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Technical Efficiency and Investment Strategy: The Case of New Energy-Intensive Technology in Finnish Greenhouse Cucumber Industry

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Summary

We study firms' technical efficiency and associated implications for investment planning for Finnish greenhouse firms. A firm's technical efficiency is measured using intra-technology and inter-technology measures. A firm's investment strategies include investments in new energy-intensive assimilation light technology, new greenhouses to enlarge the scale of operation, or a combination of the two. Alternatively, a firm's strategy is not to invest. The central question is whether one technology outperforms another, controlling for firms' technical efficiency. The main result is that the new technology in and by itself does neither provide the highest technical performance nor maximise the net cash flow for all types of firms. Small family firms reach highest technical efficiency and maximum net cash flow using a traditional energy-extensive technology with current greenhouse area. For inefficient large firms, partially adoption of new energy- intensive technology is required to fully exploit efficiency potentials. If the large firms are efficient, the area expansion with assimilation lights increase the net cash flow too. The results also indicate that the more inefficient firms the minor price reduction they tolerate when investing in energy-intensive technology.

Key words. assimilation lighting – dynamic programming – innovation – stochastic frontier analysis – supplementary lighting – technological development

Introduction

Technological developments may open new production possibilities. This is typically the case for assimilation lighting technology in Finnish greenhouse firms. Finland is one of the countries where the northern climatic conditions provide a great deal of restrictions on horticulture production. The question arises as to whether new technology is optimal for all firms. Investment models typically do not consider a firm's technical efficiency in investment planning. This paper elaborates on this.

Traditionally, Finnish greenhouse firms were forced to have a production pause during winter months because of the lack of natural light. The traditional investment strategy in those days was therefore to enlarge firm's scale of operation and continuing with conventional technology. As a result, average size of greenhouse vegetable firms increased by 89 % to 0.23 ha between 1984 and 2006 (Tike 2007a). Introduction of assimilation lights in Finland in the 1990 s created a supplementary investment strategy, enabling firms to compensate the deficiency of natural light during winter months and carry on production with prolonged growing season, or even year-round production. That changed production technology as well. Capital stock increased because of assimilation lights, requiring new cultivars as well as a new fertilisation program. The proportion of assimilation lighting cultivation area is still increasing, being about 25 % of the total 73 ha cucumber production area in 2006. However, only less than 12 % of greenhouse cucumber firms have adopted the assimilation lights (Tike 2007b), and less than 5 % of the firms use lights in their whole production area. Assimilation lighting is typically used by large firms, which might be a signal that firm's access to new technology is restricted to current greenhouse area as earlier findings suggest (Løyland and Ringstad 2001; Pietola and Heikkilä 2005).

The literature typically relates slow technology diffusion to risk, uncertainty and learning (Leather and Smale 1991; Marra et al. 2003; Lohano and King 2009), as well as the irreversibly of new technology (Ekboir 1997; Baerenklau and Knapp 2007). Partial adoption of new energy-intensive technology may well be rational as entrepreneurs are uncertain about associated net cash flow (Leather and Smale 1991). Technical efficiency is rarely combined with technology adoption, even though it is important factor of firm's current and forthcoming success.

Technical efficiency measurement is frequently made using the frontier framework, where a primal production model characterizes technological relationship between the yield and the factors of production (Borger and

Kerstens 2000; Felthoven and Morrison Paul 2004; Bye et al. 2009). In technical efficiency measurements technological choices are typically included by using dummy variables indicating whether a technology is used or not (Sipiläinen and Ryhänen 2005; Kompas and Che 2006). The obtained estimates express the mean effects of technologies on performance, neglecting systematic differences between the technologies. Xu and Jeffrey (1998) allows for systematic differences formulating separate frontiers for new and conventional technology, to compare estimates and efficiencies between technologies. Although interesting, they do not allow one technology to be best in one case, while the other technology best in another case. From an investment planning perspective one would be interested to know if, and under what conditions alternative technologies provide better technical efficiency than currently applied technology. We consider these issues of technological development in a production frontier framework using both inter- and intra-efficiency measures of technical efficiency as suggested by Oude Lansink et al. (2001).

The contribution of the paper is twofold. First, we analyse how technical efficiency varies within and between energy-extensive and energy-intensive technologies. Second, we elaborate on a firm's optimal investment strategy in energy-intensive technologies relative to its technical efficiency, firm's initial features, and price ratios. The analysis of the implemented technical efficiency between production technologies may provide insight into factors underlying new technology investments.

The organisation of this paper is as follows. Methodology section describes the data and presents a theoretical discussion of technical efficiency measurement for different technologies in a stochastic production frontier framework and presents the investment model. Empirical results section discusses the estimation results of technical efficiency and optimal investment strategy. Conclusions and directions for future research follow in the last section.

Methodology

Data

The data cover commercial Finnish greenhouse firms between 2000 and 2006 and come from TIKE, Information Centre of the Ministry of Agriculture and Forestry of Finland covering all commercial Finnish greenhouse firms. TIKE collects annual data on the production structure, with information on energy use at the firm level on a biannual basis as of 2000.

Greenhouse vegetable firms in Finland typically produce more than one output, e.g. both cucumber and tomato. In total, 500 commercial greenhouse firms produce greenhouse cucumber. In this study we focus only on the specialised greenhouse cucumber producers with cucumber production at least 90 % of the total greenhouse area. This results in 255 specialized firms. Considering these specialized firms allows assuming that energy consumption at the firm is used for cucumber production. We have an unbalanced panel data of 567 observations for 255 firms (varying between 115 and 167 per year) over 2000–2006. Each firm was observed one to four times.

Firms were categorized according to two features. First, they were categorized whether or not they used the new energy-intensive technology (assimilation lighting). Secondly, firms were categorized to be either small or large. The threshold was set at 0.20 ha, because earlier studies suggested that production area less than 0.20 ha can be operated with family labour; above 0.20 ha hired workers are needed with firms operating like corporate firms (Koivisto 2004). These two features create four groups. We allowed firms to change technology over time with firms being classified on an annual basis. Table 1 presents the four groups or states of technology by year.

Majority of the population of specialized cucumber firms are small and use traditional technology. Yet, the number of small traditional firms has decreased sharply (Table 1). Only one tenth of cucumber producers use the new technology, representing 25 % of the total cucumber area (Tike 2007b). The data reveal that over 2000–2006, six large firms switched to new technology, with four firms switching from small to large traditional firms. Later on, we use three groups of firms in the analysis, because the group of small new technology firms is too small. The absence of small new technology firms indicate that new technology and expansion of firms size are linked.

Technical efficiency models

The production frontier defines the relationship between the inputs and the output. Basically it represents the maximum output attainable from given inputs level, and hence reflects the current technology in the industry. Efficiency in production or productive efficiency is defined as

Table 1. The number of firms by groups and years.

	Year				Total
	2000	2002	2004	2006	
Large new technology firms	12	16	18	16	62
Small new technology firms[a]	1	3	1	1	6
Large traditional firms	45	40	40	39	164
Small traditional firms	109	97	56	73	335
Total	167	156	115	129	567

[a] Are excluded of the analysis

the degree of success producers achieve in allocating inputs at their disposal conditional on the output produced. If firms operate efficiently they are on the frontier, otherwise they are not fully efficient and not operating on the frontier (COELLI et al. 1999).

Technical efficiency measures typically indicate intra-technology estimates in which the performance of the firm is relative to the best performing firm within that technology group. Inter-technology estimates in which one considers the performance relative to the best performing firm over all groups show firms' performance relative to the best available technology (OUDE LANSINK et al. 2001).

Fig. 1 considers the one output and one input case; with output *y*, input *x* and three production frontiers **A**, **B**, and **C** associated with three technologies, viz. small energy-extensive firms, large energy-extensive firms, and large energy-intensive firms. Firm's a intra-technology technical efficiency using technology **A** equals y_a/y_a^A. Whereas firm's a inter-technology technical efficiency equals y_a/y_a^C. Inter-technology efficiency thus involves identifying the 'best available technology' which constitutes the outer-envelop of **A**, **B**, and **C**.

The stochastic production function for intra-technology efficiency analysis with the group-specific production frontier for observed output level is given in the equation (1):

$$(1) \qquad Y_{it}^n = \prod_{n=1}^{N} [U_{it}^n \, F^n(X_{it}\beta) + V_{it}^n \,],$$

where Y_{it}^n denotes observed output level at the t-th period (t = 1, 2,., T) for the i-th firm (i = 1, 2,...,I) belonging to n-th group (n = 1,2,...,N) describing the technology. X_{it} is a $(1 \times k)$ vector of values of inputs of production with the i-th firm at the t-th period belonging to group n, with β the unknown $(k \times 1)$ vector of production parameters. V_{it}^n is assumed to be i.i.d. $N(0,\sigma_v^2)$. The U_{it}^n is a non-negative group-specific random variable reflecting firm-specific and time-specific deviations from the frontier, associated with technical inefficiency of production. The U_{it}^n are assumed to be i.i.d. $N^+(0,\sigma_u^2)$ and independently distributed of the V_{it}^n.

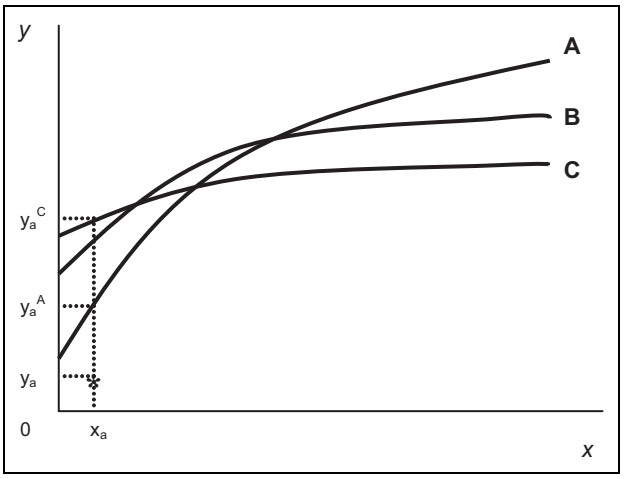


Fig. 1. Firm's a intra-technology technical efficiency using technology A equals y_a/y_a^A, inter-technology technical efficiency equals y_a/y_a^C. Best available technology constitutes the outer-envelop of A, B, and C.

Given the production frontier specification in (1), intra-technology efficiency $E_{it}^A(n)$ is determined as the ratio of actual output to the frontier output:

$$(2) \qquad E_{it}^A(n) = \frac{\prod_{n=1}^{N} [U_{it}^n \, F^n(X_{it}\beta)]}{\prod_{n=1}^{N} [F^n(X_{it}\beta)]} = U_{it}^n$$

Inter-technology efficiency involves choosing the "best practice frontier" at each time period and each input-bundle among the set of comparable groups and then evaluating each firm's belonging to group n technical efficiency degree relative to that frontier (OUDE LANSINK et al. 2001). Inter-technology efficiency, thereby, reveals a firm's performance relative to the best available technology in the industry. The "best practice frontier", $F(\cdot)^*$, is determined as the technology providing the maximum obtainable output given input vector, X_{it}:

$$(3) \qquad F(X_{it}\beta)^* = \max_n \{F^n(X_{it}\beta)\}.$$

Once the "best practice frontier" is identified, inter-technology efficiency, $E_{it}^B(n)$is determined as the ratio of actual output to the maximum obtainable output in the reference group:

$$(4) \qquad E_{it}^B(n) = \frac{\prod_{n=1}^{N} [U_{it}^n \, F^n(X_{it}\beta)]}{F(X_{it}\beta)^*}$$

The inter-technology catch-up component for a particular firm reflects the difference between the group's production technology frontier and the "best practice frontier". The inter-technology catch-up component is given by:

$$(5) \qquad E_{it}^C(n) = \frac{\prod_{n=1}^{N} F^n(X_{it}\beta)}{F(X_{it}\beta)^*}$$

The stochastic frontier production function is specified in terms of the production inputs. We propose a translog specification to avoid too strong *a priori* restrictions on the technology. The translog panel data production frontier reads as:

$$(6) \qquad \ln Y_{it} = \beta_o + \sum_{j=1}^{J} \beta_j \ln X_{jit} + \frac{1}{2} \sum_{j=1}^{J} \sum_{k=1}^{K} \beta_{jk} \ln X_{jit} \ln X_{kit} + \beta_T t + \frac{1}{2} \beta_{TT} t^2 + \sum_{j=1}^{J} \beta_{Tj} \ln X_{jit} t$$

where ln denotes natural logarithms, i refers to the i-th firm, t refers to the t-th time period, Xs are input variables defined in the previous section. The parameter vector β and σ are obtained by maximum likelihood (see BATTESE and COELLI 1995 for details about the derivation of the likelihood function and for the maximum likelihood estimation procedure used in Frontier 4.1).

We consider highly-specialized firms producing cucumbers with output measure Y denoting the annual kilograms

cucumber per square meter. Investments relate to the size of firm in square meters (SIZE) and in energy-related technology. Our data were fairly limited, restricting the number of model inputs yet enabling a parsimonious specification of equation (6). As we consider highly-specialized cucumber firms this is not overly restrictive an assumption. The final model contains inputs of energy use in mega joules per square meter (ENERGY), the size of firm in square meters (SIZE) and the time trend (TREND). The SIZE variable is assumed to pick up a major part of missing information. The variables describing greenhouse cover materials and outside weather conditions proved to be uninformative, and therefore were suppressed from the final model. The variable ENERGY was an aggregate of two components commonly bought from energy companies: electricity for greenhouse equipments, and assimilation lighting. Fuels, which consist of variety of heating substrates, are used for heating using firm-specific heating systems. These components were transformed to energy units (MJ). Summary statistics of the variables are in Table 2.

Investment Model

From a business planning perspective one would be interested to know the conditions required for a profitable technology switch relative to a firm's technical efficiency, firm's initial features, and price ratios. Greenhouse firms are assumed to maximise expected utility of terminal net cash flow. That can be expressed by Bellman equation where $V_t(r)$ is the maximum attainable sum of current and expected future rewards given that the system is in state r in period t (Equation 7). The firm decide to either invest in new technology, or/and expand the production area, or not to invest. Investments are assumed to be irreversible. First we solve the optimal investment strategy using normative and/or average parameter values. After that, we examine the conditions that trigger firms to switch technology.

$$(7) \qquad V_t(r) = \max_{x \in X(r)} \left\{ f(r,x) + \delta \sum_{r' \in R} P(r'|r,x) v(r') \right\},$$
$$r \in R, t = 1,2,..., T$$

Firm's incomes consist of selling incomes (pY) and greenhouse area based subsides (S). The technology specific yields (Y) are given in Table 2. Cucumbers have seasonal pricing (p) with high winter prices and low summer prices; with winter price is 1.3 times the summer price. Subsides have two levels: the lower one if the growing period is 2–7 months, and the higher one if growing period exceeds 7 months, which in practice require using the assimilation lights. U_n is technology depended technical efficiency measurement defined in equation 2. Costs of cucumber production are partitioned into two items: energy costs (eE) and costs of all other inputs (c). Energy price (e) is a technology depended weighted average of prices of heavy heating oil and electricity. Energy price for new energy-intensive technology is 1.1-times the energy price for traditional energy-extensive technology. This is because assimilation lighting uses electricity as energy which is more expensive than heavy heating oil used for heating. The amount of energy used (E) is based on group means in Table 2. Other inputs contain both variable and fixed costs depending on the production size and technology. Costs of other inputs are based on normative firm models (Koivisto 2004). Small traditional technology firms have lower costs of other inputs than large firms, because of lower labour input costs and lower capital costs.

Our investment model is a dynamic finite horizon deterministic model (Equation 8). The model has two decision

Table 2. Summary statistics of the variables of stochastic production frontier model.

Variable	Description	Technology[b]	Average period values			
			Mean	S.D.	Max.	Min.
Y	Yearly cucumber yield (kg m^{-2})	L+N	63.3	28.7	131.7	16.00
		L+T	30.0	11.4	74.0	8.40
		S+T	25.6	12.2	87.9	0.02
ENERGY	Yearly energy use (MJ m^{-2})	L+N	2 957	1 410	5 616	158
		L+T	1 253	754	4 851	6
		S+T	947	598	2 748	1
SIZE	Cucumber production area (ha)	L+N	0.69	0.63	2.82	0.20
		L+T	0.40	0.30	2.82	0.20
		S+T	0.11	0.04	0.20	0.01
TREND	Trend (2000 = 1, 2002 = 2, 2004 = 3, 2006 = 4)	L+N	2.6	1.1	4.0	1.0
		L+T	2.4	1.1	4.0	1.0
		S+T	2.3	1.1	4.0	1.0

[b] L+N = Large new technology firms, L+T = Large traditional firms, S+T = Small traditional firms

variables; a firm can build more greenhouse area a_t or a firm can install assimilation lights l_t. o_{t+1} refers the traditional greenhouse area in next period after greenhouse area investment in current period, and n_{t+1} refers the new technology area after assimilation lights investment, respectively. r_{t+1} is the net cash flow per firm in next period, which cumulates to net cash flow of current period. δ is the discount factor. Definitions of variables and parameters are given in Table 3.

We formally specify the investment problem as follows:

$$(8) \qquad \max_{\{(x_A, x_L)\}} V\left[\sum_{t=0}^{T} r_t\right]$$

subject to

$o_{t+1} = o_t + a_t$
$n_{t+1} = n_t + l_t$
$r_{t+1} = \delta[r_t + n_{t+1}(S_n + p_n Y_n U_n - e_n E_n - c_n) + o_{t+1}(S_o + p_o Y_o U_o - e_o E_o - c_o)]$
$a_t \in A_t$
$l_t \in L_t$

for t = 0, 1, 2,..., T.

The problem is solved using discrete time, discrete state Markov decision model for infinite time and dynamic programming algorithms, using CompEcon toolbox for Matlab. We construct a dynamic-path analysis, where we examine how the controlled process evolves over time so that the sum of current and expected future reward is maximized (Miranda and Fackler 2002). The path analysis is constructed for 30 years, which describes the average business running time of one individual entrepreneur. The upper bound of greenhouse area was set 3.00 ha, which corresponds to the present upper bound on production area. The investment unit for both area and lighting equipment investments was set on 0.10 ha.

Empirical Results

Technical efficiency

The estimates for group-based frontiers are presented in Table 4. Table 5 represents the annual mean values and growth rates of intra- and inter-technology efficiency, and catch-up component for each group. The mean intra-technology efficiency did not vary remarkably within different groups: large traditional firms had highest intra-technology efficiency; both large new technology and traditional small firms had slightly lower. The mean inter-technology efficiency of large new technology firms was substantially higher and also statistically different compared to (large and small) traditional firms.

The catch-up component indicates the ratio of group base frontier compared to best practise frontier. The higher the mean value is the closer the group's own frontier to the best practice frontier. Consequently, large new technology firms seem to locate closer to the best practice frontier, compared to both large and small traditional firms. The values of catch-up component of each group different statistically.

Although the values of catch-up components in Table 5 indicate the mean location of groups' firms compared to

Table 3. Definition and values of variables and parameters of investment model.

Variable/ parameter	Definition	Measure	Value for new technology	Value for traditional technology
t	Time index for the beginning of each year where t = 0, 1, ..., T			
r_t	Net cash flow per firm in year t	€ firm^{-1}		
δ	Discount factor		0.9	0.9
o_t	Traditional greenhouse area (without lighting equipments) in year t	ha		0.10–3.00
n_t	New technology greenhouse are (with lighting equipments) in year t	ha	0–3.00	
S	Subsidies	€ m^{-2}	11.4	4.5
p	Cucumber price	€ kg^{-1}	1.55[1)]	1.17[1)]
Y	Yield	kg m^{-2}	63.3	25.6 for S 30.0 for L
U	Technical efficiency		0–1	0–1
e	Energy price	€ MJ^{-1}	0.0116[2)]	0.0106[2)]
E	Energy use	MJ m^{-2}	2 957	1 253
c	Price of other inputs (excl. energy costs)	€ m^{-2}	95[3)]	37[3)] for S 42[3)] for L
a_t	Greenhouse area built in year t	m^2		
l_t	Area where lighting equipments are installed in year t	m^2		
A_t	Set of all levels of control variable X_{At}			
L_t	Set of all levels of control variable X_{Lt}			
V(·)	Expectation operation			

Source: [1)] Kasvistieto Oy, [2)] Finnish Energy Market Authority, Finnish Oil and Gas Federation, [3)] Koivisto 2004
S = Small firm, which production area is ≤ 0.20 ha and L = Large firm which production area is > 0.20 ha

Table 4. Estimated coefficients of stochastic production frontier model for each group using translog function.

Variables	Estimates		
	Large new technology firms	Large traditional firms	Small traditional firms
β_0 (constant)	−11.48	6.51	0.65
β_1 ln(ENERGY)	−0.09	−0.30	0.30
β_2 ln(SIZE)	2.50	−0.48	−0.20
β_3 ln(ENERGY)*ln(ENERGY)	0.14*	0.07***	0.14***
β_4 ln(SIZE)* ln(SIZE)	−0.31*	0.04	0.14
β_5 ln(ENERGY)*ln(SIZE)	0.02	0.00	−0.09
β_6 (TREND)	1.83***	−0.47	0.77
β_7 (TREND)*(TREND)	−0.15**	0.05	−0.03
β_8 (TREND) *ln(ENERGY)	−0.26***	−0.04	−0.06*
β_9 (TREND)*ln(SIZE)	0.08*	0.07*	0.06
$\sigma^2 = \sigma_v^2/\sigma_u^2$	0.49	0.84*	1.33***
Log-likelihood	11	63	358
Number of observations	62	164	335
Number of cross-sections	33	80	164
Number of time periods	4	4	4

Notes: *, **, *** Statistically significant at the 10 %, 5 %, and 1 % level.

Table 5. Mean Values of Intra-, and Inter-technology Efficiency, and Catch-up Component in the years 2000–2006.

	Intra-technology efficiency Mean	Inter-technology efficiency Mean	Catch-up component Mean
Large new technology firms	0.76	0.73	0.97
Large traditional firms	0.79	0.59	0.75
Small traditional firms	0.75	0.60	0.79

best practice frontier, one must take into consideration, that mean values are very sensitive to extreme observations. Table 6 therefore, shows the proportions of firms which locate on the best practice frontier. A value of 88 % in column "Within groups" indicates that 88 percent of the firms in that group reach the highest efficiency using the current technology. Hence, 12 % of firms in that group would reach higher efficiency levels by switching technology. The column "Within all firms" expresses the percentage of firms in the group on the best practice frontier relative to all firms. The results indicate that the position of the technologies has changed. In 2000 and 2002 the large traditional firms defined the best available technology. The situation changed between 2004 and 2006 with new technology firms now representing the best available technology. This suggests that new technology indeed push back frontiers. Note that a number of small traditional firms are on the best frontier also, suggesting that new technology does not suit all firms equally.

Our findings supports the common finding of the technical superiority of new energy-intensive technology (e.g. Oude Lansink and Bezlepkin 2003; Oude Lansink and Ondersteijn 2006). Note that our empirical results confirm that firms using new technology reach higher technical efficiency, yet at least on average. More detailed examination reveals that a substantial number of small firms do not benefit from new technology adoption; instead they attain the highest performance using traditional energy-extensive technology.

Optimal investment strategy

The investment model indicated that small traditional firms would maximise their expected net cash flow by staying as they are, regardless the technical efficiency. The most interesting results regarding the interplay of investment and technical efficiency relate to large firms. For large firms, the investment model addressed that technical efficiency affect investment decision. Optimal investment strategy for inefficient large firms is that they should only partially adopt the new technology, and cultivate the rest of the area using traditional technology. Efficient large firms, efficiency score 0.92 or higher, should also build more greenhouse area with assimilation lights to maximise the expected net cash flow with assumption, that efficient firms can also exploit the new technology fairly efficiently (Fig. 2). In practice the efficiency score 0.92 means e.g. that if firm uses traditional technology in

Table 6. The proportions of firms locating in the best practice frontier (in %) by groups and years.

	Within group				Within all firms			
	2000	2002	2004	2006	2000	2002	2004	2006
Large new technology firms	50	88	100	100	4	9	16	13
Large traditional firms	60	45	0	0	16	12	4	0
Small traditional firms	4	15	23	32	2	10	11	18

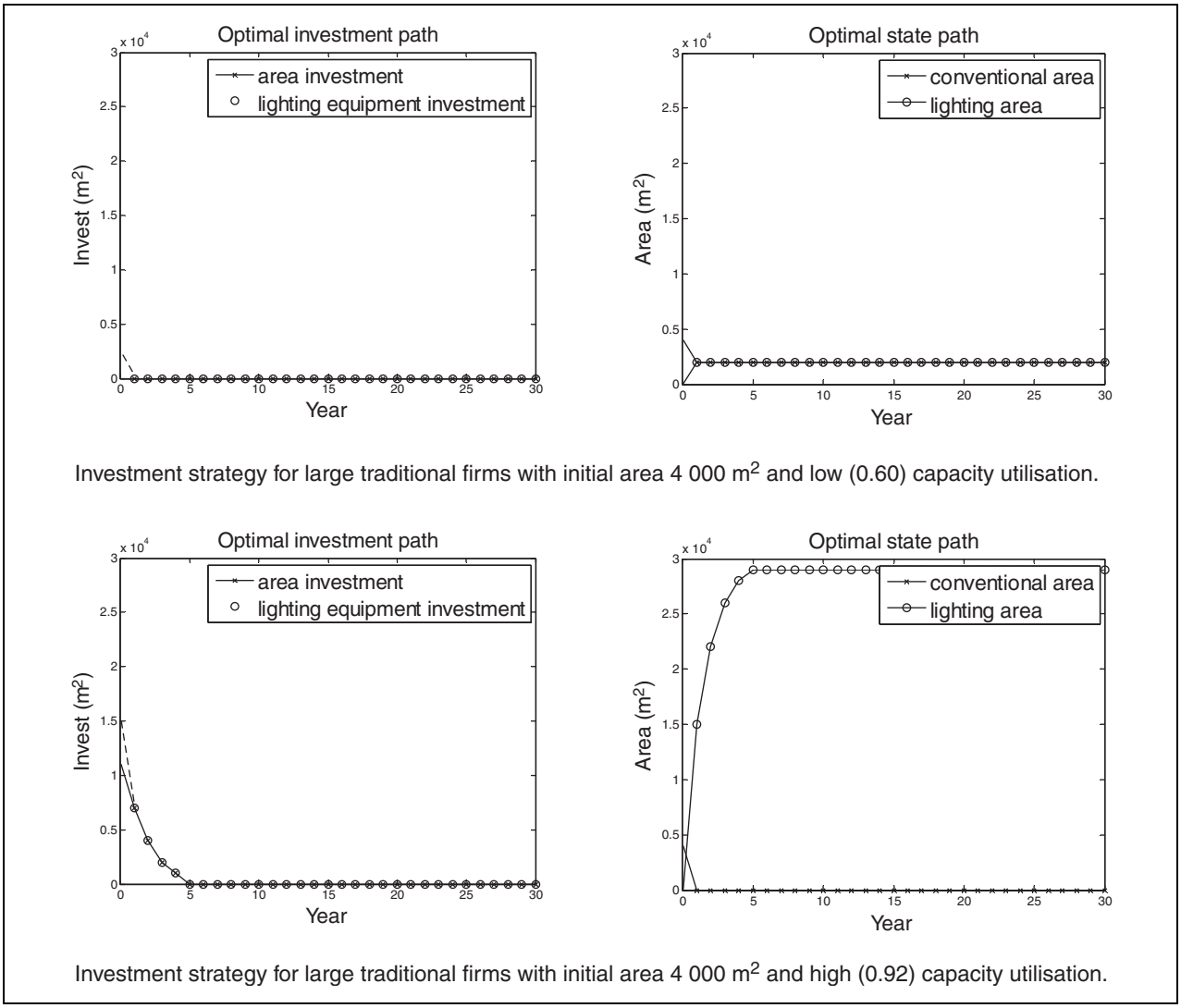


Fig. 2. Optimal investment strategy and state for different firm types.

production size of 0.50 ha and it uses 2000 MJ energy per year, it should reach at least 36 kg m^{-2} yield. Or if firm uses 1500 MJ energy per year, it should reach 34 kg m^{-2}, respectively. However, only 9 % of traditional large firms overtake the high efficiency.

The rise of energy prices connected to firm's inefficiency sharply reduces the area expansions. Fully efficient large firms bear even 1.32 times higher energy price than normative value before the area expansion appear to be unprofitable. Firms with efficiency score 0.95 tolerate 1.14 times higher energy price and firm with efficiency score 0.92 tolerate only 1.02 times higher energy price, respectively. Other costs of new technology firms are much higher than in traditional firms. If the ratio of other costs of new technology and traditional increases from current 2.3 to 2.6, which means e.g. value of 101 € m^{-2} for new technology, it concludes the assimilation light investments for fully efficient firms.

Finnish cucumber market is seasonal and hence cucumber price fluctuation has two dimensions: the low-to-high price within a season regime and the summer-to-winter price ratio. The 9 % yearly mean price reduction concludes the greenhouse area investments for fully efficient large firms, and 16 % price reduction concludes also the assimilation light investment. The more inefficient firms are the minor price reduction they tolerate. E.g. 8 % yearly mean price reduction makes assimilation lighting investment unprofitable and less than 1 % price reduction makes greenhouse area investment unprofitable for firms which have efficiency score 0.92. Both investment decisions are almost solely affected by the cucumber's winter price. Even if the summer season price collapses to half of the current value, it does not affect the investment decision of fully efficiency large firm. A decrease in the summer-to-winter price ratio from 1.30 to 1.19, which relates to 1.39 € kg^{-1} winter price, makes the conventional energy-extensive technology the most profitable one for fully efficient large firms.

Conclusions

We examined how a firm's technical efficiency affects investment planning of new energy-intensive technology in Finnish greenhouse cucumber industry. We used a stochastic production frontier using both intra- and inter-technology measures of technical efficiency. The associated implications of a firm's technical efficiency for investment planning is explored by investigating if, and under what conditions alternative technologies provide the highest technical performance. For this, we used a dynamic programming model in which the optimal solution to switch technology depend on a firm's technical efficiency, firm's initial features, and price ratios.

The model explains the slow adoption process of assimilation lighting in Finland over 2000–2006. Using intra- and inter-measures of technical efficiency we explored whether one technology dominates the other. The results suggest that the position of the technologies has changed over time. In 2000 and 2002 the large traditional firms defined the best available technology which enable to highest technical efficiency. The situation changed between 2004 and 2006 with new technology firms now representing the best available technology.

The investment model indicate that inefficient large traditional firms that maximize the terminal expected net cash flow install assimilation lights to a part of the greenhouse area only. These firms have a possibility to learn to use new technology and hence improve the technical efficiency. That might very well explain the partial adoption observed in Finland. Those large traditional firms which manage to utilise the existing capacity well with efficiency score above 0.92, maximise their net cash flow by investing in greenhouse area with assimilation lights. However, such firms which have efficiency score higher than 0.92 represents only 9 % of all large firms.

The analysis indicates that the investment decisions are very sensitive to price changes. Fully efficient firms bear even 1.32 times higher energy price than used normative value, but the firm's inefficiency sharply makes investments unprofitable. Hence, firms with inefficiency score 0.92 tolerate only 1.02 times higher energy price, which is negligible compared to recent energy price development, with a rise in electricity price of over 50 % between year 2000 and 2008. Our investment model indicated that cucumber winter price almost solely define the optimal investment strategy. That might explain the current production situation in Finland where the summer price at intervals collapse because of oversupply, but still part of greenhouse firms invest to new greenhouse area and install more assimilation lights.

Yet, the results indicate that a growing number of small traditional firms are on the best frontier also, suggesting that new technology does not suit all firms equally. Either small firms are able to utilize their inputs efficiently using traditional cultivation method and use such a technology that maximizes the profit as our investment model indicated, or firm's access to new technology may be restricted to current greenhouse area and/or technical limitations of existing greenhouse to install assimilation lights. However, more research is required to investigate also the environmental influences related to new energy-intensive technology investments. Also the wherewithal of other production technology investments, such as CO_2-enrichment, heat storage, thermal insulation and greenhouse cooling would require an economic analysis to help decision-making of greenhouse entrepreneurs.

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References

Baerenklau, K.A. and K.C. Knapp 2007: Dynamics of agricultural technology adoption: age structure, reversibility, and uncertainty. Am. J. Agr. Econ. **89**, 190–201.

Battese, G. E. and T.J. Coelli 1995: A model for technical inefficiency effects in a stochastic frontier production function for panel data. Empir. Econ. **20**, 325–332.

Borger, B.D. and K. Kerstens 2000: The Malmquist productivity index and plant capacity utilization. Scand. J. Econ. **102,** 303–310.

Bye, T., A. Bruvoll and J. Larsson 2009: Capacity utilization in a generalized Malmquist index including environmental factors: A decomposition analysis. Land Econ. **85**, 529–538.

Coelli, T., D. S. P. Rao and G. E. Battese 1999: An introduction to efficiency and productivity analysis. Kluwer Academic Publishers, Boston.

Ekboir, J.M. 1997: Technical change and irreversible investment under risk. Agr. Econ. **16**, 55–65.

Felthoven, R.G. and C.J. Morrison Paul 2004: Multi-output, nonfrontier primal measures of capacity and capacity utilization. Am. J. Agr. Econ. **86**, 619–633.

Koivisto, A. 2004: Puutarhayritysten tuotantokustannusten seurantamallit. [The production costs of horticulture products according to farm models]. MTT:n selvityksiä 71, Helsinki.

Kompas, T. and T. N. Che 2006: Technology choice and efficiency on Australian dairy farms. Aust. J. Agr. Resour. Econ. **50**, 65–83.

Leather, H.D. and M. Smale 1991: A Bayesian approach to explaining sequential adoption of components of technological package. Am. J. Agr. Econ. **73**, 734–742.

Lohano, H.D. and R.P. King 2009: A stochastic dynamic programming analysis of farmland investment and financial management. Can. J. Agr. Econ. **57**, 575–600.

Løyland, K. and V. Ringstad 2001: Gains and structural effects of exploiting scale-economies in Norwegian dairy production. Agr. Econ. **24**, 149–166.

Marra, M., D.J. Pannell and A.A. Ghadim 2003: The economics of risk, uncertainty and learning in the adoption of

new agricultural technologies: where are we on the learning curve? Agr. Syst. **75**, 215–234.
Miranda, M.J. and P.L. Fackler 2002: Applied computational economics and finance. MIT Press, USA.
Oude Lansink, A., E. Silva and S. Stefanou 2001: Inter-firm and intra-firm efficiency measures. J. Prod. Anal. **15**, 185–199.
Oude Lansink, A. and I. Bezlepkin 2003: The effect of heating technologies on CO_2 and energy efficiency of Dutch greenhouse firms. J. Environ. Manage. **68**, 73–82.
Oude Lansink, A. and C. Ondersteijn 2006: Energy productivity growth in the Dutch greenhouse industry. Am. J. Agr. Econ. **88**, 124–132.
Pietola, K. and A.-M. Heikkilä 2005: Switching toward capital-intensive technologies in Finnish dairy farms. Agr. Econ. **33**, 381–387.
Sipiläinen, T. and M. Ryhänen 2005: Technical change in Finnish grass silage production. Agr. and Food Sci. **14**, 250–263.
Tike 2007a: Puutarhayritysrekisteri 2006. [Horticultural Enterprise Register 2006]. Information Centre of Ministry of Agriculture and Forestry of Finland.
Tike 2007b: Production statistics. Information Centre of the Ministry of Agriculture and Forestry of Finland.
Xu, X. and S. Jeffrey 1998: Efficiency and technical progress in traditional and modern agriculture: evidence from rice production in China. Agr. Econ. **18**, 157–165.

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