A Within-Farm Efficiency Comparison of Silvopasture Systems with Conventional Pasture and Forestry in Northeast Argentina

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ABSTRACT. *Agroforestry, which has multiple inputs and outputs, would benefit from scrutiny of economic efficiency because levels of adoption have not met expectations. Previous literature estimated the efficiency of agricultural systems using data envelopment analysis; however, the vast variability between farms makes comparing systems difficult. This study uses paired, within-farm comparisons of silvopasture, a combination of planted trees and pasture, to conventional cattle-ranching and plantation forestry, to evaluate the relative technical efficiency. Silvopasture proves to be more efficient than conventional cattle-ranching. Forestry demonstrated increasing returns to scale, cattle-raising demonstrated decreasing returns to scale for large-scale farmers, and silvopasture was intermediate.* (JEL D24, O13)

I. INTRODUCTION

Agroforestry systems combine annual crops and/or livestock with trees or other woody perennials. A particular type of agroforestry, called silvopasture, is the combination of livestock, forage, and trees on the same plot of land. Researchers and extension agents have encouraged the adoption of silvopasture systems in various regions throughout the world, including the northeast region of Argentina. These recommendations are based on findings from experimental plots, and limited data on real farms, indicating that silvopasture is more productive than other conventional, single-output land uses such as forest plantations or full-sun pasture (Colcombet et al. 2004, 2010; Esquivel et al. 2004; Fassola, Lacorte, Esquivel, et al. 2004), as well as providing some environmental benefits (Fassola et al. 2010). However, silvopasture adoption levels have been moderate at best, raising the question of whether adopters are actually realizing the purported high levels of productivity. The primary objective of this study is to compare the economic efficiency of silvopasture systems relative to forest plantations and full-sun pasture on functioning farms, in order to test the hypothesis that silvopasture is more efficient in the northeastern region of Argentina.

One standard method for comparing economic efficiency of land uses for private land owners/managers is conventional capital budgeting techniques, based on data from surveys or experimental plots, to estimate a number of proxies for efficiency, including net present value (NPV) and internal rate of return (IRR). However, these methods depend heavily on

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numerous assumptions, such as market prices (for both inputs and outputs), that are the same for everyone in the population of potential and actual adopters. In many rural or isolated areas markets may be thin, meaning that land owners/managers may not purchase inputs or sell outputs at the market price. For instance, they may utilize family labor rather than hiring help, or they may use the outputs of the land use system for domestic consumption. These farmers, lacking access to markets for these inputs or outputs, may value inputs or outputs at a rate that is different from the prevailing market price. In these cases, it may be difficult to generate an NPV or IRR that is a consistent representation of economic efficiency for all managers.

In these situations, it is appropriate to use methods that can compare the technical efficiency of various land uses without making any assumptions about prices, or making only minimal assumptions. Data envelopment analysis (DEA) is a method that can be used to compare relative technical efficiency of decision-making units with relatively weak assumptions about prices and their change over time.

Previous studies comparing the efficiency of agricultural systems have used DEA to estimate an average technical efficiency score for groups of farms, then compare the averages (Mathijs and Swinnen 2001; Latruffe et al. 2004). However, if DEA indicates that an entire group of farmers produces less revenue per unit of inputs than some other comparison group, it may be because of any number of factors that are not included in the efficiency analysis. For instance, farm groups might be located on different soil types that are suited to different productive activities (Bhalla and Roy 1988; Rodriguez-Diaz, Camacho-Poyato, and Lopez-Luque 2004), or one group of farmers might have different cultural values. These factors may be difficult or impossible to observe or measure. When empirically comparing a new farm technology to a more conventional one, from an efficiency standpoint there also may be self-selection bias, because adopters of new technologies may have different levels of human capital, innate ability, or differential access to extension programs.

Some studies employ regression analysis to control for these factors (e.g., Otsuki, Hardie, and Reis 2002; Latruffe et al. 2004; Davidova and Latruffe 2007). While it is possible to regress DEA efficiency on numerous control variables, there is always the risk of omitting important variables; and in a more general sense the results of this second-step regression may be biased (Just 2003; see further discussion in Section II under "Controlling for Unobserved Differences between Farms").

Since our primary objective is to compare the efficiency of technologies, we must therefore find a way to more adequately control for unobserved factors. One way is to compare technologies *within farms* that utilize two or more of the technologies. By using paired comparisons of technologies within farms, we control for unobserved factors in a similar way as fixed-effects methods with panel data (Fraser and Cordina 1999; Zhang 2002; Luo 2003). In this study we utilize a nonparametric Wilcoxon signed-rank test to compare the DEA efficiency of silvopasture, plantation forestry, and full-sun pasture within the same farms.

A second objective of this study is to conduct an analysis of the nature of returns to scale of silvopasture systems. Agroforestry systems are often advocated as potentially beneficial for small-scale farmers. However, anecdotal evidence in Argentina suggests that large-scale producers are the main innovators, and that small-scale farmers often require incentives for adoption. Two logical, and potentially competing, explanations are that (1) small-scale farmers are more liquidity constrained than large-scale farmers and cannot afford the initial cost of adoption, and (2) silvopasture in fact exhibits increasing returns to scale. While DEA does not address farm-level constraints directly, it can be used to find whether each particular parcel of land is operating under increasing, constant, or decreasing returns to scale. We use a sign test to determine the general overall nature of returns to scale for silvopasture, plantation forestry, and conventional cattle-ranching.

FIGURE 1
Map of the Study Region, with Numbers Indicating Number of Respondents in Subregions

II. MATERIALS AND METHODS

Study Area

The study area of Misiones and northeastern Corrientes provinces (Figure 1[1]) corresponds to Homogeneous Agroeconomic Zones 1–5 in Misiones and Zone 3 in Corrientes, as described by Acosta et al. (2009) and Gunther, Correa de Temchuk, and Lysiak (2008). In this phytogeographic region, also known as the *Provincia Paranaense* (Cabrera 1976), two distinct districts are found: the subtropical forests of central and northern Misiones (Zones 1–4), and the grasslands of southern Misiones and northeastern Corrientes (Misiones Zone 5 and Corrientes Zone 3) (Cabrera 1976; Rodriguez et al. 2004; Acosta et al. 2009; Gunther, Correa de Temchuk, and Lysiak 2008). The soils are derived from the weathering of basaltic rocks, forming reddish clay soils, principally Ultisols and Oxisols. The climate is humid and subtropical, categorized as Cfa under the Köppen-Geiger system (Rodriguez et al. 2004). The average annual precipitation is around 1,900 mm, with an average annual temperature of approximately 21°C (Servicio Meteorológico Nacional 2008).

There are diverse farming systems in the region. Northeastern Corrientes and southern Misiones have been traditionally used for extensive cattle grazing, now operated by large *estancias* (Acosta et al. 2009; Gunther, Correa de Temchuk, and Lysiak 2008). Central and northern Misiones was only settled to a large extent starting in the 1920s, with some of the more remote areas still relatively undisturbed. This area is utilized by small- and medium-scale semisubsistence and cash cropping farmers of perennials such as tea *(Camellia sinensis),* yerba maté *(Ilex paraguariensis),* and sugarcane, or annuals such as tobacco (*Nicotiana* spp.) and cassava *(Manihot esculenta).* Since the 1970s, it has been increas-

[1] Figure 1 indicates the approximate distribution of respondents. Exact locations of respondent farms are not mapped, to protect confidentiality. Farms were selected for the survey to represent distinct geographic regions, farm scales, and farm types.

ingly occupied by forest-product firms, who primarily planted the native *Araucaria angustifolia* in the early years and now primarily plant exotic pine species (*Pinus* spp.) for timber (Gunther, Correa de Temchuk, and Lysiak 2008).

Misiones and northeastern Corrientes have experienced moderate adoption of silvopasture systems in recent years among farms of all scales. At present, silvopasture systems are common, though not pervasive. While some adoption did take place in Misiones and Corrientes in the 1970s, silvopasture became more widely investigated by researchers and farm and forestland administrators in the 1980s. This resulted in improved management of the forage, livestock, and timber components, and increased adoption of the practice (Fassola, Lacorte, Pachas et al. 2004). Silvopasture implementation had reached an extent of over 20,000 ha in Misiones by 2010 (Esquivel et al. 2004; Colcombet et al. 2010), and approximately 70,000 ha in the greater region encompassing Misiones and northern Corrientes (authors' estimate), which represents approximately 10% of all tree plantation area and 3% of private rural land (not including primary native forest) in the region (Acosta et al. 2009; Gunther, Correa de Temchuk, and Lysiak 2008). Silvopasture in Misiones and Corrientes has numerous perceived benefits, including diversified products, improved microclimate for cattle and forage, increased short-term cash flow, reduced number of weeds, improved quality of products, reduced management costs, and others (Fassola, Lacorte, Esquivel, et al. 2004a; Frey et al. 2012).

Farm Survey

A farm survey of silvopasture adopters was conducted in the Misiones and northern Corrientes provinces of northeastern Argentina during June and July of 2006 and June 2008. The survey was principally aimed at eliciting information about costs and benefits of silvopasture compared to other production systems used in the region. All questions were reviewed with a focus group of extension agents and research scientists of the *Instituto Nacional de Tecnología Agropecuaria* (INTA) from the region. Subsequently we conducted a pretest with producers of various farm scales.

TABLE 1
Descriptive Statistics of Farm-Scale Groups

Scale	*n*	Smallest Farm in Cluster (ha)	Largest Farm in Cluster (ha)	Mean Farm Area (ha)
Small	16	15	49	30.1
Medium	16	75	788	343.7
Large	12	1,108	14,000	4,096.5

Random sampling was not practical because the complete population of adopters was not known, and because of the distances between individual adopters. Instead, a stratified, purposive sample of known adopters throughout the region was used. Adopters were chosen in order to represent the continuum of diverse farm scales and farm types in various subregions throughout the larger study region, identified by INTA researchers and extension agents. We visited the relevant communities where the producers lived, and interviewed them on the farms. Most of the individuals identified by INTA for possible interviews did accept, but in a few cases other farmers in the community were selected as alternates.

In total, 47 farm managers of varying scales were interviewed, producing usable responses for 44 silvopasture plots, as well as 33 full-sun pasture plots and 14 plantation forestry plots; 11 farms had all three systems. Surveyed farmers were classified into three groups using natural clusters: small, medium, and large (Table 1). Total farm size for all farms (including all noncontiguous properties managed by the same nuclear family or firm within the province) ranged from 15 to 14,000 ha, with a mean of 1,253 ha and median of 233 ha.

Data Compilation

The data from the surveys were compiled into spreadsheets to sum the inputs and outputs of each of the three systems (where applicable) for each year of the system on each of the surveyed farms. We used a real discount rate of 7%, similar to the rate previously utilized for comparing systems in Misiones (Esquivel et al. 2004; Colcombet et al. 2010).

We simulated future output of timber by using growth and yield models calibrated to current stand measurements, and farmers' stated management regimes. Output for *P. taeda*, *P. elliottii, and A. angustifolia* was estimated with *Simulador Forestal* (Crechi, Fassola, and Freidl 1997); and for *P. caribaea* and *Eucalyptus* spp. with published growth and yield equations (Ferrere and Fassola 1999; Ferrere et al. 2001; Barth et al. 2002; Fassola et al. 2007). The effect of increasing shade on future pasture yields was estimated using published data and calibrated with stated yields at the time of the interview (Fassola et al. 2002; INTA 2002).

Input and Output Classification

An agroforestry system can have dozens of distinct inputs and outputs. Ideally, we would split our inputs and outputs into as many categories as possible, to attach the most precise value to each. For instance, labor might be broken into types of labor, such as skilled and unskilled labor, or by the time of year during which labor is required, because in certain months there may be a higher demand for labor for other crops, making labor more expensive. Timber output might be divided into classes such as small, medium, and large diameter and by year of harvest. In theory, DEA is able to handle many inputs and outputs, but in practice, the methodology loses power to identify the inefficient decision-making units (which in our case represent farm plots) as the number of variables increases (Kao, Chang, and Hwang 1993; Sowlati 2005).

We chose as inputs (1) land area, (2) labor in person-days, (3) value of field crops used as livestock feed in 2006 Argentine pesos, and (4) value of capital and supplies invested in 2006 pesos. For (2)–(4), present values of future inputs were computed using the 7% discount rate. Field crops were separated from the other capital supplies because many small-scale farmers produce these crops on-farm rather than purchasing from a market, so market prices may not adequately represent their value with respect to other supplies such as herbicide or diesel fuel. However, we did use market prices to combine the crops such as maize, cassava, and sugarcane in a single variable. In this case, the market prices do not represent the value of the crop to the farmer, but rather an approximation of the relative cost of production. The outputs were discounted timber value, discounted beef value, and discounted milk value. Milk was separated from beef because it is generally used for household consumption, not for sale.

At a broad level, Misiones and Corrientes have fairly well functioning markets for most of the relevant inputs and outputs of silvopasture systems. However, in some areas, particularly remote areas where small family farms are prevalent, markets may not exist or may be impeded by high transaction costs. Some examples include unclear land tenure leading to difficulties in land transactions; lack of a well-defined land rental market; occasional lack of labor for hire or highly variable prices of labor by subregion or farm type; donation of capital inputs, including fencing supplies, tree seedlings, grass seed/transplants, herbicide, and ant pesticide, to small-scale farmers by extension agencies; thin markets for dairy products (most cattle were raised primarily for beef); production of cattle feed (maize, cassava, sugarcane) on-farm rather than purchasing through markets; and long distances to pulp mills. Each one of these market imperfections leads to a situation under which farmers may value inputs and outputs at a different rate than their market price.

Labor was a particularly tricky variable to deal with. Some type of market for labor existed in all the communities we visited. However, there was wide variability in the price of labor, mostly depending on the size and legal status of the farm. Small-scale farms occasionally hired neighbors on an informal basis, usually for about 15 pesos/day (a little less than US $5 during 2006–2008). Large-scale farm firms, on the other hand, had to comply with minimum wage laws, which pushed the base cost of labor to about 39 pesos per day (US $12–US $13), and some firms had to pay additional social taxes, food, and housing, depending on legal status. This would push the cost of labor to over 58 pesos per day (about US $19).

Data Envelopment Analysis

As noted, capital budgeting techniques are simple and appropriate measures of efficiency when market prices drive decisions, and the prices are common to all farms in the sample. However, when this is not the case, DEA is an appealing tool for comparing the technical efficiency of silvopasture to other production systems.

Over the past 30 years, DEA has emerged as one of the primary ways of measuring technical productive efficiency. The method was pioneered by Charnes, Cooper, and Rhodes (1978) and Banker, Charnes, and Cooper (1984), based on Debreu's (1951) and Farrell's (1957) seminal works on the measurement of inefficiency. Numerous review and meta-analysis papers (e.g., Coelli 1995; Townsend, Kirsten, and Vink 1998; Thiam, Bravo-Ureta, and Rivas 2001; Sowlati 2005; Bravo-Ureta et al. 2007) and books (e.g., Ramanathan 2003; Cooper, Seiford, and Zhu 2004; Ray 2004) have been written on the subject of DEA, so a comprehensive description of the methodology is not necessary here.

We utilized the model from Charnes, Cooper, and Rhodes (1978) (CCR model) to estimate the total technical efficiency, and the model from Banker, Charnes, and Cooper (1984) (BCC model) to estimate the pure technical efficiency (assuming variable returns to scale). The ratio of the two measures provides the scale efficiency (Banker, Charnes, and Cooper 1984).

Essentially, the DEA model (Charnes, Cooper, and Rhodes 1978) picks weights, which can be viewed as relative shadow prices, for each input and output, to maximize the relative technical efficiency with respect to the other firms, none of which, when facing the same shadow prices, are allowed to pass 100% efficiency. Allowing the weights (prices) to vary provides flexibility that is useful in at least three ways. First, markets may be thin or nonexistent because of high transaction costs. Second, prices for certain inputs or outputs may vary somewhat from region to region. Third, the preferences of an individual farmer may cause him or her to value a particular input or output differently than the market price.

By allowing the model to pick the weights, the measure is one of technical efficiency rather than allocative efficiency, utilizing very weak assumptions about prices. Being inefficient under DEA demonstrates that there is a way for each technically inefficient firm to maintain the same allocative efficiency while improving technical efficiency.

Strengths and Weaknesses of DEA

DEA offers numerous benefits for efficiency analysis. Often cited as a benefit is the nonparametric nature of DEA, which means there is no need to specify a form for the production function. Also, DEA is suited for comparing the efficiency in situations, such as agroforestry systems, with multiple inputs and outputs of which some or all have no market value (Alene, Manyong, and Gockowski 2006). DEA can be used to improve understanding of agroforestry production for researchers, extension agents, and most importantly, farmers (Salehirad and Sowlati 2005).

One of the assumptions underlying DEA that can be one of its weaknesses is the homogeneity of decision-making units. That is, the various decision-making units are producing the same outputs with the same inputs, and there are no underlying, inherent differences between specific decision-making units that make one subset less able to achieve maximum output per unit of input. For instance, in farming applications, DEA would assume that there are no differences in the quality of soils, climate, and so forth from one farm to another, which would make one farm inherently more or less productive than other. We deal with this below by using only within-farm efficiency comparisons.

Also, the deterministic nature of DEA makes it sensitive to outliers or errors in measurement or stochastic variation (Thiam, Bravo-Ureta, and Rivas 2001). Suppose, for example, that one farmer, or some small subset of farmers, had a very good (or bad) year in terms of productivity because of localized weather conditions. Standard regression techniques would account for this variability theoretically by incorporating an error term. DEA, however, would attribute all of this variability to "inefficiency," implying that the differences are due to good or poor management of the resources, even though they might be due to other uncontrollable factors.

We accounted for this weakness in DEA with respect to stochastic variability by asking farmers about typical, representative parcels and representative years. Unfortunately, in some cases this may cause some farmers to think hypothetically instead of concretely in terms of remembering precise estimates of input use and output production, so there could be some error. We only compare plots that are operated by the same farmer, so he or she is more likely to have the same hypothetical biases when recounting inputs to and outputs from two systems than would be the case if two separate farmers were reporting on the two systems.

There are numerous practical issues involved with the implementation of DEA for real-world questions with empirical data. There are two points that have not received satisfactory treatment in the literature and have important implications for this study: the comparison of the efficiency of distinct agricultural technologies, and methods for controlling for unobserved differences between farms and farmers.

Comparison of the Efficiency of Distinct Agricultural Technologies

DEA provides an estimate of *relative* technical efficiency among the decision-making units in the sample, not any type of measure of *absolute* technical efficiency. Because DEA measures efficiency relative to an envelope of the data from the sample, an efficiency score of 1 signifies efficiency relative only to the other observations in the sample, not relative to any absolute efficiency standard. This has important implications for the comparison of the efficiency of technologies. Some literature has taken a high average DEA score of the set of data being analyzed to mean that those decision-making units are more efficient than groups with a lower average score from a separate DEA analysis (e.g., Alene, Manyong, and Gockowski 2006; Binici et al. 2006). A high average DEA efficiency score for a set of decision-making units simply indicates a measure of relative homogeneity among the efficiency of the decision-making units, not necessarily that the set as a whole is more efficient than another set with a lower average score from a separate DEA efficiency measurement.

The only appropriate way to compare distinct sets of decision-making units is to include them in the same model, as in Figure 2.[2] In this case, the decision-making units from the set represented by x's would be accurately classified as being further from the relative efficiency frontier. If however, the x's and o's were measured independently, the DEA methodology would estimate a lower frontier for the x's (represented by the dotted line), and the average efficiency score (measured as the closeness to the frontier) would therefore be higher by comparison.

This is complicated by the fact that the decision-making units must have the same inputs and outputs for DEA to be effective (Haas and Murphy 2003). If we think of DEA creating a frontier in an *n*-dimensional space where each of the *n* dimensions represents a distinct input or output, this becomes clear. For instance, if one subset of a sample is dairy farms and the other subset is crop farms, as described by Latruffe et al. (2004), and none of the farms produce both outputs, then each subset will be measured only along one of the two axes, rendering them de facto separate DEA sets, even when measured in the same model. In order to maximize each decision-making unit's efficiency, DEA will model each decision-making unit as placing zero value on the output that it does not produce.

Statistical comparisons between the technical efficiency scores of the two subsets would be largely devoid of the meaning a researcher would like to attribute to them, such as that one group of farms or a farm technology is more efficient than the other. Latruffe

[2] In Figure 2, the DEA would appropriately label the set of decision-making units marked with o's as being relatively more efficient, on average, than the x's because they are closer to the estimated efficiency frontier (represented by dashed line). If however, the x's and o's were measured independently, the DEA methodology would estimate a lower frontier for the x's (represented by dotted line), and the average efficiency score (measured as the closeness to the frontier) would therefore be higher by comparison.

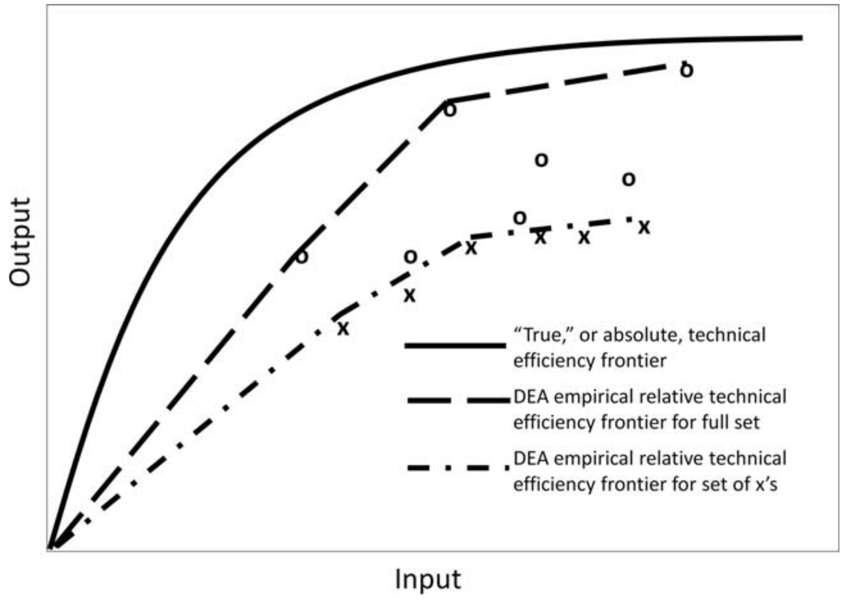

FIGURE 2
Representation of Efficiency Estimation Pooling Two Sets of Decision-Making Units

et al. (2004) gets around this by multiplying by price per unit output to get both outputs into common terms (i.e., total revenue). This is satisfactory in some situations where revenue is the important output, but not in the case where each decision-making unit might value different resources differently (such as non-market goods and services).

A simple compromise between allowing DEA to place zero-value weights on the outputs that are not produced and requiring that all outputs be valued exactly at their market prices is to place limits on the variation of the relative weights. This method, known as the "assurance region" method, was first developed by Thompson et al. (1986). It is very easy to add additional constraints into the DEA linear program of the form

$$LB \leq \frac{w_i}{w_j} \leq UB \text{ for } i \neq j, \quad [1]$$

where w_i is the weight or value that each decision-making unit places on input or output i, and LB and UB are the lower and upper bounds of the ratio of weights.

In essence, adding restrictions to the weights used creates a measure of efficiency that is a compromise between a pure technical efficiency measure and a capital budgeting measure. By including some of the a priori knowledge we have from markets, we acknowledge that market prices are likely to be central in farmers' valuation of inputs and outputs, while at the same time by placing upper and lower bounds rather than firm prices, we recognize that farmers also have unobservable nonmarket values of many items, including time preferences (personal discount rates), cultural values, and so forth.

Table 2 shows lower and upper bounds we placed on the ratios of weights in this study. No limits were placed on the ratios of input to output weights, only input to input and output to output. In cases where the pair includes two inputs or outputs both expressed in peso terms, it would be expected that the ratio would be approximately equal to one, for instance, farmers value a peso's worth of beef the same as a peso's worth of timber. However, the goal is to allow some flexibility to allow for differences in farmers preferences, slightly different market prices from one re-

TABLE 2
Upper and Lower Bounds on the Relative Weights of Inputs and Outputs (Assurance Region)

Inputs			Outputs		
Weight Ratio	Lower Bound	Upper Bound	Weight Ratio	Lower Bound	Upper Bound
Labor (days)/Land (ha)	0.00006	0.6	Timber (pesos)/Beef (pesos)	0.1	10
Capital (pesos)/Land (ha)	0.00002	0.002	Timber (pesos)/Milk (pesos)	0.01	100
Crops (pesos)/Land (ha)	0.000002	0.02	Beef (pesos)/Milk (pesos)	0.01	100
Capital (pesos)/Labor (days)	0.00333	0.333			
Crops (pesos)/Labor (days)	0.000333	3.333			
Crops (pesos)/Capital (pesos)	0.01	100			

gion to another, and so on. While the decision for how much flexibility to allow is somewhat arbitrary, it was decided that a 10-fold differential in both directions, for instance, a farmer may value a peso's worth of beef 10 times more or 10 times less than a peso's worth of timber, would be more than adequate to encompass farmers' preferences and other factors and still greatly enhance the power of the DEA tool. Therefore, the lower and upper limits for the ratio of weights of the timber to beef are 0.1 and 10, respectively (two orders of magnitude total). In the cases where the input or output may not be commonly traded on the market in some communities (labor, field crops, milk), an additional order of magnitude was added to both the upper and lower bound. This allows for up to a two order of magnitude differential in relative values in either direction, from 0.01 to 100 (four orders of magnitude total). This situation applied to all of the remaining inputs and outputs except land and labor. The market value of land was generally considered to range from 1,000 to 7,500 pesos/ha, depending on tenure and other factors, so the weight was allowed to vary from 500 to 50,000 times the weight of one peso. The market price of labor was between 15 and 60 pesos/day, so the weight was allowed to vary from 3 to 300 times the weight of one peso.

Using Efficient Peers to Test Whether Technologies Are Acting as De Facto Separate DEA Sets

In principle, then, using the assurance region method in the manner described above can help to unify different technologies, some of which do not use all the same inputs or produce all the same outputs that the others do. However, we should still be concerned that pasture systems are only being compared to other pasture systems, forestry to forestry, and silvopasture to silvopasture, and if that were the case, there would be no basis for comparison of the efficiency statistics.

Fortunately, we can use a quick check of "efficient peers" to see whether plots are being measured solely against plots of the same technology. Consider that in DEA each inefficient decision-making unit is measured against a linear combination of efficient decision-making units. The decision-making units that form this linear combination are called the "efficient peers" of the inefficient decision-making unit (Cooper, Seiford, and Zhu 2004; Ray 2004). This serves as an easy way to check whether decision-making units of one type are only being measured against decision-making units of the same type.

Controlling for Unobserved Differences between Farms

When comparing the efficiency of different farm technologies, one must control for the differences in the farms and farmers utilizing each technology. Some studies try to control for these factors using a regression after the efficiency analysis (e.g., Otsuki, Hardie, and Reis 2002; Latruffe et al. 2004; Davidova and Latruffe 2007). While it is possible to regress DEA efficiency on numerous control variables, there is the risk of omitting important variables, and in a more general sense the results of this second-step regression may be biased. This is because the following question arises when performing an ex-post regression on DEA results: Which factors should be included as inputs in the DEA calculation, and which should be included as explanatory variables in the regression? Just (2003, 143) explains the potential for biased estimates for the coefficient values in the regression:

> A little-recognized fact is that [the choice of which variables to include in the DEA analysis and which to include in the regression] has an important effect on endogeneity bias. To see this, note that the approach first tries to attribute all variation among firms to efficient behavior of firms. Only then are the implicit residuals regressed on other variables in an ex post analysis, whether with formal regression or informal classification analysis. . . . It produces biased results because it first tries to attribute all of the variation to one set of variables, thus biasing their coefficients away from zero, and then tries to attribute only the remaining variation to the remaining set of variables, thus biasing their coefficients toward zero.

Haas and Murphy (2003) discuss several potential methods for controlling for operating conditions by adjusting the CCR efficiency scores but find that none of them appear to be superior to using the unadjusted scores.

Econometricians have often used fixed-effects panel methods to control for all unobserved factors related to one particular observation through time. DEA practitioners have also used this concept when observations exist at various points in time. A practice used in the literature is to estimate a Wilcoxon signed-rank statistic to test whether farms' efficiencies have increased over time, making paired comparisons of the efficiencies of individual farms at two points in time (Fraser and Cordina 1999; Luo 2003).

To our knowledge, the Wilcoxon signed-rank test has not been used to test for efficiency differences in multiple farm technologies at the same point in time, but the same logic applies. Since many of these farms practice multiple technologies, we can control for characteristics of individual farms and farmers by making paired comparisons of technologies on the same farms. This test also avoids making parametric assumptions about distributions. First, the difference in efficiency scores, d_i, between the two technologies being compared is calculated for each farm i. The d_i's are given rank r_i in order of increasing absolute value. The test statistic T^+ is calculated by

$$T^+ = \sum_{i=1}^{n} r_i I(d_i > 0), \qquad [2]$$

where $I(d_i > 0)$ is an indicator function equal to 1 if $d_i > 0$ and 0 otherwise (the test should be altered to calculate T^- using $I(d_i < 0)$, when appropriate). The statistic is used to calculate a p-value assuming that d_i has an equal probability of being positive or negative (Wilcoxon 1945; Siegel 1965). If the p-value is sufficiently small, we can reject the null hypothesis that the two technologies have equal efficiency. We utilized a two-tailed hypothesis test because of competing possible alternative hypotheses: while capital budgeting studies suggest that silvopasture systems are a more efficient use of land, the lack of large-scale spontaneous adoption suggests that it could actually be less efficient.

Testing for Increasing or Decreasing Returns to Scale

The sum of the weights of the CCR model can be used to determine whether a decision-making unit is operating at an efficient scale (if the sum equals 1, constant returns to scale, CRTS), is smaller than the efficient scale for its particular combination of inputs and outputs (sum < 1, increasing RTS) or is larger than the efficient scale (sum > 1, decreasing RTS). A sign test, which is slightly different from the Wilcoxon signed-rank test, was used to test whether silvopasture, forestry, and pasture were significantly more likely to have increasing or decreasing returns to scale as a group than would be expected under the null hypothesis that increasing and decreasing returns to scale are equally likely. This test was conducted on the entire sample, then on the subgroups of small-, medium-, and large-scale farms separately.

Usually, the sign test, like the Wilcoxon signed-rank test, is used to test for differences in paired observations. In this case, however, we utilized the same methodology to test whether a group of single observations (the nature of returns to scale for each plot) is more likely to have positive or negative sign. Zero-

TABLE 3
Mean Input and Output Levels for the Three Production Systems on Each of the Three Farm Scales

		Inputs				Outputs		
Farm Scale	System	System Area (ha)	Labor[a] (person-days/ha)	Capital[a] (pesos/ha)	Field Crops[b] (pesos/ha)	Timber Revenue[a] (pesos/ha)	Beef Revenue[a] (pesos/ha)	Milk[b] (pesos/ha)
Small	Silvopasture	5.8	161	4,972	1,640	17,511	2,023	3,686
	Pasture	9.0	94	1,358	2,584	0	3,579	2,916
	Forestry	2.3	78	4,513	0	13,908	0	0
Medium	Silvopasture	92.0	84	9,148	377	15,357	6,539	40
	Pasture	44.5	48	1,714	440	0	2,904	40
	Forestry	33.5	38	5,605	0	12,913	0	0
Large	Silvopasture	1,136.6	40	3,829	0	8,915	1,925	0
	Pasture	1,382.9	12	455	0	0	1,151	0
	Forestry	1,265.0	71	8,964	0	38,214	0	0

[a] Future values were discounted at a 7% discount rate.
[b] For field crops input and milk output, an approximate market price was used, even though these inputs and outputs were not generally purchased or sold on the market. Future values were discounted at a 7% discount rate.

valued observations (indicating CRTS) are thrown out, so that all remaining observations are either positively (indicating IRTS) or negatively (indicating DRTS) signed. The sign test statistic (M) is simply

$$M = \frac{n^{+} - n^{-}}{2}, \qquad [3]$$

where n^{+} and n^{-} are the number of positively and negatively signed observations, respectively. A p-value is determined by the binomial distribution under the null hypothesis that positive and negative signs are equally likely.

III. RESULTS AND DISCUSSION

Inputs and Outputs

The mean estimated inputs and outputs for silvopasture, (conventional plantation) forestry, and (full-sun) pasture for small-, medium-, and large-scale farms are given in Table 3. On average, small-scale farmers use more labor per hectare for all the systems than medium or large-scale farmers. This could be because labor was relatively cheaper for small-scale farmers, who, in most instances, indicated that labor could be hired from neighbors for about 15 pesos/day. In reality, small-scale farmers mainly use household labor, so the use of a relatively large quantity of labor seems to indicate that there is a relatively large supply of household labor at low or no monetary cost. Also, small-scale farmers used less capital inputs, except in the case of silvopasture. It is interesting that small-scale farmers utilize more capital inputs per hectare for silvopasture than medium- or large-scale farmers, given that small-scale farmers are generally considered to be more constrained by capital. However, in the case of silvopasture, many of the small-scale farmers received in-kind provision of capital inputs from government programs for silvopasture. In addition, large-scale farmers did not cultivate their own crops to supplement the diet of cattle (small-scale farmers were more likely to need to supplement cattle diets because they had a larger quantity of cattle per hectare of land), nor did they produce dairy products.

The average inputs and outputs also indicate that, on average, smaller-scale farmers utilize more inputs and produce more outputs per hectare, that is, they utilize more intensive practices. This seems to make sense since they have smaller farms and thus are more constrained by land and may have more free time to dedicate to the enterprise.

Total and Pure Technical Efficiency Estimation

DEA total technical efficiency under constant returns to scale assumption was calculated with the CCR model, and scale

TABLE 4
Percentage of Efficient Peer Farms from Each Farm Type

	Total Technical Efficiency Percentage of Efficient Peers That Are:			Pure Technical Efficiency Percentage of Efficient Peers That Are:		
	Silvopasture	Pasture	Forestry	Silvopasture	Pasture	Forestry
Silvopasture	69	0	31	66	0	34
Pasture	80	20	0	71	10	19
Forestry	0	0	100	14	0	86

efficiency and pure technical efficiency under variable returns to scale were calculated with the BCC model for all farm plots in the sample, using an assurance region. The total technical efficiency is appropriate when considering the overarching productivity of a plot per hectare, while the pure technical efficiency factors out inefficiencies that might be due to the scale of the plot. By construction, some of the plots will be rated at 100% efficiency. For total technical efficiency, which is equal to pure technical efficiency times scale efficiency, there were 4 of 44 silvopasture, 1 of 33 pasture, and 1 of 14 forestry plots operating at 100% efficiency relative to the full set of silvopasture, pasture, and forestry plots. For pure technical efficiency, five silvopasture, two pasture, and two forestry were operating at 100% relative efficiency.

Using Efficient Peers to Test Whether Technologies Are Acting as De Facto Separate DEA Sets

We checked the efficient peers of the inefficient decision-making units to make sure that efficiency comparisons are being made between decision-making units of the different technologies (silvopasture, pasture, forestry) rather than simply among them. Based on the results in Table 4, we would be skeptical of comparisons that would suggest forestry plots are less efficient than either silvopasture or pasture. One hundred percent of the efficient peers for inefficient forestry plots in the total technical efficiency calculation were other forestry plots, and a large majority included forestry plots in the pure technical calculation. This is highly suggestive that the forestry plots have formed a de facto separate DEA set and are being compared to one another rather than the silvopasture and pasture plots. A low average technical efficiency measurement would suggest a lack of homogeneity among forestry plots, rather than forestry being actually less efficient than silvopasture or pasture.

Inefficient silvopasture and pasture plots, on the other hand, had a higher percentage of efficient peers that were among other technologies. This suggests that it is fair to compare them to the other technologies. The fact that no pasture plots are efficient peers for silvopasture, but a large number of silvopasture plots are efficient peers for pasture suggests that silvopasture is more efficient than pasture, which is demonstrated more clearly below.

Comparison of Efficiencies

The average relative total and pure technical efficiency levels for the three technologies (silvopasture, pasture, and forestry) are shown in Figure 3. The average total technical efficiency levels for the three technologies at first seem fairly low at 50.9%, 23.4%, and 40.0% for silvopasture, pasture, and forestry systems, respectively. This means that an average farm produces only 50.9%, 23.4%, or 40.0% of the weighed output that a farm on the efficient frontier would produce using the same inputs. Recall that the technical efficiency measure accounts for variable nonmarket values and preferences that farmers may have for various inputs and outputs. In light of this, it is somewhat disconcerting at first that relative productivity could be so low on average, but the farms are operating under quite variable circumstances such as soil quality, education, and extension. This clearly reinforces the need to control for differences

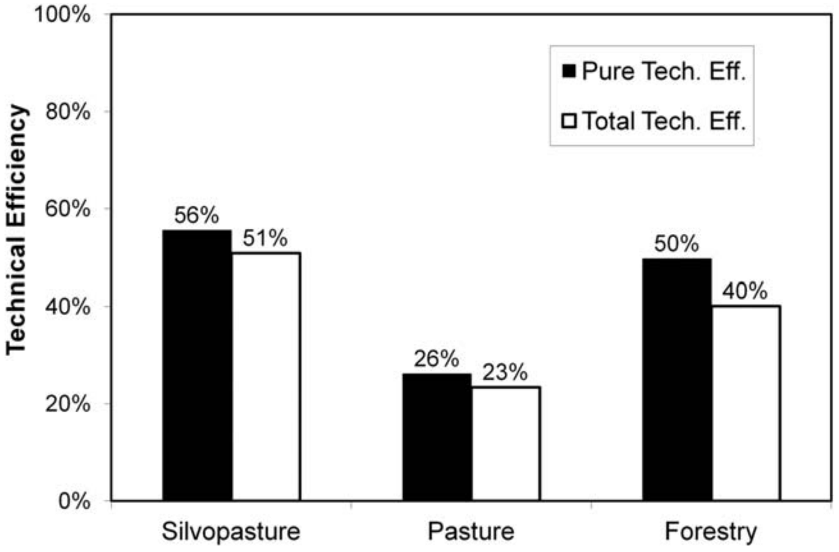

FIGURE 3
Pure (Variable Returns to Scale, BCC Model) and Total (Constant Returns to Scale, CCR Model) Technical Efficiency

between farms, which was achieved by using the Wilcoxon signed-rank test.

The Wilcoxon signed-rank test statistic for pairwise comparisons of silvopasture and pasture ($n = 33$) indicates that silvopasture is more efficient than pasture ($T^+ = 265.5$, two-tailed p-value < 0.0001). Comparisons between silvopasture and forestry ($n = 14$) resulted in a T^+ of 25.5 (two-tailed p-value $= 0.1189$), and between forestry and pasture ($n = 12$) resulted in a T^+ of 9 (p-value $= 0.5186$), neither of which was statistically significant.

When using pure technical efficiency, there is a similar pattern. The pairwise comparison of silvopasture and pasture indicated that silvopasture is a more efficient use of resources than pasture ($T^+ = 246$, two-tailed p-value $<$ 0.0001), even when factoring out the differences in relative efficiencies due to scale. Comparing silvopasture and forestry yields a T^+ of 11.5 (p-value $= 0.5016$), and forestry and pasture a T^+ of 16 (p-value $= 0.2334$), neither of which is statistically significant.

The pairwise comparison of plots is an important way to control for between-farm variability, including farmers' education, cultural values, and age; the broad land classification; and many other factors. However, it does not control for within-farm variability. It may be possible that silvopasture plots are more often placed on better sites within a farm and pasture plots on worse sites, or different extension agents aid the farmer with different aspects of farming (some extension agents specialize in agroforestry, while others work more with livestock). Unfortunately, farm-level soil-survey data does not exist.

Even though completely controlling for within-farm variability is difficult, there are some simple things that can be done. Our survey did ask farmers about the previous state of the silvopasture plots. Of the 44 silvopasture plots, 5 were planted on parcels that were clear-cut high-quality native forest, 5 were clear-cut secondary native forest, 5 were clear-cut plantation forest (pines), 7 were old yerba maté plantations (a perennial woody plant whose leaves are harvested annually), 10 were old agricultural fields, and 12 were old pastures.

It is possible that those silvopasture plots planted on cleared native and plantation forest may be less degraded and eroded and therefore have better soil fertility characteristics than pasture plots planted on old agricultural fields (however, we are not confident that this

TABLE 5
Average Scale Efficiencies, Sign Test M-Statistic, and Two-Tailed p-Value for Returns to Scale of Three Farm Technologies by Farm Scale

	Silvopasture			Pasture			Forestry		
	Scale Efficiency (%)	M	p-Value	Scale Efficiency (%)	M	p-Value	Scale Efficiency (%)	M	p-Value
Small	93.5	3.5	0.09	92.3	0.5	1.00	77.1	3	0.03
Medium	96.8	4.5	0.04	98.2	2	0.39	86.4	3	0.03
Large	87.2	1	0.77	70.2	−2.5	0.13	99.3	0.5	1.00
All farms	90.3	9	0.01	86.3	0	1.00	91.0	6.5	0.00

Note: Positive M-values represent increasing returns to scale, negative decreasing returns to scale.

is true, because lands that are left in forestry the longest are also often those sites that are the most marginal for agriculture—they have the lowest opportunity cost). On the other hand, it is likely that the silvopasture plots that were implemented on old pastures, old agricultural fields, and cleared yerba maté plantations may be more similar to pasture sites.

A Wilcoxon signed-rank test was conducted using only those silvopasture plots that were planted on old pasture or agricultural or yerba maté fields. The same direction and statistical significance was found between silvopasture and pasture as with the full sample. For the total technical efficiency CCR model, the T^+ was 139 ($n = 24$), corresponding to a two-tailed p-value < 0.0001. For the pure technical efficiency BCC model, the T^+ was 124.5, corresponding to a two-tailed p-value < 0.0001.

The same analysis was conducted for only silvopasture plots planted on old agricultural fields and pasture, excluding old yerba maté fields. Old yerba fields might retain somewhat more fertility than agricultural fields or pasture because the perennial plant's roots help somewhat to prevent erosion. The same difference was found for the CCR model (two-tailed p-value $= 0.0001$) and the BCC model (two-tailed p-value < 0.0001).

Because of this relatively high profitability of silvopasture, confirmed by our results that silvopasture is more efficient than pasture under broad relative price conditions, we should expect ongoing adoption. The fact that adoption is only moderate is still somewhat troubling. It is possible that many potential future adopters have taken a wait-and-see attitude toward silvopasture plots they see on friends' and neighbors' farms. Since silvopasture takes a long time (around 20 years) to produce one of the main outputs, timber, diffusion is likely to be slow. There is also a continued role for education and incentive programs. Government incentive programs are likely to be especially important for small farmers, who are constrained by up-front capital costs.

Scale Efficiency and Returns to Scale

The nature of returns to scale (RTS), whether increasing, decreasing, or constant, was calculated for each plot using the weights from the CCR model. A sign test was conducted to test whether increasing (IRTS) or decreasing RTS (DRTS) were more common for any of the technologies than would be expected under the null hypothesis that IRTS and DRTS are equally likely. The average scale efficiencies and nature of RTS for each technology by farm scale group is in Table 5. The sign test on the entire set of silvopasture parcels can reject the null hypothesis that IRTS and DRTS are equally likely for silvopasture. IRTS are more likely for silvopasture. For forestry, the sign and significance of M indicates that IRTS are more likely. For pasture, we could not reject the null.

There are several reasons why forestry might demonstrate IRTS. First, small-scale farmers seemed less able to market low-value products such as timber thinnings for paper pulp. Second, practices such as pruning and thinning are difficult to master, and large-scale farms are able to obtain labor that is specialized for the task. Both of these reasons why forestry might have IRTS would also apply to silvopasture. However, the tendency for IRTS for silvopasture is not as strong as for forestry.

A more detailed examination of RTS by farm scale group provides more insights into its nature. The IRTS for forestry are statistically significant for small and medium farms. Large-scale farms appear to be closer to operating at efficient scale for forestry. The same conclusion is true for silvopasture plots. However, silvopasture seems to have weaker IRTS than forestry. This can be observed in the lower statistical significance (higher p-value) of IRTS for small farms with silvopasture, despite the smaller sample size for forestry. For pasture plots, large-scale farms appear somewhat likely to be operating under a portion of the production frontier with DRTS, while small- and medium-scale farms appear to be close to efficient scale. One possible reason for DRTS with pasture systems is that family labor on small farms may develop a more intimate knowledge of each particular animal, making care of the cattle more productive. Perhaps the IRTS for silvopasture are weaker than for forestry because silvopasture includes a pasture component, which may weakly favor smaller farms.

The existence of IRTS or DRTS does not suggest that forestry or silvopasture is not profitable for small farms, or that cattle-ranching is not profitable for large farms. What this does suggest is that the quantity of output per unit of input in some cases might be limited by the scale of the farm.

These results support the hypothesis that the nature of RTS depends on numerous factors, including the characteristics of the particular technology. Further, the nature of RTS may be variable at different points along the production frontier. For some technologies, there may be IRTS for small farmers, but DRTS for large farmers.

Small-scale farmers in the region have expressed a preference for silvopasture over forestry based on a preference for receiving more revenue in the short term (Frey et al. 2012). According to these results, there may also be reasons for supporting silvopasture over forestry on efficiency grounds. Assuming optimal use of resources at their scale, small-scale farmers using silvopasture produce more weighted output for each unit of weighted input than those using forestry systems (93.5% vs. 77.1%).

Implications for Policy, Research, and Extension

Public policy related to silvopasture would likely focus on two main issues: direct economic growth including poverty reduction and creation of jobs, and environmental impacts. Our research has implications for both issues, particularly the first.

Our results indicate that there is much to be gained in terms of technical efficiency by expanding silvopasture, including both small- and large-scale operations. These operations could generate more outputs while using similar amounts of, or even less, inputs. In terms of improving efficiency, our results suggest that initiatives to increase adoption should focus on the pastures of cattle farmers.

Focusing on adoption of small landholders is likely to have the largest impact in terms of poverty reduction. The IRTS for silvopasture are somewhat less strong than for conventional forestry, meaning silvopasture could be a method for involving small landholders in forest management and timber production, a major industry in the region. Since most small farmers do own some cattle and maintain some pastureland, there is ample room for increased silvopasture on those lands.

Generation of employment is often a key goal of policy makers. Our results do indicate that silvopasture tends to utilize more labor inputs per hectare than pasture (see Table 3), but results compared to forestry were mixed. This analysis only includes employment on the side of land management; it does not include potential impacts on employment in the wood products industry. Other research in Misiones does indicate that silvopasture tends to generate higher-quality wood than conventional forestry practices (Fassola, Crechi, and Keller 2007). Misiones, in turn, has policies that favor undertaking value-added processes (sawmilling) within the province. Since higher-quality wood is more likely to be transformed into lumber than to be chipped for fuel or paper pulp, it is quite possible that silvopasture could generate more employment than conventional forestry in terms of the wood products industry.

Our results also indicate that slow adoption is not due to poor economic returns for the landholders. Slow adoption must then be due to other causes, which we speculate include the following: (1) lack of understanding of the system among many landholders, (2) cultural norms that create pressure to use traditional systems, (3) high initial investment costs, and (4) relatively long time horizon for investment return, compared to annual crops (although payback period is shorter than typical forestry investments [Colcombet et al. 2010]). INTA extension agents have strived to educate landholders to address issues (1) and (2); these programs we believe should be continued.

Issue (3) is of particular note, since Table 3 indicates a higher level of capital investment per hectare for silvopasture than for conventional cattle-raising systems. Extension programs in Misiones have provided capital inputs to some small landholders to help them get started with silvopasture. However, since these funds are relatively limited compared to the number of small- or limited-resource farmers who might benefit from silvopasture, other approaches might be necessary. For instance, in some rural areas, if a landholder would like to plant a certain grass or tree species, it is relatively common to visit (with permission) a neighbor who already has that species, and extract naturally regenerated seedlings or sprouts in order to transplant onto another property. This is a way to obtain materials, which otherwise would have to be purchased, free or cheaply. However, these small farmers may not know the best practices in terms of selection of the best seedlings/sprouts, timing of extraction, methods of extraction, maintenance between extraction and replanting, methods of planting, and maintenance after planting. Extension programs could focus on these practices and provide guidance to small landowners on how to utilize these cheap, culturally acceptable methods.

Our analysis says nothing about potential environmental impacts (positive or negative), such as the repercussions in terms of downstream water, wildlife habitat, carbon sequestration, and so forth. One's perspective on this issue most likely depends on what he or she views as the alternative land use, that is, whether silvopasture is replacing primary native forest, secondary native forest, exotic timber plantations, perennial crop lands, native grasslands, or degraded agricultural and pasture lands. Our survey results showed that all these scenarios do play out in the real world. If, in one's mind, the baseline is primary native forest, then silvopasture likely has a negative environmental impact. If the baseline is native, unmanaged grasslands, then the environmental impacts may be mixed—there might be some loss of habitat for certain wildlife species, but positive effects in terms of carbon sequestration (Fassola et al. 2010). However, if one's alternative scenario consists of highly degraded agricultural and pasture lands, then silvopasture systems likely have a positive environmental impact. The public policy implication would be to focus extension and incentives on these degraded lands, to promote adoption on lands that are not native ecosystems. However, if carbon sequestration is a key goal, then adoption on native grasslands might also be reasonable—if those grasslands do not provide critical wildlife habitat.

More research is needed to quantify the environmental effects of silvopasture with respect to all these potential baselines, and to value the environmental services that silvopasture and other land uses provide. This would provide information to feed into other policy decisions.

There is also need for further research to evaluate which specific practices within the framework of silvopasture are the most productive. These include when and how to prune or thin trees; how to manage cattle within the trees; and which species of trees and grass, and breeds of cattle perform the best in specific circumstances. Research into these aspects is ongoing in Misiones and Corrientes. In light of our study, researchers should consider the different returns properties of silvopasture for various scales of farms, and how this may influence which specific practices are the most productive for them.

IV. CONCLUSIONS

One method for comparing technologies is to use simple criteria from a capital budgeting model, but this approach has some limitations. The DEA model with within-farm comparisons uses weaker assumptions to compute a single efficiency statistic that elucidates some of the questions arising from the capital budgeting model.

DEA uses linear programming to find relative values for inputs and outputs that maximize the output to input ratio with relation to other decision-making units. This relative input to output ratio is the technical efficiency, a number between 0 and 1. However, when comparing the DEA relative technical efficiencies for systems or technologies on various farms, one must control for between-farm differences. We used a Wilcoxon signed-rank test as a simple, yet powerful way to compare the efficiencies of the three systems. Because we have used paired comparisons to test the difference in efficiency, we have controlled for variability between farms and farmers. There remains a question as to whether within-farm variability may affect the results; however, even when omitting silvopasture plots that were planted over less degraded sites such as clear-cut native and plantation forests, the efficiency difference between silvopasture and pasture remains.

The results of the within-farm comparisons of the three farm technologies demonstrate that silvopasture practices are generally more technically efficient than pasture. We were not able to reject the lack of an efficiency difference between silvopasture and forestry or forestry and pasture. However, the direction of the differences in pairwise comparisons, and the average efficiency scores for forestry suggest that forestry plots may be of intermediate efficiency.

Overall, plots of silvopasture and forestry systems were more likely to be operating under increasing returns to scale. There is some evidence to suggest that plots of small-scale farms might be able to increase efficiency by increasing scale. Interestingly, this appears to be a combination of the patterns seen in pasture systems, where large-scale farms operated under decreasing returns to scale (though not significantly), and forestry plantations, where small-scale farms operated under increasing returns to scale.

In the context of public policy and programs, silvopasture could play an important role in increasing overall rural productive efficiency, restoring productivity of degraded agricultural and pastureland, and generating returns and employment for limited-resource farmers. Our results indicated that programs should focus on small or limited-resource farmers, and lands that are currently utilized for pasture. Further, future research and extension should highlight practices that can lower up-front capital investment costs, as well as delineate the most productive practices within the set of silvopasture systems.

Efficiency, or profitability, is not necessarily sufficient to guarantee adoption, if there are capital cost or education barriers. If increased silvopasture adoption is viewed as beneficial from the public standpoint, in terms of benefits such as poverty reduction, job creation, or environmental services, the government should continue offering extension and incentives to promote adoption. Further research would be desirable to quantify environmental impacts of silvopasture.

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