ISSN 1832-7435

Australian Centre for International Agricultural Research (ACIAR)
Project: ADP/2002/015

Managing Groundwater Access in the Central Highlands (Tay Nguyen), Viet Nam

Research Report No. 6

Valuing irrigation water for coffee production in Dak Lak, Viet Nam: a marginal productivity analysis

Jeremy Cheesman, Tran Vo Hung Son and Jeff Bennett

November 2007

About the authors

Jeremy Cheesman is a research associate in the Environmental Management and Development program at the Crawford School of Economics and Government, The Australian National University. Tran Vo Hung Son is Professor at the Faculty of Development Economics, Ho Chi Minh City University of Economics (HCMCUE). Jeff Bennett is Professor and Head of the Environmental Management and Development program at the Crawford School, The Australian National University.

Managing Groundwater Access in the Central Highlands (Tay Nguyen), Viet Nam Research Reports are published by the Crawford School of Economics and Government, The Australian National University, Canberra, ACT, 0200, Australia.

These reports present discussion and preliminary findings of the research project 'Managing Groundwater Access in the Central Highlands (Tay Nguyen), Viet Nam'. This is a collaborative project between the Australian National University, the Ministry of Natural Resources and Environment (MONRE) Viet Nam, Ho Chi Minh City University of Economics and Tay Nguyen University, funded by the Australian Centre for International Agricultural Research (ACIAR).

Any comments on these reports should be directed to:

Professor Jeff Bennett
Asia Pacific School of Economics and Government
The Australian National University
ACTON ACT 0200
Australia
Telephone: +61 2 6125 0154
Facsimile: +61 2 61258448
Email: Jeff.Bennett@anu.edu.au

Acknowledgments

The authors gratefully acknowledge Dr Nguyen Thai Lai, Director General of Viet Nam's Ministry of Natural Resources and Environment's Department of Water Resources Management for his ongoing support for the research project this research is part of. We also gratefully recognise the Dak Lak Peoples' Committee's support and cooperation in this research effort. We thank Truong Dang Thuy and Doan Kim Thanh from Ho Chi Minh City University of Economics for their contributions towards this research, plus the graduate students from Ho Chi Minh City University of Economics and Tay Nguyen University who were farm survey enumerators. We are grateful to Dave D'haeze from EDE Consulting Asia Pacific (Hanoi) for commenting on early survey drafts, providing secondary research data and giving valuable insights about smallholder coffee production processes in Dak Lak. We thank Dr Céline Nauges from the Toulouse School of Economics, LERNA-INRA for her constructive comments on report drafts. Finally, we thank the coffee smallholders who participated in the farm survey for their time and cooperation.

SUMMARY

In 2006, export earnings from coffee grown in Viet Nam's Dak Lak Plateau totalled around USD330 million. Approximately 50 percent of the Dak Lak Plateau is now planted with coffee, with smallholders producing on plots totalling less than 1.5 hectares dominating the sector. Most smallholders source their irrigation water from the Plateau's unconfined aquifer via privately owned wells and pumps. The sustained and largely unregulated expansion of coffee smallholdings in the Plateau over the past three decades has driven the Plateau's rapid growth but has also strained its natural resources. One growth consequence is that the Dak Lak Plateau's water resources may now be over-allocated. Over-allocation risks the region's development plans, agro-environmental stability and the smallholder coffee sector's ongoing viability. In recent years sustained declines in the unconfined aquifer's water table have been reported, which potentially indicates groundwater mining is occurring. Drought conditions have caused widespread agricultural production losses and household water shortages. The confluence of the Plateau's hydrodynamics, high irrigation well density and a general lack of enforceable controls over irrigation water use create a classic open access resource dilemma.

Viet Nam's Law on Water Resources calls for water resource management and allocation based on rationality, economy, efficiency, fairness and sustainability principles. The Law also instructs that agricultural water users must allocate water economically and efficiently. From a regional planner's viewpoint, implementing the Law at a river basin level therefore requires a minimum understanding of: (1) waters' economic value in competing uses; (2) how the region's surface and groundwater systems interact and would probably respond to water reallocations; and (3) the extent to which water use efficiency could be increased in a region via behavioural and technical intervention in the main water using sectors. Towards these objectives, this research paper uses a marginal productivity approach to estimate the economic value of dry season irrigation water to Dak Lak's coffee smallholders. The technical, behavioural, socio-economic and institutional bases for productivity differences amongst coffee smallholders are also examined. Further, given efficient irrigation water markets do not operate in Dak Lak Plateau, a short run marginal cost of water use is estimated in substitute for the efficient market price. These estimates are subsequently used to explore changes in producers' surpluses resulting from varying irrigation input and irrigation schedules.

Results show that in the 2005 / 2006 production year, coffee smallholders over-allocated elemental nutrient and labour inputs. Information failure and risk aversion are both seen as reasonable explanations for respondents' behaviour. Estimates suggest that a total of 1.65 cubic meters of dry season irrigation water per production stage coffee tree is more than sufficient for full flower set during a normal climatic year, as long as the technically efficient irrigation schedule is followed. Shifting from average to efficient irrigation practices lifts production by around 500 kilograms per hectare, reduces irrigation water inputs by 2,300 cubic meters per annum and cuts short run irrigation costs by VND2.7 million per annum. Combined, these findings suggest training programs to increase coffee smallholders' irrigation aptitude have the potential to deliver a double dividend in Viet Nam's Dak Lak Plateau, first by increasing coffee smallholders' productivity and cutting their irrigation costs and second by reducing the incidence and severity of dry season pumping and stock externalities that are potentially caused by over-irrigation on coffee smallholdings.

CONTENTS

1 INTRODUCTION

In 2006 Viet Nam exported approximately 900,000 tons of mainly Robusta coffee, contributing USD1.1 billion to national earnings (Investment and Trade Promotion Centre of Ho Chi Minh City, 2007, The World Bank, 2007). Around 60 percent of Viet Nam's coffee output originates in Dak Lak Province, with the majority produced on smallholdings of less than 1.5 hectares. Robusta requires irrigation during Dak Lak's dry season and competition for scarce water has been increasing in recent years between coffee smallholders and among the urban and agricultural sectors, especially when the preceding wet season rainfall has fallen below the historical average (Ahmad, 2000, Dak Lak Peoples' Committee, 2001, D'haeze, et al., 2003, Riddell, 1999). Viet Nam's Law on Water Resources (1998) legislates that water resources should be allocated in a rational, efficient, fair and sustainable manner. These objectives cannot be achieved without knowing the economic value of water in its competing uses. Because irrigation water is not efficiently priced in Dak Lak, its economic value in competing uses cannot be directly estimated from observed transactions. Alternative valuation approaches are called for.

This research paper values dry season water in Dak Lak's smallholder coffee sector with a marginal productivity analysis approach. The research also investigates the bases for productivity differences amongst coffee smallholders and aims to identify profit maximizing factor input levels for irrigation water, elemental nutrients, labour and capital. The combined analysis provides a basis for identifying approaches to strengthen Dak Lak's smallholder coffee sector. Value estimates for dry season irrigation water provide a partial basis for developing formal water allocation guidelines. Observed productivity differences between smallholders provides a foundation for developing policies that improve farm management practices, increase returns and sustain the Dak Lak Plateau's agro-ecology.

The research paper is organized in six sections. Section two overviews the key background issues. Section three outlines the marginal productivity analysis approach that serves as the research's analytic basis. Section four first overviews the data collection method, then presents descriptive statistics. Departing from previous econometric analyses of crop production that focus on the relationship between static inputs and output, a quasi-dynamic stochastic production frontier incorporating irrigation scheduling as well as socio-economic and institutional factors is employed. The single stage approach used means the marginal physical productivity of irrigation water as well as irrigation scheduling behaviours and technological, socio-economic and institutional variables can be observed directly from the estimated stochastic production frontier. A short run irrigation cost model serving as the basis for irrigation water's marginal use cost is also estimated. Section five synthesizes marginal physical productivity and marginal use cost analyses to compare producer surpluses with different irrigation schedules and water input levels. Section six concludes.

2 BACKGROUND

Between 1976 and 2002 coffee plantation area in Dak Lak increased from roughly 20,000 to 285,000 hectares (Dak Lak Statistical Department, 2002, Lenin Babu, et al., 2003). Smallholders generally operating on less than 1.5 hectares control over 80 percent of this production area. Local climatic conditions result in only the Robusta coffee variety (*Coffea canephora*) being propagated. A detailed discussion of the causes and consequences of the rapid and largely uncontrolled expansion in smallholder Robusta production in Dak Lak is provided in Cheesman and Bennett (2005).

The Dak Lak Plateau, which dominates Dak Lak Province's central region, accounts for roughly 50 percent of Dak Lak's annual Robusta output. A key consequence of uncontrolled land conversion to coffee is that many areas in the Dak Lak Plateau now cropped with coffee are mismatched to local water availability (Ahmad, 2000, D'haeze, et al., 2005). Over 70 percent of the Dak Lak Plateau's coffee smallholders draw groundwater from the region's unconfined aquifer for dry season irrigation. Most smallholders own their own mobile pump and have access to at least one private well (Ahmad, 2000, Chi and D'haeze, 2005). Groundwater withdrawals for coffee irrigation have a pervasive influence on Dak Lak's hydrodynamics, and contribute to the increasing incidence of well exhaustion and baseflow disruption, especially during low and very low rainfall years (Basberg, et al., 2006, Chi and D'haeze, 2005, D'haeze, et al., 2005, Moller, 1997, Moller, 1997). The high incidence of private well and pump ownership, absent controls on smallholder irrigation and the local unconfined aquifer's hydrodynamics combine to create a classic open access resource dilemma.

Improving allocative and technical efficiency[1] on coffee smallholdings should be fundamental to increasing farm level total factor productivity[2], returns to coffee smallholders and stabilizing the region's underling agro-ecology. From 1990 to 2000, Dak Lak's average coffee output increased by 30 percent per annum with on-farm productivity improvements accounting for less than one third of these increases (ICARD and OXFAM, 2002: 13). Output from smallholdings averages between 1,700 to 3,000 kilograms per hectare, lagging potential production by anywhere between 17 and 250 percent (Chi and D'haeze, 2005, D'haeze, 2004)[3]. There is evidence that Robusta smallholders allocate production inputs inefficiently, over-irrigating and over-fertilizing relative to local government recommendations (Chi and D'haeze, 2005, D'haeze, et al., 2003). Technical inefficiencies are also evident, particularly in irrigation and fertilizer scheduling and management. Poor irrigation timing leads to uneven and reduced flower onset, uneven berry ripening and lower bean quality (D'haeze, et al., 2003, Titus and Pereira, 2007).

---

[1] A producer is technically efficient when they maximise output for given set of inputs and production technology; this can only be achieved when optimal input mixes and timing is used. A producer is allocatively efficient when they employ factor inputs in production up to the point where the marginal benefit gained from an additional unit of each input equals their respective marginal opportunity cost. A producer who is both technically and allocatively efficient is economically efficient.

[2] Productivity = total factor productivity = outputs / all production factor inputs

[3] The suggested production potential of Dak Lak's coffee smallholdings varies between sources between 3500 and 6000 kilograms per hectare D'haeze, D. "Water management and land use planning in the Central Highlands of Vietnam. The case of Coffea canephora in Dak Lak province." Leuven University, 2004, ICARD, and OXFAM. "The Impact of the Global Coffee Trade on Dak Lak Province, Viet Nam: Analysis and Policy Recommendations." ICARD..

3 THE MARGINAL PRODUCTIVITY APPROACH TO DETERMINING ECONOMIC VALUE

Lacking an efficient water market in Dak Lak from which water's economic value to the coffee sector could be inferred, the marginal productivity analysis approach is used to estimate dry season water's economic value amongst Dak Lak's coffee smallholders. Marginal productivity analysis values water as the net change in revenue resulting from a unit change in irrigation water supplied (Wang and Lall, 2002). Marginal productivity analyses are based on a production function describing the relationship between the physical output that can be achieved with different input combinations and a fixed production process (Beattie and Taylor, 1985). Specify a single crop production function as:

$$y = f\left(\mathbf{X}, W, \mathbf{E}\right) \tag{1}$$

where $\mathbf{X}$ is matrix of fixed and variable inputs other than water (W) directly under the farmer's control. **E** characterises a matrix of agro-environmental production variables that also determine the location of the production possibility frontier but are essentially beyond the farmer's control, such as rainfall, temperature, humidity, initial soil quality and land slope. Assuming the production function specified in (1) is continuous and twice differentiable for all inputs, marginal physical product is obtained via the partial derivative of output for each input. For example, the water input's marginal physical product of water is given by:

$$\frac{\partial y}{\partial W} = \frac{\partial f\left(\mathbf{X}, W, \mathbf{E}\right)}{\partial W} \tag{2}$$

Assuming the smallholder (i) faces perfectly elastic supplies for all factor inputs other than water and perfectly elastic demand for output such that prices are known and constant and (ii) that irrigation costs are given by p_w and (iii) the producer is a risk neutral profit maximiser, their profit function is (Young, 2005: 54):

$$\Pi\left(\mathbf{X}, W, \mathbf{E}, p_y, \mathbf{P_x}, p_W\right) = p_y f\left(\mathbf{X}, W, \mathbf{E}\right) - \left(\mathbf{P_x}\mathbf{X} + p_W W\right) \tag{3}$$

Where p_y is the output's market price and $\mathbf{P_x}$ denotes input prices. Conditions for solution of the maximum are:

$$\begin{aligned} \frac{\partial \Pi\left(\mathbf{X}, W, \mathbf{E}, p_y, \mathbf{P_x}, c_W\right)}{\partial x_i} &= p_y \frac{\partial f\left(\mathbf{X}, W, \mathbf{E}\right)}{\partial x_i} - p_{x_i} = 0 \qquad \forall x_i \\ \frac{\partial \Pi\left(\mathbf{X}, W, \mathbf{E}, p_y, \mathbf{P_x}, c_W\right)}{\partial W} &= p_y \frac{\partial f\left(\mathbf{X}, W, \mathbf{E}\right)}{\partial W} - p_W = 0 \end{aligned} \tag{4}$$

In (4) $p_y f\left(\mathbf{X}, W, \mathbf{E}\right)$ defines the total value product whereas $p_y \frac{\partial f\left(\mathbf{X}, W, \mathbf{E}\right)}{\partial x_i}$ defines the value marginal product (VMP) of the i[th] input and $p_y \frac{\partial f\left(\mathbf{X}, W, \mathbf{E}\right)}{\partial W}$ defines irrigation water's VMP.

Profit is maximised when each input's VMP equals its price (4). Marginal cost can be substituted for price when efficient prices do not exist (Wang and Lall, 2002). Note that the producer is allocatively efficient when the first order conditions are met for all production inputs (Ali and Byerlee, 1991: 3). Failure to achieve the first order conditions may reflect incomplete information, inadequate technical capacity, risk aversion or socio-economic-institutional factors (Ali and Byerlee, 1991: 7). The change in a producer's surplus is measured by altering one input's level in the production function while holding all others fixed. Because the level of all other inputs cannot be adjusted in this approach, the estimated producer surplus resulting from a change in one input's level is a lower bound welfare estimate (Young, 2005: 56). See Johansson (1993) or Young (2005) for further discussion.

4 APPLICATION

4.1 Data

Research data comes from a small but comprehensive coffee producer survey completed in early 2007 for the 2005 / 2006 production year. Dak Lak's 2005 wet season was characterized by average rainfall, meaning output and coffee smallholder's management practices in the 2005 / 2006 production are for typical climatic conditions. The survey obtained production data for respondents' most important production stage coffee plot, as well as broader farm, agro-environmental, irrigation scheduling, infrastructure and cost data as well as socio-economic and institutional data[4]. Combined, these data enable each input's VMP to be calculated from (4) using an estimated production function. A marginal use cost for irrigation water can also be calculated from these data and substituted for (p_w) given irrigation water is not efficiently priced in the Plateau.

In view of the challenges in obtaining reliable data based on smallholders' best recall, substantial effort was directed towards developing a survey that allowed for cross-validation in order to detect and resolve discrepancies during the interview. An on-site walk through approach was used to estimate total dry season irrigation for the production plot. The enumerator randomly selected and measured four production stage tree's irrigation basin dimensions in the respondent's plot and asked the smallholder to indicate the level to which the basin was normally filled[5]. Generally, there was minimal within plot variation in basin dimension measurements. The total dry season irrigation for the plot was estimated based on an average of the four micro-basin observations and the respondent's estimated number of dry season irrigations. This approach was favoured given evidence that coffee smallholders in Dak Lak generally have no idea how much irrigation water they apply per tree per annum (D'haeze, 2005).

[4] One conjecture is that the most important plot is also the best-managed plot, which may result in a non-representative output levels if there are yield differentials. In the survey sample however the most important field accounted for approximately 65 percent of each respondent's total farmed area and was considered satisfactorily representative as a result.

[5] Note the approach did not incorporate a leakage factor for percolation during irrigation because this was believed to be negligible. As a result the irrigation volumes represent a lower bound. A leakage coefficient could easily be incorporated in the estimates. Further, for sprinkler irrigators respondents used a 'best guess' since they did not directly observe the level to which each basin was filled in all cases.

Primary data was collected from 105 Robusta smallholdings, unevenly but randomly selected from the six districts in the Dak Lak Plateau: Buôn Đôn, Cu' m'gar, Krông Ana, Krông Buk, KrôngPak and TP Buon Ma Thuot. Each of these districts fall into one of four distinct climatic zones (D'haeze, 2004: 17). The farm survey was supplemented by key informant interviews with experienced local coffee agronomists. Rainfall and reference evapotranspiration data were obtained for seven government-run observation stations in the research area. Regional soil and topography classification were based on field survey work reported in D'haeze (2004).

4.2 Descriptive statistics

Descriptive statistics are presented in Table 1, categorised on the basis of whether basin or sprinkler irrigation was used and the respondent plot's soil classification. Table 2 summarises prices for output and the main fertilizer, pesticide and labour inputs. Paired t-tests confirmed prices were common across sprinkler and micro-basin irrigators[6]. Only 11 respondents used the sprinkler irrigation method. Of the respondents using micro-basin irrigation only 14 operated on soils other than Rhodic Ferralsols. Subsequent discussion concentrates on micro-irrigators operating on Rhodic Ferralsols only given this clearly is the dominant production group.

Average production amongst respondents was approximately 3,850 kilograms per hectare and 3.8 kilograms per tree. Output per hectare and per tree was normally distributed[7]. These figures are high compared to previous studies in Dak Lak (Chi and D'haeze, 2005, D'haeze, et al., 2003, ICARD and OXFAM, 2002, Rios and Shively, 2005), but below suggested maximum achievable yields (Lich, et al., 2005).

On average respondents over-applied fertilizer and water compared to the maximum requirements advised by the local agricultural services. The advised elemental nutrient requirement for production stage coffee trees in Dak Lak (> 4 years) are 0.25 kilograms nitrogen tree^{-1}, 0.09 kilograms phosphorous tree^{-1} and 0.27 kilograms potassium tree^{-1} per annum (Lich, et al., 2005). Respondents averaged 0.44 kilograms N, 0.19 kilograms P and 0.41 kilograms K tree^{-1}. The distribution of input quantities for all elemental nutrients is negatively (left) skewed. Smallholders receiving extension training during the previous 12 months (n=17) averaged 0.34 kilograms N, 0.13 kilograms P and 0.29 kilograms K tree^{-1}. One sided two-sample t-tests assuming unequal variances rejected the null hypothesis of mean equivalence for the trained and untrained sub-samples at the one percent level for P(t = 2.45 P > t = 0.0082) and at the 5 percent level for N (t = 1.80 P > t = 0.0395) and K (t = 2.0137 P > t = 0.0242).

The average respondents applied 1,050 litres per tree per irrigation and irrigated 3.8 times during the dry season. These figures are substantially higher than the recommended irrigation application which falls between 390 and 650 litres per tree and 2 to 4 dry season irrigations (D'haeze, et al., 2005). None of the respondents used less than 390 litres irrigation per tree, which D'haeze, et al. (2003) determined was all that is required to ensure maximum flower set in Robusta in Dak Lak as long as the

[6] Results available on request from corresponding author.
[7] A joint skewness / kurtosis test did not reject the null hypothesis that per hectare yields followed a normal distribution.

water was applied whenever average soil water content in the top 60 centimetres dropped to 30 percent volume. Only nine respondents applied less than 650 litres on average per irrigation. Notably, the same 17 respondents who had participated in extension training in the previous 12 months and had significantly lower nutrient input levels than their untrained counterparts had a significantly higher average irrigation volume of 1,300 litres per tree compared to smallholders who did not receive training whose average dose was 900 litres per tree. Further, trained smallholders' total dry season irrigation volume per tree was 4,960 litres per tree, compared to 3,480 litres per tree for farmers who did not receive training. A one sided two-sample t-test assuming unequal variances rejected the null hypothesis of equal means for the trained and untrained sub-samples at the one percent level (t= t = -3.2982 P < t=0.0018) and also total dry season water input (t = -2.6335 P < t = 0.0084).

Analyses of respondents' irrigation scheduling suggests average scheduling behaviours approximate those local agricultural authorities advise, but that substantial deviations from mean practice exist. Based on a series of farm experiments, D'haeze, et al. (2003) concluded to obtain complete blossom set water stress must be avoided for at least seven days after irrigation. In Dak Lak this broadly translates to a first irrigation of 390 litres or more before the second half of January and subsequent irrigations every 20 to 25 days until the dry season finishes. Moreover, the first irrigation is the most important in stimulating the majority of buds to open and achieving even flower set. Respondents' average irrigation spacing was 24 days with a seven-day standard deviation. More than 40 percent of respondents had average irrigation rotations exceeding 25 days. Approximately 20 percent reported not applying more water for the first dry season irrigation and a further 15 percent commenced dry season irrigation after mid-January.

Average reported tree density per hectare is approximately 1,050 trees, marginally lower than the advised optimal spacing of 1,100 trees per hectare (D'haeze, et al., 2005). The average tree age was just under 15 years, at the upper bound of the reported maximum productive age range of between 5 and 15 years (D'haeze, 2004: 64). Shade trees were used on approximately 50 percent of plots. The average plot slope was between moderately sloped to flat, consistent with recommendations that coffee grows best on plots with land slopes less than 30 degrees (D'haeze, 2004). Eighty percent of respondents using micro-basin irrigation drew groundwater, with 70 percent using groundwater as their only irrigation source and just over 20 percent relying exclusively on surface water supplies. The average distance between the main dry season irrigation water source and the plot was around 160 meters.

Virtually all respondents are Kinh, reflecting their domination of coffee production in Dak Lak. Total average farm area was one hectare, spread over an average 1.5 plots. Eighty percent of respondents' mono-cropped coffee and 60 percent had registered land titles.

4.3 Production function estimate

4.3.1 Variables

The input, irrigation scheduling, agro-environmental and socio-economic-institutional variables used in the analysis are summarised in Table 3. The output variable is the average 2006 dry bean yield per tree in kilograms. Elemental nutrient, labour and operating capital inputs are also measured on a per tree, per annum basis and are obtained by dividing total estimated inputs for the plot by the estimated number of trees in the plot. Elemental nutrient estimates were obtained using conversion tables for the main classes of chemical fertilizer used in coffee production in the Dak Lak Plateau. Irrigation water input is the average volume applied per tree per irrigation. This measure provides a better index of each plant's dry season root zone soil moisture condition compared to using the total dry season irrigation volume per tree or per hectare alternatives. While applying organic fertilizer in combination with chemical fertilizer should increase production and improve soil moisture retention (Chi and D'haeze, 2005), there are insufficient observations to justify interaction variables. Manure is modelled using a dummy variable as a result.

Irrigation season length is estimated based on each respondent's reported dry season irrigation start and end dates, less the average reported length of an irrigation event; i.e. the irrigation season is measured as the number of days between the first day of the first irrigation and the first day of the last irrigation. For consistency, the length of an irrigation event is based on a per hectare conversion. The average duration between irrigation events is measured as the ratio of each respondent's irrigation season duration variable over their number of dry season irrigations. A dummy variable is constructed to differentiate between smallholders who begin irrigation late in the season, taking the value of one if irrigation commenced after January 15 and zero otherwise. The dummy variable "First irrigation" takes a value of one if respondents applied more water for the first dry season irrigation.

Dummy variables are also employed to evaluate the partial physical productivity of receiving agricultural training in the previous 12 months, coffee mono-cropping and land registration, with each of these variables taking the value of one for occurrence and zero otherwise. Variables for respondents' age and years of education are also included. The variables 'Plots', 'Area', 'Pumps', 'Non-farm income' and 'Household labour potential' measure the number of plots the respondent farms on, total farmed area, number of irrigation pumps owned, total annual household income from non-farm employment and the total number of permanent household members over the age 13 respectively. A variable measuring the number of pumps used on the farm is included to evaluate Rios and Shively's (2006) finding that technical efficiency on coffee smallholdings in Dak Lak was increasing with the number of pumps, regardless of farm size.

Five observations were discarded from the dataset due to missing data for key input variables. Three further observations were discarded out of concern for large potential measurement errors and excessive influence on estimation results.

4.3.2 Empirical specification

The production relationship specified in (1) can be estimated with a frontier or a non-frontier approach. The frontier approach estimates (1) as the maximum possible output given fixed inputs and a production technology (Ali and Byerlee, 1991). The extent to which farm production differs from the frontier provides a measure of technical inefficiency for the sample as a whole or for each firm individually. The non-frontier approach estimates the average output given fixed inputs and a production technology. The non-frontier approach allows producers' relative efficiency to be established but does not allow analysis of producers' absolute deviations from the production frontier. Derived demand for irrigation water using the marginal productivity approach should theoretically be based on the production frontier because the VMP derived in (4) then defines the maximum the technically efficient producer would be willing to pay for the additional input, as opposed to an average willingness to pay.

A transcendental form is used to define the unknown coffee production frontier:

$$\begin{aligned}\ln y_i &= \alpha_0 + \sum_{j=1}^{J} \alpha_{j1} x_{ji} + \sum_{j=1}^{J} \alpha_{j2} \ln x_{ji} + \sum_{j=1}^{J} \sum_{k=1}^{K} \alpha_{jk} x_{ji} x_{ki} \\ &+ \alpha_{w1} w_i + \alpha_{w2} \ln w_i + \sum_{j=1}^{J} \alpha_{jw} x_{ji} w_i + \sum_{j=1}^{J} \alpha_j e_{ji} + \sum_{j=1}^{J} \alpha_j s_{ji} + \sum_{j=1}^{J} \alpha_j c_{ji} + v_i - u_i\end{aligned} \quad (5)$$

Where the dependent variable y is 2006 yield per tree in kilograms, i indexes the respondent, j identifies the j^{th} factor input amount per tree (x) and environmental (e) and irrigation scheduling (s) input, w_i is the average irrigation application in cubic meters per tree and the α are unknown parameters to be estimated. v_i defines the symmetric and normally distributed error term, which are assumed to be iid., $N(0,\sigma_v^2)$, and independent of the one-sided non-negative error term with a truncated normal distribution, $u_i \geq 0$, reflecting the shortfall of farm's output from its production frontier due to the existence of technical inefficiency. Following Battese and Coelli's (1995) specification, the one-sided inefficiency term is:

$$u_i = g(z_i, \delta) + \varpi_i \quad (6)$$

Where Z_i defines a vector of variables used to explain efficiency differences between producers, δ is a vector of unknown parameters to be estimated and ϖ_i is an iid random variable with zero mean and variance defined by the truncation of the normal distribution. Note that when Z_i contains only a constant then the model reduces to the truncated normal specification in Stevenson (1980), where δ_0 has the same interpretation as the μ parameter in Stevenson (1980). The variance parameters of the likelihood function are estimated by $\sigma^2= \sigma_v^2+ \sigma_u^2$ and $\gamma= \sigma_u^2/(\sigma_v^2+ \sigma_u^2)$, with γ taking a value between zero and one. A γ approaching one increasingly indicates variance is explained by systematic differences in production efficiency amongst respondents, whereas a value near zero shows all variation is due to white noise. Note when σ_u^2 is approximately zero (5) collapses to a specification that can be consistently estimated using ordinary least squares. See Coelli et. al (1998) and Coelli (1996) for more details.

The frontier specified in (5) is a "one-stage" approach for evaluating technical efficiency (Weir and Knight, 2006). The one-stage approach includes all variables of interest in the production frontier model. The two-stage alternative follows in the tradition of Farrell's (1957) original specification by including one set of variables to estimate efficiency scores in the first stage and a second variable set to explain the efficiency scores in the second stage. The one-stage approach is favoured in this research because it allows the partial physical productivity of irrigation scheduling and socio-economic-institutional covariates to be directly estimated. This is compared to only being able to identifying these parameters' direction of influence if they are included in the technical inefficiency model (Liu, 2006). Further, the approach means observed differences in technical efficiency occur between producers who are essentially identical in input, irrigation behaviour, agro-environmental and socio-economic-institutional terms. This in itself is of policy interest because finding technical inefficiency would indicate training programs cannot be developed based on an assumption that essentially identical producers have similar technical efficiency levels[8].

4.3.3 Hypothesis

The relationship between factor inputs and output. Estimated coefficients for elemental nutrient, irrigation water, labour and other variable inputs should satisfy basic assumptions of crop response: (1) diminishing returns from factor inputs and (2) decreasing returns to scale, implying that equal proportionate increases in factor inputs result in a less than proportionate output (Dillon and Anderson, 1990: 6). Because respondents generally over-irrigate and over apply elemental nutrients relative to local extension services' recommendations, an insignificant coefficient is also feasible for these variables. This is given Rhodic Ferralsols' drainage properties, which are characterised by high hydraulic conductivity when the soil is near saturation and decreasing rapidly as soil moisture content decreases. Production should be increasing in capital and other operating cost variables assuming these are general production intensity indices. Average smallholders are expected to be allocatively inefficient by the economic standard defined in (4) that is they will not equate value marginal product with the marginal input price. If respondents apply inputs in excess of the economically efficient allocation, the ratio of value marginal product to marginal operating cost will be less than one.

As a growth facilitating input, a negative relationship between pesticide and herbicide use and total physical production is expected[9] (Zhengfei, et al., 2006). Herbicides and pesticide inputs abate coffee crop damage but do not directly increase yields, meaning a positive relationship should never be observed in principle. When farmers apply herbicides or pesticides reactively to an infestation a negative coefficient is expected given some yield losses will probably already have been experienced.

Irrigation scheduling influences on the production frontier. The null hypotheses to be tested are (1) respondents' irrigation season length depends on their local climate, specifically the observed dry season duration; (2) a longer irrigation season is a proxy for drier climatic conditions, increasing the potential for yield declines due to water stress; (3) the optimal irrigation spacing is within the range

8 Of course technical efficiency differences within the idiosyncratic frontier need to be considered in the context of their broader productivity evidenced through the frontier estimates.

[9] Note as a damage abating input pesticide use could also be expressed in damage abatement/ reduction form. Zilbermann suggests treating pesticides as yield increasing inputs overestimates their marginal productivity and suggests the damage abatement approach as an alternative. See Foti, R., and T. Chikuvire, J. "Farm Level Pesticide Use and Productivity in Smallholder Cotton Production in Zimbabwe: The Case of Gokwe Communal Area Farmers." For a simple application. Implementing the exponential form of the damage abatement function on this data resulted in no change in the coeffs and a lower F value, so the approach was not followed.

of 20 and 25 days. Moreover, (4) recalling that the first dry season irrigation is responsible for opening the majority of buds and ensuring a homogenous yield quality (Chi and D'haeze, 2005, Titus and Pereira, 2007), a positive main effect is anticipated for farmers apply more irrigation water on the first irrigation.

The impact of plot specific characteristics on the production frontier. The presence of shade and wind-shield trees on the production plot should increase partial physical productivity by reducing plant stress (ICARD and OXFAM, 2002).

Maximum productivity per tree is expected between the age of 5 and 15 years, based on (D'haeze, et al., 2005).

In Dak Lak, an optimal planting density of 1,100 trees per hectare is recommended D'haeze, et al. (2005). It is hypothesized that lower planting densities will increase yields per as crowding is eliminated.

Recalling that Robusta favours land with gradient less than 15 degrees, it is hypothesized that yield per tree will be greater on flat land compared to moderately and steeply sloped land.

Socio-economic, demographic and institutional impacts on the production frontier. The empirical impact of tenancy status on agricultural productivity in developing countries is not conclusive (Ali and Byerlee, 1991). Rios and Shively (2006) found tenancy did not explain technical or cost efficiency amongst Dak Lak’s coffee smallholders in 2004. However, defensible land tenure has been linked to long term increases in farm productivity because it provides an incentive to maintain and improve the underlying land asset as opposed to maximizing short term returns through exploitative production technologies (Ray, 2005). The hypothesis tested here is that secure tenure, in the form of registered land titles, encourages investment and higher productivity over the long run (Liu, 2006).

The relationship between farm size and technical efficiency are mixed (Liu, 2006). Rios and Shively (2006) found farm size did not directly contribute to technical inefficiency amongst coffee smallholders in Dak Lak. Land fragmentation, measured by the number of plots farmed by the smallholder, has been found to increase technical inefficiency, family labour use and other money expenses in Viet Nam (Hung, et al., 2007). On these grounds the null hypothesis is that increasing fragmentation will correlate with decreasing productivity. Productivity is anticipated to be increasing with farm size.

Empirical evidence suggests that farmers who have recently participated in training programs should be both technically and allocatively more efficient than untrained counterparts (Ali and Byerlee, 1991). Respondents’ participation in local extension programs is therefore expected to have a significant positive correlation with productivity.

It is hypothesized that partial physical productivity should increase with respondents' years of farming experience (Ali and Byerlee, 1991). This may be due to attrition or as an index of technical skill.

Better education has been shown to increase productivity but has also been linked to reduced labour availability for farm production (Ali and Byerlee, 1991, Liu, 2006, Rios and Shively, 2006). Here, it is hypothesized that increasing education will result in managerial skill being withdrawn from the farm thereby shifting the frontier inwards.

We hypothesize that increasing non-farm income should increase productivity, with this effect reflecting a relaxing of financial constraints similar to the basis for why credit is generally found to increase on-farm productivity (Liu, 2006). Coffee's growing cycle includes several periods where bottlenecks can occur, for example during harvesting. Smallholders facing financial constraints may be less able to arrange production at the best timing - this constraint may be relaxed with increasing off-farm income.

Households with larger labour endowments have been found to be more technically efficient, possibly due to having slack labour available for peak production times (Tesfay, et al., 2005). A consistent productivity effect is hypothesized.

4.3.4 Results

Given smallholders' potentially determine their coffee irrigation season length based on local climatic conditions, climatic zone dummy variables were tested to determine if these were strong instruments for irrigation season duration. The climate zone variables were significantly correlated with irrigation season duration and had the expected signs, given the climate zone set as the baseline has the warmest and driest conditions, implying a longer dry season irrigation season (Table 4). The F statistic in each model is less than 10 however, suggesting the optimal instrument combination is weak (Bound, et al., 1995). As a result the stochastic frontier model was implemented assuming irrigation season duration was exogenous for estimation purposes.

Table 5 presents the stochastic production frontier estimates. The inefficiency component of the disturbance term is significantly different from zero indicating the presence of statistically significant inefficiency in the data. The gamma (γ) value is 99 percent. This demonstrates essentially all departures from the estimated production frontier are caused by systematic technical inefficiency rather than random disturbances. The result shows that the estimated frontier is statistically free from random variation, which may indicate the agro-environmental variables specified in the frontier control for stochastic production influences. Even though technical inefficiency is present, average technical efficiency is 92 percent. The technical inefficiency means the use of Ordinary Least Squares (OLS) for estimation is inappropriate and would yield biased estimates.

With the exception of the coefficients for labour, the estimated input coefficients are either insignificant or do not satisfy the basic crop response assumption of diminishing returns from factor inputs (Dillon and Anderson, 1990: 6). These results can largely be explained by noting the sizable majority of surveyed smallholders exceeded the minimum input levels for elemental nutrients, with the result that well-behaved input-output relationships could not be observed. The most important finding given the research focus is that the coefficients for water input per tree per irrigation and its natural logarithm are insignificant. This result demonstrates that applying more irrigation water does not increase yield over the range used by respondents. Respondents' minimum water input per irrigation was 450 litres, meaning all respondents average input per irrigation exceeded the 390 litres that D'haeze et. al (2003) concluded was needed for a maximum yield. Roughly 85 percent of respondents also exceeded the upper bound 650 litres irrigation advised by State extension services. Given this, the insignificant result is consistent with expectations formed on the basis of Rhodic Ferralsols rapid drainage properties when at high moisture content. In summary, over-irrigating Robusta on Rhodic Ferralsols prevents soil moisture stress in the plant's root zone for at least seven days after the irrigation and excess water rapidly drains from the plant's root zone thereby preventing aeration stress. Using more than 450 litres per irrigation does not cause yields to increase and is therefore unnecessary input.

Estimates show plot-specific agro-environmental conditions have significant impact on yields per tree. Farmers who responded to infestation with pesticides recorded 20 percent lower yields on average compared to those not experiencing infestation. Production increases by 13 percent on flat land compared to moderate land. The lack of a significant result for steep land gradients is probably attributable to the group's small respondent number. Partial physical product is maximized between 15 and 16 years, which is at the upper end of Robusta's reported maximum productivity age range, but may also be because older Robusta varieties in Dak Lak are more resilient to environmental stresses (Titus and Pereira, 2007). As tree density per hectare increases, yield per tree declines, possibly due to crowding and resource competition.

By way of their significance, the importance of several irrigation scheduling behaviours on production outcomes are confirmed in the estimated frontier. Smallholders who applied more water on the first dry season irrigation achieved a 40 percent increase in partial physical product compared to smallholders who did not apply more water for the first irrigation. Moreover those farmers commencing irrigation after mid-January obtained 10 percent lower yields then their counterparts, significant at 15 percent. Further, the optimal average irrigation spacing occurs within the 16 to 21 day range. These results are broadly consistent with experimental results for Robusta production in Dak Lak reported in D'haeze, Deckers et al. (2003). Neither irrigation season duration or late commencing irrigators were found to be significant yield predictors. For late starters this may be due to the small number of available observations (n=11). The insignificant coefficients on irrigation season duration and its natural logarithm do not imply the irrigation season length is unimportant to coffee productivity in Dak Lak, rather that 90 percent of respondents had an irrigation season duration in excess of 50 days, which indicates the majority of respondents maintained soil moisture via irrigation for the whole dry season.

Outcomes for the socio-economic and institutional variables are also generally consistent with maintained hypothesis. Fragmentation, measured by the number of plots the smallholder cultivates, increases technical inefficiency. Registered land title increases partial productivity by approximately 17 percent. Results also suggest productivity increases with farmed area, consistent with previous analysis in Dak Lak (Rios and Shively, 2006). Productivity also increases with household non-farm income. Against expectations, smallholders mono-cropping coffee were less productive then their diversified counterparts. There is no intuitive explanation for this result, given the initial expectation that more technically efficient coffee farmers would only favour mono-cropping. Productivity increases with household adult labour endowment supporting a production premium based on labour flexibility. Respondents who had received technical irrigation and fertilizer training in the previous twelve months were not more productive than their counterparts.

Finally, the impact of omitting the irrigation scheduling variables from the frontier is considered to show how this influences estimates. The null hypothesis that the irrigation scheduling coefficients are jointly insignificant was evaluated for the full semi-dated production frontier specification including irrigation scheduling variables, against the nested traditional static production estimate omitting the irrigation timing covariates. The log likelihood-ratio test overwhelmingly rejects the null hypothesis (LR(6 d.f)= 88.04, Prob LR > $\chi^2_{6d.f.}$ =0.000), indicating the restricted static production function is not a valid representation of the coffee production process.

4.4 Marginal irrigation cost estimate

4.4.1 Specification

Given irrigation water is not priced in Dak Lak, this section estimates irrigation water's marginal use cost, which substitutes for p_w in equation (4). Smallholders' total irrigation cost comprises both the variable costs they incur as a result of getting water from the source to the production plot and long run costs from irrigation capital depreciation. A short-run irrigation cost model is estimated in this research as a result of the dataset having a large number of incomplete irrigation capital observations. Moreover, practical issues also arise when attempting to apportion irrigation capital depreciation to specific plots on multi-plot, multi-crop smallholdings. In this analysis the short-run irrigation cost comprises energy and labour costs, which are variable within a single irrigation season.

The fuel required to deliver one cubic meter of water from source to the production plot is used as the dependent variable in the energy cost function. Fuel price fluctuations (refer Table 2) make this approach preferable to directly estimating the irrigation energy cost per cubic meter. The dependent variable is constructed based on respondent reports of the average amount of dry season fuel required per hour and their reported average time to fill their average micro-basin. The average time to irrigate one cubic meter of water during the dry season is used as the dependent variable in the irrigation labour cost estimate. The same logic applies for not directly estimating irrigation labour cost per cubic meter. The irrigation labour time dependent variable is the ratio of each respondent's average time requirement to fill their average micro-basin and their average irrigation volume.

A transcendental form is used to specify the unknown functional relationship:

$$\begin{cases} \ln f_i = \alpha_{10} + \sum_{j=1}^{J} \alpha_{1j} x_{ji} + \sum_{j=1}^{J} \alpha_{1j} \ln x_{ji} + \sum_{j=1}^{J} \sum_{k=1}^{K} \alpha_{1jk} x_{ji} x_{ki} + v_i \\ \ln l_i = \alpha_{20} + \sum_{j=1}^{J} \alpha_{2j} x_{ji} + \sum_{j=1}^{J} \alpha_{2j} \ln x_{ji} + \sum_{j=1}^{J} \sum_{k=1}^{K} \alpha_{2jk} x_{ji} x_{ki} + v_i \end{cases} \quad (7)$$

Where ($\ln f$) and ($\ln l$) are the natural logarithms of fuel in litres and labour time in minutes respectively. The functional input output relationship for both fuel and labour are defined in terms of the same inputs (x). These are: pump horsepower; the distance from the irrigation plot to the water source; whether groundwater or surface water is used for irrigation; and the depth of the well if groundwater is used (Table 6). Respondents whose water source is on the plot have a distance to water source equalling zero. Battese's (1997) coding approach is used to overcome the problem of zero values being converted to natural logarithms for these respondents.

4.4.2 Hypothesis

Null hypotheses are that increasing pump capacity increases the fuel amount and lowers the labour time required to deliver one cubic meter of water from the source to plot. Energy and labour time requirements should positively correlate with the distance between the plot and the water sources and also with increasing well lift. When irrigators use surface water, labour and energy requirements per cubic meter should be lower compared to an otherwise identical delivery from a groundwater source.

4.4.3 Results

The energy and labour functions in (7) are estimated as a system of equations using seemingly unrelated regression to control for contemporaneous correlation between the error terms across equations, which could otherwise reduce the standard error estimates' efficiency (Baum, 2006). Table 7 summarises the results. Both models are significant at the one percent level. The estimated model suggests fuel requirements are minimized with a pump capacity around 10 HP and are then increasing with HP. Fuel required to deliver one cubic meter of water to the plot is increasing beyond 90 meters between the plot and water source. The Battese variable for distance (batDist) takes a value of one when respondents source water from the plot and zero otherwise. Its statistically significant negative coefficient is consistent with the maintained hypothesis that fuel requirements are lower per unit water for on-plot water sources, all other factors constant. Consistently, surface water users incur significantly lower fuel requirements per unit water than respondents who have to lift well water. Fuel required to lift well water are decreasing in depth to around 20 meters and increasing after this point.

Coefficients measuring the time required to deliver one cubic meter of water to the plot generally have consistent signs with the fuel function, but different magnitudes and precisions. Labour delivery times increase linearly as a function of the distance between the source and plot, significant at the 15 percent level. Lifting well water imposes a significant labour time penalty compared to smallholders irrigating from surface water sources. Labour time required to deliver one cubic meter of water to the plot is again decreasing in well depth to approximately 20 meters and increasing after this point.

5 WATER'S ECONOMIC VALUE IN COFFEE PRODUCTION IN THE DAK LAK PLATEAU

The insignificance of the estimated coefficients for water input and its natural logarithm show the VMP of dry season irrigation water in smallholder coffee production is zero above 450 litres per tree per irrigation, i.e. applying more than 450 litres per tree per irrigation does not increase yield per tree. Notably, this result is consistent with D'haeze, et al. (2003), who found 390 litres per irrigation during flower set was sufficient. Our irrigation scheduling results are also broadly consistent with D'haeze, et al. (2003), highlighting the importance of the first irrigation commencing before mid-January and then spacing irrigations around 20 days apart until the dry season finishes. Incurring an irrigation water use cost without increasing value product is inconsistent with production economics' allocation rules. Production theory assumes producers know their production and cost functions and also factor price relationships with certainty however (Beattie and Taylor, 1985). Clearly this was not the case amongst our respondents who generally believed more water per tree drives increased yields or at least hedges against yield losses caused by water stress.

In substitute to deriving dry season water's economic value in the coffee production process using (3) and (4), i.e. based on input amounts, this section estimates the value to producers in profit terms of shifting from a baseline of irrigation behaviours to more allocatively efficient application depths and technically efficient irrigation schedules. The production frontier estimates in section 4.3 and the short-run marginal use cost function from section 4.4 are used as the basis for these estimates. Comparative analyses show how irrigation scheduling changes total physical and total value product and impacts short run marginal use costs.

The baseline condition is defined by respondents' statistically average irrigation practices. An average irrigation of 550 litres per tree is assumed in the other scenarios. This corresponds to the 5th percentile irrigation volume amongst respondents, is just above the 540 litres per irrigation that D'haeze, et al. (2003) empirically confirmed was sufficient for optimal flower set and also equals the lower bound irrigation application currently recommended by Dak Lak's extension services. The alternative scenarios are: (1) same as the baseline but assuming a 40 day irrigation season, more irrigation on the first irrigation and a 20 day irrigation rotation; (2) same as (1) but not applying more irrigation on the first irrigation; and (3) same as (1) but assuming a 100 day irrigation season, which is equivalent to commencing irrigation in mid-December and concluding at the end of March.

Results are presented in Table 8. Shifting from the baseline to a shorter irrigation season and an optimal 20 day irrigation interval increases yield per tree from 4.3 to 4.9 kilograms and reduces total dry season irrigation per tree from 3.8 to 1.65 cubic meters. Short run variable irrigation costs are reduced by VND2,600 per tree. On a per hectare basis and assuming a 1,050 tree planting density, output increases from approximately 4,550 kilograms to 5,100 kilograms and short run irrigation costs are reduced by VND2.7 million. Comparing scenarios (1) and (2) highlights the importance of applying more water on the first irrigation in yield and value product terms. Not applying more water on the first irrigation (scenario 2) reduces yield to 3.4 kilograms per tree. This result begs the question of how much water should be applied on the first irrigation. Unfortunately, the survey did not obtain this information directly. Assuming smallholders who use more water completely fills each plant's micro-basin at the first irrigation suggests 15 percent more water is input on average, with a standard deviation of 13 percent. For smallholders using 550 litres, this suggests the first irrigation should be approximately 650 litres per tree.

6 CONCLUSIONS

This paper estimated the private benefits and short run user cost of dry season irrigation water on Robusta smallholdings in Viet Nam's Dak Lak Plateau. Results suggest smallholders over-allocate elemental nutrient, labour and irrigation water compared to the economic standard of equating marginal benefits and costs. Information failure and risk aversion are both reasonable explanations for respondents' behaviour. The research estimates that during the 2005/2006 dry season, coffee smallholders in the Dak Lak Plateau over-allocated around 2,300 cubic meters of water per hectare on average, thereby incurring VND2.7 million in short run irrigation costs without benefit. Results suggest diverting this excess water to other sectors in 2006 could have taken place without yield declines on coffee smallholdings as long as a technically efficient irrigation schedule is simultaneously adopted.

Extending these average results to the 130,000 hectares of Robusta currently planted in the Dak Lak Plateau broadly suggests dry season diversions to Robusta could be reduced by around 300 million cubic meters per annum and short run irrigation costs could be reduced by approximately VND350 billion (approximately AUD27 million). As a point of comparison, this demand reduction is roughly equivalent to 25 percent of the annual average recharge to the Plateau's unconfined aquifer (Moller, 1997: 95). The research findings are consistent with recent experimental farm research on optimal irrigation scheduling for Robusta in Dak Lak. Moreover, the research supports previous assertions that relatively uncontrollable agro-environmental factors and controllable irrigation scheduling aptitude are fundamental to production outcomes on Dak Lak's coffee smallholdings.

The estimated results and small sample make it difficult to draw reliable conclusions about the ability of State extension services' to strengthen coffee smallholders' crop management. The estimated main effect for training is not significant. This shows smallholders who received training in irrigation and fertilizer management in the 12 months before the survey were not more productive than respondents who did not receive training. However, trained respondents did use significantly less elemental nutrient input than their un-trained counterparts and closer to advised application rates. Combined with the insignificant coefficients for elemental nutrients, qualified support for the argument that fertilizer training "works" on coffee smallholders in Dak Lak is provided in the sense that trained smallholders' fertilizer application rates are more allocatively efficient than their untrained counterparts. In contrast, the same trained smallholders used significantly more water per tree per application and per season than their un-trained counterparts, i.e. they were more allocatively inefficient. There are several possible explanations for this outcome, but none of them are compelling. One hypothesis is that smallholders simply have no idea how much water they apply to each tree, whereas it is easier to estimate dry chemical fertilizer inputs based on the number of bags purchased and the elemental nutrient breakdown that is printed on each bag. Alternatively, smallholders may be sensitised to the importance of water as a production factor input through training, and given water is un-priced, they may hedge against yield losses by applying more water than is required. Whatever the cause, these research findings point towards the need for a more detailed outcomes analysis of the irrigation training provided by Dak Lak's various State and non-government extension service providers.

Despite being unable to estimate the marginal economic value of dry season irrigation water in coffee production, this research provides valuable information for developing the Dak Lak Plateau's smallholder coffee sector and water policies in line with the Law on Water Resources. The research provides information on how much water use could be decreased without altering output, production technology and the quantities of other inputs used in the coffee production process. Moreover, the results strongly imply that programs training coffee smallholders to improve their irrigation scheduling behaviours could achieve substantial improvements in technical and allocative efficiency without requiring new technology uptake.

One criticism of the econometric literature that analyses response in crop production is its near exclusive focus on the relationship between static input quantities and output without considering the role that input timing plays in the production process (Vaux and Pruitt, 1983). The production frontier estimates in this research support this critique by showing that omitting irrigation scheduling covariates significantly reduces overall model efficiency and also the precision of the individual coefficients. From a practical perspective, the results highlight the relative importance of input timing versus input levels as production determinants in Dak Lak. This research's practical implication is that production frontiers defined solely in static input output terms will tell a biased story about the production efficiency of Dak Lak's coffee smallholders. From a statistical standpoint, the results raise misspecification concerns about the widespread practice of estimating production functions solely using static input output relationships. When input scheduling can be expected to play an important role in the production process and there is no prior basis for assuming homogenous input schedules within the producer population, estimating the production relationship with static input volumes alone will increase the potential for estimation bias. Biased parameter estimates will in turn prejudice technical and cost efficiency estimates, non-market resource valuations and distort policy recommendations. While near-collinearity can present practical estimation challenges and reduce the statistical significance of near-collinear variables, this is less of an estimation problem than the omitted variable bias alternative.

Viet Nam's Law on Water Resources requires that regional developments take into account the natural water supply capacity. Previous research in the Dak Lak Plateau suggests dry season water resources are over-allocated at a minimum during dry and very dry years. Reducing dry season diversions to coffee irrigation by 300 million cubic meters per annum would set fundamental changes in the Plateau's hydrology in motion. Potential for moving towards a more sustainable water management regime in Dak Lak via increased irrigation efficiency on coffee smallholdings is evident.

7 References

Ahmad, A. (2000) An institutional analysis of changes in land use pattern and water scarcity in Dak Lak Province, Vietnam. Copenhagen, University of Lund.

Ali, M., and D. Byerlee. "Economic efficiency of small farmers in a changing world: a survey of recent evidence." *Journal of International Development* 3(1991): 1-27.

Basberg, L., V. K. Hoc, and J. Cheesman. "Groundwater and surface water modeling in the Dak Lak Plateau, Viet Nam (forthcoming)." The Australian National University.

Battese, G. E. "A note on the estimation of Cobb-Douglas production functions when some explanatory variables have zero values." *Journal of Agricultural Economics* 48, no. 2(1997): 250-252.

Baum, C. *Introduction to modern econometrics using STATA*. College Station: Stata Press, 2006.

Beattie, B. R., and C. R. Taylor. *The economics of production*. New York: Wiley, 1985.

Cheesman, J., and J. W. Bennett. "Natural resources, institutions and livelihoods in Dak Lak, Viet Nam." The Australian National University.

Chi, T. T. Q., and D. D'haeze. "Assessment of water, fertilizer and pesticide use for coffee production in Dak Lak Province." Ministry of Agriculture and Rural Development, Institute of Policy and Strategy for Agriculture and Rural Development, Centre for Agricultural Policy.

Coelli, T. "A Guide to FRONTIER Version 4.1: A Computer Program for Stochastic Frontier Production and Cost Function Estimation." Centre for Efficiency and Productivity Analysis, University of New England.

Coelli, T., D. S. P. Rao, and G. E. Battese. *An Introduction to Efficiency and Productivity Analysis*. Boston: Kluwer Academic Publishers, 1998.

Dak Lak Peoples' Committee. "Provincial Forestry Development Program of Dak lak. In period of 2001-2010." Dak Lak Peoples' Committee.

Dak Lak Statistical Department. *Statistical Yearbook 2001*. Buon Ma Thuot, Viet Nam., 2002.

D'haeze, D. Personal communication.

D'haeze, D. "Water management and land use planning in the Central Highlands of Vietnam. The case of Coffea canephora in Dak Lak province." Leuven University, 2004.

D'haeze, D., et al. "Over-irrigation of Coffea Canephora in the Central Highlands of Vietnam revisited. Simulation of soil moisture dynamics in Rhodic Ferralsols." *Agricultural Water Management* 63(2003): 185-202.

D'haeze, D., et al. "Environmental and socio-economic impacts of institutional reforms on the agricultural sector of Vietnam: Land suitability assessment for Robusta coffee in the Dak Gan region." *Agriculture, Ecosystems & Environment* 105, no. 1-2(2005): 59-76.

D'haeze, D., et al. "Groundwater extraction for irrigation of Coffea canephora in Ea Tul watershed, Vietnam—a risk evaluation." *Agricultural Water Management* 73, no. 1(2005): 1-19.

Dillon, J. L., and J. R. Anderson. *The Analysis of Response in Crop and Livestock Production*. 3rd ed. Oxford: Pergamon Press, 1990.

Farrell, M. J. "The measurement of productive efficiency." *Journal of Royal Statistical Society* Series A, no. 120(1957): 253-281.

Foti, R., and T. Chikuvire, J. "Farm Level Pesticide Use and Productivity in Smallholder Cotton Production in Zimbabwe: The Case of Gokwe Communal Area Farmers."

Hung, P. V., T. G. MacAulay, and S. P. Marsh. "The economics of land fragmentation in the north of Vietnam." *The Australian Journal of Agricultural and Resource Economics* 51, no. 2(2007): 195-211.

ICARD, and OXFAM. "The Impact of the Global Coffee Trade on Dak Lak Province, Viet Nam: Analysis and Policy Recommendations." ICARD.

Investment and Trade Promotion Centre of Ho Chi Minh City (2007) Vietnam coffee exports soar in Q1, vol. 2007. Ho Chi Minh City, Investment and Trade Promotion Centre of Ho Chi Minh City.

Lenin Babu, K., B. Guha-Khasnobis, and R. K. Somashekar (2003) Impact of Globalization on Marginal Farmers : A case study of Coffee farmers of India and Vietnam, ed. U. N. U. (UNU). Helsinki, United Nations University (UNU).

Lich, L. H., B. Tuan, and D. D'haeze (2005) Technical training of trainers module 3: Fertilizer management. Buon Ma Thuot.

Liu, Y. (2006) Model Selection and Implications in Stochastic Frontier Analysis: Maize Production in Kenya.

Moller, K. N. (1997) Working Paper No. 19. Hydrogeology and Water Resources of the Dak Lak Plateau. Denmark.

Moller, K. N. (1997) Working Paper No. 22. Groundwater modelling of the Ea Co Tam area. Ha Noi.

Ray, T. "Sharecropping, land exploitation and land- improving investments." *The Japaneese Economic Review* 56, no. 2(2005): 127-143.

Riddell, P. (1999) A Holistic Analysis of Constraints on the Sustainable Management of Water Resources Dak Lak Province and an Integrated Approach to Resolving Them. Buon Ma Thuot.

Rios, A. R., and G. Shively (2005) Farm size and nonparametric efficiency measurements for coffee farms in Vietnam. Providence, Rhode Island.

Rios, A. R., and G. Shively. "Farm size, irrigation infrastructure, and the efficiency of coffee production in Viet Nam." *Forests, Trees, and Livelihoods* 16, no. 4(2006): 397-412.

Rios, A. R., and G. Shively. "Farm size, irrigation infrastructure, and the efficiency of coffee production in Vietnam." *Forests, Trees, and Livelihoods* 16(2006): 397-412.

Socialist Republic of Vietnam. *The Law on Water Resource*. Hanoi, 1998.

Stevenson, R. E. "Likelihood functions for generalised stochastic frontier estimation." *Journal of Econometrics* 13.(1980): 57-66.

Tesfay, G., et al. (2005) Resource use efficiency on own and sharecropped plots iun Northern Ethiopia: determinants and implications for sustainability. Wageningen.

The World Bank (2007) East Asia & Pacific Update - Ten Years After Asia's Financial Crisis, vol. 2007. Washington D.C, The World Bank.

Titus, A., and G. N. Pereira (2007) The fine art of irrigation in Robusta coffee plantations, vol. 2007.

Vaux, H. J., and W. Pruitt (1983) Crop-water production functions, ed. D. Hillel, vol. 2. New York, Academic Press.

Wang, H., and S. Lall. "Valuing water for Chinese industries: a marginal productivity assessment." *Applied Economics* 34(2002): 759-765.

Weir, S., and J. Knight. "Production externalities of education: evidence from rural Ethiopia." *Journal of African Economies* 16, no. 1(2006): 134–165.

Young, M. D. (2005) Economic criteria for water allocation and valuation, ed. R. Brouwer, and P. D. W. Cheltenham UK, Edward Elgar Publishing Limited.

Young, R. *Determining the Econmic Value of Water: Concepts and Methods*. Washington D.C: Resources for the Future, 2005.

Zhengfei, G., et al. "Integrating agronomic principles into production function specification: a dichotomy of growth inputs and facilitating inputs." *American Journal of Agricultural Economics* 88, no. 1(2006): 203-214.

8 TABLES

Table 1: Descriptive statistics

		Micro-basin irrigators, Rhodic Ferralsols					All micro-basin irrigators					All sprinkler irrigators				
Variable	Unit	Obs.	Mean	SD	Min	Max	Obs.	Mean	SD	Min	Max	Obs.	Mean	SD	Min	Max
Output (standardized hectare)																
Yield	Kilogram	79	3,863	1,055	739	6,167	95	3,832	1,112	739	6,167	11	3,569	1,373	1,143	6,000
Inputs (standardized hectare)																
Labour																
Total		79	282	142	24	850	94	297	145	24	850	10	243	120	115	539
Applying fertilizer	Labour days	79	15	15	1	75	95	15	15	1	80	11	14	15	2	42
Applying pesticide	Labour days	79	1	2	0	9	95	2	3	0	23	11	1	1	0	2
Irrigating	Labour days	79	28	22	5	160	95	29	21	5	160	11	17	15	2	48
Pruning	Labour days	7	38	23	6	120	93	44	34	4	240	10	29	25	5	86
Weeding	Labour days	78	27	24	4	120	94	32	31	4	175	10	39	48	3	165
Harvesting	Labour days	76	138	103	4	625	92	137	96	4	625	10	121	50	45	235
Other	Labour days	76	69	17	0	208	92	75	18	0	208	10	53	14	1	38
Mineral fertilizer																
Total	Kilogram	79	3,002	2,058	400	11,000	95	2,901	1,965	400	11,000	11	2,874	1,588	700	6,600
Urea	Kilogram	79	421	621	0	3,000	95	369	581	0	3,000	11	514	550	0	1,571
SA	Kilogram	79	168	371	0	2,500	95	185	356	0	2,500	11	138	241	0	588
Super phosphate	Kilogram	79	495	727	0	3,000	95	473	688	0	3,000	11	604	530	0	1,300
NPK	Kilogram	79	1,475	1,316	0	5,000	95	1,450	1,238	0	5,000	11	1,070	1,468	0	5,000
KCl	Kilogram	79	321	652	0	5,208	95	281	606	0	5,208	11	465	530	0	1,650
Elemental nutrient supplied																
Nitrogen	Kilogram	79	465	323	64	1,538	95	447	307	64	1,538	11	436	265	92	891
Phosphorus	Kilogram	79	200	159	0	813	95	194	150	0	813	11	185	150	26	565
Potassium	Kilogram	79	429	431	0	3,292	95	401	404	0	3,292	11	450	304	112	1,043
Pesticide																
Pesticide	Litres	79	6	14	0	105	95	8	14	0	105					
Irrigation																
Average irrigation per irrigation	m^3	78	1.06	0.36	0.45	2.02	94	1.00	0.37	0.31	2.02					

Variable	Unit	Micro-basin irrigators, Rhodic Ferralsols Obs.	Mean	SD	Min	Max	All micro-basin irrigators Obs.	Mean	SD	Min	Max	All sprinkler irrigators Obs.	Mean	SD	Min	Max
Total irrigation per tree season^{-1}	m^3	78	3.81	1.61	1.12	10.08	94	3.79	1.55	1.12	10.08					
Total irrigation per hectare season^{-1}	m^3	77	3,960	1,731	602	9,451	93	3,938	1,659	602	9,451					
Irrigation practices																
Water source																
Hand-dug well	1=yes	49	0.65				56	0.58				2	0.18			
Deep drilled well	1=yes	3	0.04				4	0.04				1	0.09			
Surface water	1=yes	16	0.18				18	0.16				4	0.36			
Hand dug well + second source	1=yes	7	0.09				12	0.11				3	0.27			
Other	1=yes	0	0.00				6	0.06				1	0.09			
Distance source to plot	Meter	79	164	189	0	800	95	151	185	0	800	10	228	197	0	500
Irrigation start date	Dd/mm/yy	79	21/12/05	23.1	15/09/05	20/02/06	95	20/12/05	21.33	15/09/05	12/02/06	10	38,730.67	27.66	38,698.00	38,768.00
Irrigation end date	Dd/mm/yy	79	24/03/06	20.5	27/01/06	15/05/06	95	27/03/06	21.35	27/01/06	15/05/06	10	38,790.00	26.41	38,750.00	38,822.00
Number of irrigations	Unit	79	3.62	0.95	2.00	7.00	95	3.95	1.31	2.00	9.00	11	2.64	1.29	1.00	4.00
Irrigation season duration	Day	79	85	29	10	175	95	97	27	17	181	11	60	48	0	121
Average days between irrigations	Day	79	24	7	3	39	96	22	7	2	47	7	25	6	20	35
More water applied first irrigation	1=yes	79	0.82	0.38	0.00	1.00	95	0.81	0.39	0.00	1.00	9	0.78	0.44	0.00	1.00
Micro-basin dimensions																
Width	Meter	79	2.34	0.35	0.00	2.78	95	2.32	0.34	0.00	2.78					
Length	Meter	79	2.55	0.38	0.00	3.13	95	2.53	0.37	0.00	3.13					
Depth	Meter	79	0.18	0.05	0.00	0.31	95	0.18	0.06	0.00	0.31					
Average time to fill basin	Minutes	79	3.57	1.02	0.88	6.50	95	3.65	1.07	0.88	6.50					
Use irrigation tubing	1=yes	79	0.97	0.16	0.00	1.00	95	0.98	0.14	0.00	1.00	10	0.70	0.48	0.00	1.00
Total tubing length	Meter	77	233	145	25	800	93	221	136	25	800					
Use a pump	1=yes	77	0.94	0.42	0.00	1.00	93	0.95	0.41	0.00	1.00					
Engine horsepower	HP	46	16	9	1	54	59	14	9	1	54					
Main production well depth	Meter	63	23	7	8	41	76	22	8	8	41					
Agro-environmental production conditions for the recorded plot																
Tree density per ha	Unit	79	1,045	181	200	1,371	95	1,044	169	200	1,371	11	1,073	73	966	1,200
Tree age	Year	79	14.85	4.66	6.00	30.00	95	14.53	4.83	4.00	30.00	11	17.36	6.73	10.00	29.00
Shade trees	1=yes	79	0.48	0.50	0.00	1.00	95	0.43	0.50	0.00	1.00	11	0.09	0.00	0.00	1.00

		Micro-basin irrigators, Rhodic Ferralsols					All micro-basin irrigators					All sprinkler irrigators				
Variable	Unit	Obs.	Mean	SD	Min	Max	Obs.	Mean	SD	Min	Max	Obs.	Mean	SD	Min	Max
Intercropping	1=yes	79	0.34	0.48	0.00	1.00	95	0.34	0.48	0.00	1.00	11	0.64	0.50	0.00	1.00
Slope	1=Steep 3=flat	79	2.49	0.70	1.00	3.00	95	2.42	0.72	1.00	3.00	11	2.45	0.52	2.00	3.00
Socio-economic and institutional variables																
Age	Years	79	43	12	24	80	92	44	12	24	80	10	48	13	33	69
Gender	Male=1	79	0.86	0.35	0.00	1.00	95	0.86	0.35	0.00	1.00	11	1.00	0.00	1.00	1.00
Ethnicity	Kinh=1	79	0.97	0.16	0.00	1.00	95	1.11	0.61	1.00	5.00	11	1.00	0.00	1.00	1.00
Education	Years	76	8.74	3.29	0.00	16.00	92	8.58	3.30	0.00	16.00	11	9.91	2.81	7.00	15.00
Household inhabitants	Head	77	2.00	0.92	0.00	5.00	93	2.03	1.00	0.00	7.00	10	1.60	0.70	1.00	3.00
Non-farm income	VND'mil	79	9.89	24.42	0.00	200.00	95	8.99	22.68	0.00	200.00	11	13.27	14.45	0.00	40.00
Farm area	Hectare	79	1.03	0.74	0.10	3.50	95	0.99	0.72	0.10	3.50	11	1.02	0.46	0.22	2.00
Area planted with coffee	Hectare	79	0.98	0.70	0.10	3.00	95	0.93	0.67	0.10	3.00	11	0.94	0.36	0.22	1.50
Monocropping coffee	1=Yes	79	0.84	0.37	0.00	1.00	95	0.82	0.39	0.00	1.00	11	0.64	0.50	0.00	1.00
Number of plots	Unit	79	1.52	0.77	1.00	5.00	95	1.48	0.74	1.00	5.00	11	1.18	0.40	1.00	2.00
Number of pumps owned	Unit	79	0.73	0.47	0.00	2.00	95	0.80	0.56	0.00	3.00	11	0.64	0.67	0.00	2.00
Well	1=Yes	79	0.85	0.36	0.00	1.00	95	0.83	0.38	0.00	1.00	11	0.45	0.52	0.00	1.00
Drying yard	1=Yes	79	0.95	0.22	0.00	1.00	95	0.96	0.20	0.00	1.00	11	0.73	0.47	0.00	1.00
Registered land title	1=Yes	79	0.62	0.49	0.00	1.00	95	0.61	0.49	0.00	1.00	11	0.36	0.50	0.00	1.00

Table 2: Coffee price data

Variable	Unit	Obs.	Mean	SD	Min	Max
Output price	VND kg^{-1}	106	20,515	2,239	2,100	24,000
Input price						
Mineral fertilizers						
Urea	VND kg^{-1}	53	4,905	576	1,450	5,500
SA	VND kg^{-1}	36	2,624	379	2,000	4,000
Super phosphate	VND kg^{-1}	55	1,277	367	1,000	2,700
NPK	VND kg^{-1}	88	4,507	634	3,000	6,500
KCl	VND kg^{-1}	51	4,254	982	1,000	8,700
Pesticides						
Pesticide	VND lt^{-1}	59	22,657	24,126	600	100,000
Fuel						
Fuel	VND lt^{-1}	83	6,879	3,335	670	9,500
Labour						
Family labour	VND day^{-1}	106	37,000	0	37,000	37,000
Hired labour	VND day^{-1}	78	40,564	7,718	30,000	65,000
Irrigation						
Irrigation tubing	VND $meter^{-1}$	99	18,052	5,936	7,000	32,000
Average pump cost	VND million	73	3.07	2.78	1	15

Table 3: Production variables

Variable	Description	Unit
	Dependent variable	
Yt	Yield per tree	Kilogram
	Explanatory variables	
	Production input vairables	
Nt	Elemental nitrogen input per tree per annum	Kilogram
Pt	Elemental Phosphorous input per tree per annum	Kilogram
Kt	Elemental Potassium input per tree per annum	Kilogram
Lt	Labour per tree per annum (family and hired)	Days
Wti	Average water applied per tree per irrigation	m^3
Ct	Total all other variable costs	VND
Manure	Dummy variable describing whether organic fertilizer applied	Yes=1
PestHerb	Dummy variable describing whether pesticide and / or herbicide applied	Yes=1
	Irrigation management factors	
IrrSeasonDur	Irrigation season duration	Days
IrrInt	Average interval between irrigations	Days
IrrSLate	Dummy variable if irrigation commced after 15 January	>15/1=1
FirstIrr	Dummy variable if more water applied for the first irrigation	Yes=1
GW	Dummy variable if groundwater being used for irrigation	Yes=1
	Endogenous plot factors	
Shade	Dummy variable for shade trees on plot	Yes=1
InterCrop	Dummy variable for intercropping on plot	Yes=1
TreeAge	Average tree age	Years
Density	Tree density per hectare	Unit
	Exogenous agro-environmental factors	
Steep	Dummy variable for steeply sloped plots	Yes=1
Moderate	Dummy variable for moderately sloped plots	Yes=1
Dry_06	Dummy variable for whether the main irrigation water source ran dry during the 2006 coffee irrigation season	Yes=1
	Socio-economic, farm and institutional factors	
Registered	Dummy variable describing whether producer has land title	Yes=1
Area	Total farm area	Hectares
Plots	Number of plots farmed	Unit
Pumps	Number of pumps used in production	Unit
Ext	Dummy variable describing whether smallholder received extension training	Yes=1
Mono	Dummy variable describing whether smallholder monocrops coffee	Yes=1
Edu	HH years of education	Years
Age	HH age	Years
HH	Number of adult family members available to farm	Head
NFI	Non-farm income	VND million

Table 4: Ordinary least squares estimate

Variable	Coefficient	t-ratio
Dependent variable: Irrigation season duration (Days)		
Climate zone 2	-38.19(16.23)**	-2.35
Climate zone 3	-32.54(15.83)**	-2.06
Climate zone 4	-49.04(17.91)***	-2.74
Constant	118.67(15.27)***	7.77
Observations	74	
F(3,70)	2.73	
Prob > F	0.05	

Note: In all tables *, ** and *** indicate statistical significance at the 10, 5 and 1 percent levels in that order. Standard errors are in parenthesis.

Table 5: Stochastic production frontier estimate

Variable	Coefficient	t-ratio
	Dependent variable: natural log of Yt	
Lt	-1.86(0.883)**	-2.10
lnLt	0.29(0.155)*	1.85
Nt	-1.28(0.645)*	-1.99
lnNt	0.02(0.082)	0.19
Pt	1.59(0.753)**	2.11
lnPt	0.00(0.027)	0.01
Kt	0.59(0.706)	0.83
lnKt	-0.05(0.031)	-1.60
Wti	0.38(0.574)	0.66
lnWti	-0.21(0.624)	-0.33
Ct	0.00(0.000)	0.93
lnCt	-0.08(0.029)***	-2.77
Nt x Pt	1.81(0.752)**	2.40
Nt x Kt	0.54(0.491)	1.09
Nt x Wti	0.42(0.552)	0.76
Pt x Kt	-3.62(0.773)***	-4.68
Pt x Wti	-1.54(0.697)**	-2.21
Kt x Wti	0.93(0.540)*	1.72
Manure	0.00(0.056)	-0.07
Pest	-0.23(0.043)***	-5.25
Shade	-0.22(0.048)***	-4.57
Steep	0.02(0.067)	0.30
Moderate	-0.10(0.036)***	-2.68
GW	0.00(0.068)	0.06
Intercrop	-0.01(0.069)	-0.10
Dry06	0.06(0.036)*	1.37
T	0.00(0.000)***	9.13
lnT	-3.46(0.245)***	-14.09
TreeAge	-0.07(0.037)*	-1.83
lnTreeAge	1.12(0.591)*	1.89
IrrSeasonDays	0.01(0.008)	0.88
lnIrrSeasonDays	-0.65(0.571)	-1.15
FirstIrr	0.35(0.071)***	4.88
IrrSLate	-0.10(0.060)	-1.62
IrrDur	-0.06(0.024)**	-2.45
lnIrrDur	1.09(0.562)*	1.95
Ext	-0.01(0.066)	-0.15
Mono	-0.24(0.085)**	-2.78
Plots	-0.04(0.032)	-1.28
Pumps	-0.06(0.092)	-0.68
Area	0.10(0.040)**	2.38
Regist	0.15(0.072)**	2.12
NFI	0.00(0.000)**	2.36
Edu	0.01(0.031)	0.29
Edu2	0.00(0.001)	-1.04
Age	0.02(0.009)*	1.84
Age2	0.00(0.000)*	-1.89

Variable	Coefficient	t-ratio
HH	0.03(0.014)*	1.85
Constant	20.61(0.985)***	20.92
$\sigma^2 = \sigma_v^2 + \sigma_u^2$	0.01(0.002)***	4.20
$\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$	1.00(0.066)***	14.89
Observations	72	
Log likelihood	14.82	

Table 6: Fuel and labour variables

Variable	Description	Unit
	Dependent variables	
Fm^3	Fuel required per average cubic meter water delivered	Litre
Lm^3	Labour time requirement per cubic meter water delivered	Minute
	Explanatory variables	
HP	Pump horsepower	HP
batDist	Dummy variable describing if water source is on plot, i.e. distance=0	0=Yes
Dist	Distance between water source and production plot	Meters
batWell	Dummy variable describing if main irrigation water source is well water	0=Yes
WD	Well depth	Meters

Table 7: Seemingly unrelated regression fuel and labour estimates

	Coefficient	t-ratio
	Dependent variable: ln Fm^3	
HP	0.08(0.031)***	2.47
lnHP	-0.61(0.177)***	-3.46
batDist	-2.69(1.612)*	-1.67
Dist	0.01(0.002)***	3.16
lnDist	-0.82(0.493)*	-1.67
batWell	-5.17(1.246)***	-4.15
WD	0.25(0.058)***	4.28
lnWD	-5.02(1.224)***	-4.1
HP x Dist	-1.21E-04(6.54E-05)*	-1.85
HP x WD	-6.79E-04(7.22E-04)	-0.94
Dist x WD	-1.37E-04(3.74E-05)***	-3.66
Constant	11.69(2.873)***	4.07
F-statistic	54.29	
Adjusted R-squared	0.54	
Observations	47	
	Dependent variable: ln Lm^3	
HP	0.02 (0.022)	0.72
lnHP	-0.14 (0.125)	-1.13
batDist	-0.86 (1.138)	-0.76
Dist	0.00 (0.001)	1.49
lnDist	-0.32(0.348)	-0.93
batWell	-4.31(0.879)***	-4.9
WD	0.19 (0.041)***	4.69
lnWD	-4.17 (0.864)***	-4.82
HP x Dist	-2.80E-05 (4.62E-05)	-0.61
HP x WD	-3.37E-04 (5.10E-04)	-0.66
Dist x WD	-1.95E-05 (2.64E-05)	-0.74
Constant	11.20(2.029)	5.52
F-statistic	44.67	
Adjusted R-squared	0.35	
Observations	47	
Correlation between ln Lm^3 and ln Fm^3	0.72	
Breusch-Pagan test of independence: chi2(1)	24.57	

Table 8: Irrigation simulations

	Unit	Baseline	Scenario 1	Scenario 2	Scenario 3
	Assumptions				
Irrigation per application	m^3	1.06	0.55	0.55	0.55
First irrigation	Unit	1	1	0	1
Irrigation season duration	Days	85	40	40	100
Irrigation interval	Days	24	20.00	20.00	20.00
Equivalent number irrigations	Unit	3.6	3.00	3.00	6.00
Total irrigation per tree per season	m^3	3.8	1.65	1.65	3.30
Trees per hectare	Unit	1,050	1,050	1,050	1,050
Irrigation m3 per ha	m^3	4,016	1,733	1,733	3,465
Cost per m3	VND	1,188	1,188	1,188	1,188
Total short run variable irrigation cost per hectare	VND million	5.895	2.058	2.058	4. 116
Output price VND kg-1	VND kg^{-1}	21,000	21,000	21,000	21,000
	Results				
	Per tree				
Total physical product per tree	Kilogram	4.3	4.9	3.4	4.3
Change in total physical product per tree: scenario - baseline	Kilogram		0.55	(0.89)	(0.03)
Change in irrigation volume per tree per season: scenario - baseline	m^3		(2.17)	(2.17)	(0.52)
Change in revenue per tree: scenario - baseline	VND		11,644	(18,771)	(690)
Change in irrigation cost per tree: scenario - baseline	VND		(2,583)	(2,583)	(624)
Change in profit per tree	VND		14,227	(16,188)	(67)
	Per hectare				
Total physical product per hectare	Kilogram	4,533	5,135	3,614	4,518
Change in total physical product per hectare: scenario - baseline	Kilogram		582	(939)	(35)
Change in irrigation volume per hectare per annum: scenario - baseline	m^3		(2,284)	(2,284)	(551)
Change in revenue per hectare	VND million		12,226,083	(19,709,584)	(724,993)
Change in irrigation cost per hectare: scenario - baseline	VND million		(2,712,490)	(2,712,490)	(654,677)
Change in profit per hectare	VND million		14,938,573	(16,997,094)	(70,315)