those produced using synthetic inputs (Alphonce and Alfnes, 2012). Our estimated elasticities of input substitution demonstrate that a complete substitution to organic fertilisers can be detrimental to farm productivity, and will thus require some compensation in terms of high output prices for such a substitution to be profitable. Price premiums can provide incentives to farmers to invest in organic fertilisation practices that maintain or improve soil quality. Organic soil amendments build long-term soil fertility benefits that are usually heavily discounted by land users, who mostly seek to maximise their present farm benefits. As a result, there is less investment in conservation practices by the land users, partly because organic produce are considered as a non-differentiated product. Thus, the prevailing commodity prices underpay and deprive farmers of the revenues that would otherwise make conservation agriculture more attractive. We contend that price premiums could be a better alternative and more cost-effective policy instrument for promoting LBCS than the subsidies or public-support programs that are currently being used to promote legume production in Malawi and other African countries. We therefore recommend that future research should investigate the potential demand for organic produce, and mechanisms through which farmers can be integrated into existing or emerging regional and export markets for organic produce. Policy makers could focus on creating and promoting an enabling environment that allows the potential benefits of LBCS to be fully exploited by: 1) promoting knowledge about soil and other benefits of the integrated cropping systems; 2) supporting organic farming practices through certification and labelling requirements; and 3) channelling support from current input subsidies to the support of extension and market development activities.

Appendix

Computation of symbiotic nitrogen using the harvest index approach

The quantity of grain harvested reflects directly the total amount of crop N that the plant fixes, and some of this nitrogen is assimilated in the grain and straw or biomass. The quantities of biological nitrogen fixed (BNF^F) and the resulting nitrogen transfer to companion crop (BNF^{cc}) are derived from above-ground and below-ground biomass as follows (Herridge et al., 2008; Høgh-Jensen et al., 2004; Peoples et al., 2009):

$$BNF^F = \varphi N^{cn} \; ; N^{cn} = \left(\gamma_s Q_s\right)\delta \tag{A1}$$

$$BNF^F = \varphi\left[\left(\gamma_s Q_s\right)\delta\right] \tag{A2}$$

$$h = \frac{Q_g}{Q_g + Q_s}; \qquad Q_s = \left(\frac{1-h}{h}\right)Q_g \tag{A3}$$

$$BNF^F = \varphi\left[Q_g\left(\frac{1-h}{h}\right)\gamma_s\delta\right] = \varphi\gamma_s\delta Q_g\left(\frac{1-h}{h}\right) \tag{A4}$$

$$BNF^{cc} = \left[\varphi\gamma_s\delta Q_g\left(\frac{1-h}{h}\right)\right]\phi \tag{A5}$$

where φ represents the proportion of crop N that is derived from the atmosphere (%Ndfa), and γ_s is the percent N-concentration available in the shoot dry matter. The parameter δ is used to derive below-ground biomass-N equivalent of the shoot dry matter. Equation (A1) shows that the amount of nitrogen fixed is given as a product of crop-N concentration (N^{cn}) and the capacity for that crop to transform atmospheric nitrogen (φ) into a form that is usable by plants. The ability to convert atmospheric-nitrogen into plant-nitrogen is represented by the fractional N derived from atmosphere (%Ndfa) i.e. a proportion of total crop N that is attributable to symbiotic nitrogen fixation. The crop nitrogen concentration can be expressed as the amount of shoot dry matter at harvest (Q_s) and the percent N-concentration (γ_s) available in that component of plant biomass. The parameter δ is used to derive below-ground biomass-N equivalent of the shoot dry matter (Equation A2).

In situations where biological yield is not reported as part of the normal crop statistics, the quantity of dry matter can be estimated from the amount of grain harvested (Q_g) using the harvest index (h) as denoted in equation (A3). For grain crops, the harvest index is a ratio of the economic yield (grain) and the above-ground biomass (i.e. shoot dry matter inclusive of grain). In equations (A4)-(A5), grain weight and harvest index substitute for the quantity of dry matter, Q_s. Finally, the N transfer/credit available for the companion crop (BNF^{cc}) in equation (A5), allows for low crop density due to intercropping and interference of fertiliser N (Stern, 1993; Smil, 1999; Herridge et al., 2008; Unkovich et al., 2008). We use the adjustment coefficient, ϕ, to cater for the intercropping and fertiliser suppression effects. Parameter values used to estimate equations (A1-A5) are synthesised from various long-term agronomic experiments as reported in the original publications (Table A1). Alternatively, one could use total area under leguminous crops to quantify farm-level symbiotic nitrogen. However, we prefer to use grain-weight, because the quantity and quality of grain harvested also reflects the growth conditions in which the crop developed and matured (Stern, 1993).

Table A1 Estimates of SNF for the sample grain-legume cropping systems

Parameter	Notation	Data source[‡]	Mean		
			Beans	Groundnuts	Soybeans
Grain harvested (kg/acre)	Q_g	1	49.03	96.41	67.01
Harvest index	h	2	0.35	0.4	0.4
Dry matter yield (kg/acre)	$Q_s = \left(\frac{1-h}{h}\right)Q_g$	8	91.05	144.62	100.52
Dry matter N concentration (%)	γ_s	2	2.0	2.3	3.0
Below-ground N conversion factor	δ	2	1.4	1.4	1.5
Average %Ndfa	φ	3	44	51	40
Amount of N fixed (kg/acre)	$BNF^F = \varphi\gamma_s\delta Q_g\left(\frac{1-h}{h}\right)$	8	1.12	2.37	2.31
N-credit transfer factor (%)	ϕ	4,5,6,7	40	40	20
Total N-transfer to a non-legume crop (kg/acre)	BNF^{cc}	8	0.45	0.95	0.46

[‡] 1: Own survey; 2: Herridge et al. (2008); 3: Ronner and Franke (2012); 4: Smil (1999), 5: Sanginga et al. (2003), 6: Chianu et al. (2011), 7: Patra et al. (1986), 8: Own computation

Table A2 Coefficient estimates for the quadratic crop-response model

Variable	Variable unit	Coefficient estimate	Robust SE	t-value
Constant	-	-0.21	0.20	-1.05
Fertiliser N	kg N/acre	0.55^{**}	0.24	2.27
Symbiotic N	kg N/acre	0.29^{**}	0.12	2.46
Labour	AEU/acre	0.43^{**}	0.18	2.44
Other expenses	MKW/acre	0.08	0.11	0.76
$(\text{Fertiliser N})^2$		0.02	0.18	0.10
$(\text{Symbiotic N})^2$		0.02	0.03	0.53
$(\text{Labour})^2$		-0.35^{***}	0.10	-3.34
$(\text{Other expenses})^2$		0.04^{*}	0.02	1.76
Fertiliser N x Symbiotic N		-0.13	0.10	-1.37
Fertiliser N x Labour		0.07	0.23	0.28
Fertiliser N x Other expenses		-0.11	0.07	-1.48
Symbiotic N x Labour		0.13	0.11	1.21
Symbiotic N x Other expenses		-0.01	0.04	-0.24
Labour x Other expenses		0.01	0.07	0.11
Legume break 2012/13 season	1 if a legume was the main crop grown on the plot one year ago	0.33^{***}	0.12	2.82
Tobacco break 2012/13 season	1 if tobacco was the main crop grown on the plot one year ago	0.19	0.15	1.29
Monoculture 2012/13 season	1 if maize was the main crop grown on the plot one year ago	0.18^{*}	0.10	1.93
Sowing time	Time of planting relative to first rains (weeks after first rains)	-0.09	0.06	-1.57
R^2		0.62		

Note: The dependent variable is aggregate crop value per acre, expressed in Malawi kwacha; SE=standard error; $^{*}p<0.10$; $^{**}p<0.05$; $^{***}p<0.01$; $n=135$

Table A3 Estimated parameters for the quadratic directional distance function

Variable	Coefficient	Estimate	BC estimate	SE.
Intercept	β_0	0.034	-0.017	0.090
y_1	β_1	-0.371	-0.335	0.091
x_1	β_2	0.306	0.381	0.090
x_2	β_3	0.104	0.084	0.082
x_3	β_4	0.192	0.169	0.097
x_4	β_5	0.026	0.031	0.027
$y_1.y_1$	β_{11}	0.050	0.058	0.044
$y_1.x_1$	β_{12}	-0.018	-0.050	0.033
$y_1.x_2$	β_{13}	0.018	0.015	0.033
$y_1.x_3$	β_{14}	0.054	0.101	0.045
$y_1.x_4$	β_{15}	-0.005	-0.009	0.008
$x_1.x_1$	β_{22}	-0.084	-0.104	0.048
$x_1.x_2$	β_{23}	-0.018	-0.059	0.045
$x_1.x_3$	β_{24}	0.084	0.113	0.048
$x_1.x_4$	β_{25}	0.000	0.000	0.009
$x_2.x_2$	β_{33}	-0.015	-0.001	0.029
$x_2.x_3$	β_{34}	0.052	0.076	0.037
$x_2.x_4$	β_{35}	-0.001	0.000	0.006
$x_3.x_3$	β_{44}	-0.079	-0.080	0.037
$x_3.x_4$	β_{45}	-0.003	-0.007	0.008
$x_4.x_4$	β_{55}	-0.001	-0.001	0.005

Note: BC= bias corrected; SE = bootstrap standard error

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