Environmental efficiency of smallholder rubber production

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Abstract:

The economic benefits of Indonesia's rubber production are increasingly questioned because of their associated problematic effects on the environment, such as disturbances of the native ecosystem through alien and invasive organisms and overall negative effects on biodiversity. In order to reconcile economic benefits and threats to ecological functions, the exact nature of the interaction between rubber production and the surrounding ecosystems needs to be analyzed so that adequate policy interventions could be devised. In this paper, we focus on the trade-off relationship between rubber output and the ecosystem disturbance, proxied by the prevalence of invasive plants. Our approach is based on a directional output distance function, which allows the simultaneous estimation of efficiency and of the determinants of environmental efficiency. We apply this model to a household level socioeconomic data set and a plot-level environmental data set, from Jambi in 2012. Our results point towards a concave trade-off curve, indicating that an increase in rubber output is accompanied by an increase in ecosystem disturbance. Farm specific efficiency estimates indicate subdued level of efficiency, illustrating the possibility to reduce ecosystem disturbance while simultaneously increasing rubber output. The inefficiency levels are found affected by several management related variables, e.g., the glyphosate application.

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1 Introduction

In the last decades, concerns about sustainable development and environmental problems have risen from society. As a result, organizations, firms and producers face a demand for sustainable production to demonstrate all-encompassing environmental performance. In light of this demand, a widespread definition of sustainable development was consolidated in three components by Welford (1995). Firstly, the environment is included in the economic process and not observed as separate from it. Secondly, the equal distribution of goods between all members of society are important and thirdly, the prospective recognition of resources is also considered a vital component (Welford, 1995).

In order to translate Welford's ideas to the production of agricultural products, which is an important source of income, we must consider that its economic benefits are simultaneously accompanied by impacts on the environment such as pollution, nutrient losses, biodiversity losses and climate change effects. These factors must of course be taken into close consideration for an environmental efficiency analysis.

Our study area Sumatra (and especially Jambi) in Indonesia, is a typical example of environmental degradation as a result of economic development in terms of agricultural expansion and intensification, highlighting the scarcity of land resources and potential inefficiency in terms of eco-efficiency (Laumonier et al., 2010; Gaveau et al., 2007). The rapid change and intensive production of cash crops has been favorable for economic development, but various environmental and social concerns can be attributed to this development.

The expansion of production into areas of lowland rainforest is seen as a major threat to biodiversity conservation, the functionality of ecological systems, climate change, and the sustainability of production with respect to soil and water pollution (Eye on Aceh, 2007; Belcher et al., 2005). Next to deforestation, monoculture production is often linked to undesired side-effects and by-products. One of the by-products of production is seen in the abundance of alien plant species in the natural ecosystem habitats in the plantation sites. Through agricultural intensification, a change from preceding subsistence strategies, in the form of extensive swidden farming, to monoculture cash-crop cultivation, has been observed (Potter, 2001).

This change gives exotic organisms the chance to settle in the disturbed habitats of Indonesia. Consequently, invasive plants have the potential to cause problems in monoculture rubber and oil palm plantations. The threat originating from invasive plants altering the surrounding environment can be categorized as a direct and indirect effect. Firstly, the direct effect occurs through the invasive plants' excretion of secondary compounds via leaf leachates, leaf litter, and root exudates. The excretion of secondary compounds is part of the general physiology of plants, but invasive plants are exotic to their infested environment, and consequently impact the nutrient cycles in a different manner to native plants. This effect is manifested by a reduced abundance of supporting microbial communities and altered litter compositions in the invaded areas (Weidenhamer and Callaway, 2010; Liao et al., 2008; Sanon et al., 2009; Standish et al., 2004).

As a second direct effect, secondary compounds create a disadvantaged environment for native plants, giving the invasive species an advantage. This direct effect is also called the 'novel weapon hypothesis' (Weidenhamer and Callaway, 2010). The oppression of the native flora and fauna may diminish or eradicate important supporters of the ecosystem, as well agents essential for tree pollination.

The indirect effects of invasive plants on the environment are seen in the new or elevated need for herbicides to reduce or extinguish the exotic plants. Literature shows a variety of findings on the impact of herbicide application on the surrounding environment, from small and ephemeral to high. The majority of this paper focuses on glyphosate and paraquat. The most common impact concerns the alteration of the functional structure of soil bacteria and its resultant reduction (Lupwayi et al., 2009; Widenfalk, 2005; Allen et al., 2015).

Alongside the direct and indirect effect, the more general concern lies in the expansion of the distribution of invasive plants, resulting in an identical flora and fauna without local diversification covering all five continents. Due to the high competitiveness of the invasive plants, this threat can already be observed in some parts of the world.

Considering the stated main concerns from the ecological point of view, a reduction – or ideally extinction – of the invasive plant population would be a small accomplishment in terms of the environmental impact on monoculture plantations. Nevertheless, profit maximizing attitudes of producers lead to the presence of the undesired by-product maximizing production decisions, contradicting the environmental goal. Thus, determining the interdependence of economic performance and the disturbance of the ecosystem function – invasive plants – and the overall efficiency of the production is a crucial step in reconciling both goals and sustainable development. At the same time the high participation of smallholder producers and the heterogenity, as a result of diverse establishment and management settings, is possibly linked to potential losses of outputs. Eradicating these potential losses by augmenting the efficiency of production reduces this already, depending on the present inefficiency level.

Based on this goal, this chapter seizes on the works of Färe et al. (2005, 2007), Chung et al. (1997), and Njuki and Bravo-Ureta (2014) and applies a Directional Output Distance Function (DODF) to quantify the interdependency of both outputs through the underlying trade-off function, on the grounds of a multidisciplinary data-set incorporating variables on economic performance and plot-level data describing the state of the environment.

Even though the productivity and efficiency of oil palm and rubber have been the objective a few researches (Hasnah et al., 2004; Alwarritzi et al., 2015; Lee et al., 2013; Wilcove and Koh, 2010; Allen et al., 2015; Rubiana et al., 2015) the strength and novelty of this research lies in the unique combination of data-sets on plot-level. This accurate measure of the heterogeneity inside the production system, as a result of diverse establishment and management settings, enables us to estimate individual environmental efficiency. Thus we can derive the potential output losses and reduction possibilities of the environmental disturbances due to inefficiency, before entering the costly trade-off between the desired and the undesired production outputs.

The structure of this paper is as follows: the first section briefly presents and explains the methodology of the (DODF) approach. The second part introduces the specific empirical model adjusted to our research aim and the collected data is presented in the same section. In section 3, the estimates' outcomes are introduced and analyzed under certain economic criteria[1]. Finally, we conclude our research with a summary of our findings and prospects for production.

2 Methods and Material

2.1 Environmental production function and efficiency

First attempts to estimate and analyze production's trade-off function and the overall efficiency under consideration of undesired by-products embedded their reciprocal into the production function as an input (see Pittman, 1981; Knox Lovell et al., 1995; Reinhard et al., 1999; Hailu and Veeman, 2001).

Even though the approach was justified by the stronger similarities between the undesirable output and input characteristics, as opposed to general output characteristics (Pittman, 1981; Knox Lovell et al., 1995), this concept was challenged by Färe et al. (2005). He argues that environmental disturbances are

[1]Ideas for the analysis were inspired by Färe et al. (2005), which form the focus of this paper.

more likely consequences of production and by-products and the strong disposability of undesired output. This reviewed concept lead to numerous deterministic approaches using the nonparametric linear programming technique of Data Envelopment Analysis (DEA) in combination with transformed distance functions to compose a best practice frontier. Färe et al. (1986) established a hyperbolic distance function, following the concept of input-output oriented distance functions by Debreu (1951), Malmquist (1953), and Shephard (1953), allowing for an expansion in the desirable output and a reduction in the undesirable input. They went on to introduce differentiation between the weak and strong disposability of outputs in a parametric setting. From these various approaches, two main paths to measure efficiency in the presence of desired and undesired outputs have come forth: the Directional Distance Function (DDF) approach introduced by Färe et al. (2005) and Chung et al. (1997), and the by-production approach.
The latter displays the production of the desired and undesired output separately over individual production functions. (Murty et al., 2012; Fernández et al., 2002). The DDF, based on the concept of the distance function of Shephard (1953, 1970), allows for the simultaneous reduction in the undesired output, while enhancing the production of the desired output in different proportions, reflecting the maximizing strategy of our producers.

The transformation function is estimated in a single equation combining undesired outputs and polluting and non-polluting inputs together. This concept, and the related transformation function concepts, have been applied by various researchers, such as Färe et al. (2005), Atkinson and Dorfman (2005), Fernández et al. (2005), Färe et al. (2007), Macpherson et al. (2010), and Njuki and Bravo-Ureta (2014). The by-production approach separates the production of the undesired outputs and individual production functions.

The DODF, originally developed by Chambers et al. (1998), represents a special case of the Output Distance Functions (ODF) introduced by Shephard (1970). The difference lies in the use of a directional vector in comparison to a radial measurement for the technical inefficiency which is advantageous for non-proportional scaling. Considering a production process, where output set $P(x)$ represents the set of desired outputs and undesired outputs (y, b), the set of outputs that can be produced by the inputs $(x_1, ...x_k)$ is specified by

$$P(x) = \{(y, b) : x \quad \text{can produce} \quad (y, b)\} \qquad x \in \Re^N_+$$

For the specification of the ODF, we introduce the directional vector $g = (g_y, -g_b)$ with $g \in \Re^M$, as presented by Färe et al. (2005). After incorporating this, the direction of the maximization of distance between the observed output (y, b) and the frontier is defined, leading to the parametrization of the DODF as

$$\vec{D}_o(x, y, b, g_y; -g_b) = max \quad \{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{1}$$

From the axioms underlying the ODF, we can derive the properties of the DODF to extract further information in the following way: firstly, the output set needs to be a closed set, implying that when no inputs are used, no outputs are produced. This allows us to assume that an increase in inputs can only increase, or at least not decrease, the output set. This is also known as *strong disposability.*

Likewise, we can assume *strong disposability* for the desired output. By virtue of this assumption, we allow the desired output to be reduced without any losses, if an observed vector combination of both outputs was already attained at a higher level. Therefore,

$$\text{if} \quad (y, b) \in P(x) \quad \text{and} \quad (y', b) \leq (y, b) \quad \text{then} \quad (y', b) \in P(x) \tag{2}$$

In contrast to the strong disposability of inputs, we assume only a joint weak disposability for the outputs.

This assumption reflects the idea of abatement costs for a reduction in the undesired output. Decreasing the undesired output over a given vector of inputs must lead to a proportional decrease in the desired output (Färe et al., 2015).

By default, production of the desired output is always linked to the production of bad output, therefore neither output can be produced without the other. This is stated by the null-jointness assumption (Färe et al., 2015). This assumption has been challenged by Henningsen and Henningsen (2015) for special productions, where a simultaneous reduction in the undesired output and increase in the desired output might not be suitable.

While the radially measuring ODF, introduced by Shephard (1970), includes a multiplicative homogeneity function, we make use of an additive translation property for the estimation of the DODF. Through the translation property, a value θg_q is added to the desired output, while θg_b is simultaneously subtracted from the undesired output. The θ value represents the possible reduction in the distance.

$$\begin{aligned} \vec{D}_o(x, q+\theta g_q, b-\theta g_b, g_q, -g_b) = \vec{D}_o(x, q, b, g_q, -g_b) - \theta \\ \theta \in \Re \end{aligned} \tag{3}$$

Applying a DODF stochastically takes two components into account when a deviance between the observation and the frontier occurs. On the one hand, the traditional random noise term captures the stochastic effects, while on the other hand, a one-sided error term u_i captures the technical inefficiency, defined by $-\vec{D}_o(x, q, b; g_q, -g_b)$. As a result, we add the error term v_i to the previous equation and write the frontier as:

$$\begin{aligned} -\theta \equiv \vec{D}_o(x, q+\theta g_q, b-\theta g_b, g_q, -g_b) - u_i + v_i \\ \theta \in \Re \end{aligned} \tag{4}$$

While the random noise term v_i is normally distributed $N(0; \sigma_v^2)$, independently from x_i, various distributions were attributed to the positive inefficiency term u_i, $u_i \geq 0$. These ranged from an underlying distribution of $N^+(0; \sigma_u^2)$ applied by Aigner et al. (1977) to distributions dependent on observation characteristic variables (Wang and Schmidt, 2002).

The first inclusion of the latter proposal by Pitt and Lee (1981) and Kalirajan (1981) allowed for a two-step estimation regressing the characteristics on the predicted inefficiency values via Ordinary Least Square (OLS). This was highly criticized because of bias issues. Consequently, Kumbhakar et al. (1991), Battese and Coelli (1995), Reifschneider and Stevenson (1991), Caudill and Ford (1993), Caudill et al. (1995), and Simar et al. (1994) proposed a simultaneous estimation of the production function and the effects arising from firm characteristics on the efficiency under adequate distributional assumptions. Kumbhakar et al. (1991) and Battese and Coelli (1995) included the effect of the characteristics through the mean of the u distribution, while Reifschneider and Stevenson (1991), Caudill and Ford (1993), and Caudill et al. (1995) implemented the scaling property, where the variance parameter of the distribution of u is dependent on the efficiency effects.

Adapting the latter dependence with an underlying half-normal distribution of the u, we can say that $\sigma_u(z, \delta)$ depends on the characteristics z, leading to a distribution of u in the form of $N^+(0; \sigma_u(z, \delta)^2)$, where $\sigma_{u,i}^2(z, \delta) = \sigma \exp(z_i^{'}\delta)$.

The magnitude of the effect of the z-variables is computed by equation 5, due to the non-linear relationship between $E(u_i)$ and z. Based on the half-normal distribution of u and the parametrization of the exogenous effects on inefficiency the computation of the marginal effect is given by

$$\frac{\partial E(u_i)}{\partial z[k]} = \delta[k] \frac{\sigma_{u,i}}{2} \left[\frac{\phi(0)}{\Phi(0)} \right] = \delta[k] \sigma_{u,i} \phi(0) \tag{5}$$

The technical efficiency and corresponding noise term for each individual can be extracted through the mode of the conditional distribution of u as proposed by Jondrow et al. (1982) or Battese and Coelli (1988). The point obtained estimates the efficiency values and can be derived via

$$TE_i = E\left[e^{-u_i} \mid \varepsilon_i\right] \tag{6}$$

as presented by Kumbhakar and Lovell (2000).

2.2 Specifications for the Directional Output Distance Function (DODF)

Given the axioms of the DODF, an empirical specification is needed which allows for the most flexible functional form, while still abiding with the underlying axiom. Following Chambers (2002) and Färe et al. (2005), we choose a quadratic functional form, as the translation property can be easily applied via restricting the estimation parameters.
A crucial point of the empirical specification of the model concerns the choice of the directional vector. Sensitivities of results towards different implemented directional vectors have been shown in several studies; the latest was presented by Tsionas et al. (2015) in a Bayesian estimation approach. Despite their concerns, the implied data-driven vector produced results analogous to those from the commonly used $g = (1, -1)$ vector. The latter vector has the advantage of being able to facilitate the parametrization of the quadratic function according to the translation property. Furthermore, it perfectly mirrors the reduction of the undesired output and the increase in the desired output (Feng and Serletis, 2014).
Criticism can be made regarding the equal weight given to both the reduction and the increase, which might not reflect the political desire for the elimination of undesired by-products (Hampf and Kruger, 2014). As a result of the susceptibility in this case, we apply a variety of vector directions, as a means of comparison. Nevertheless, after adequate discussion, the $g = (1, -1)$ vector seems to be the best fit for the primary analysis and general empirical specification.

In order to estimate the DODF stochastically, we avail ourselves of the translation property. The choice of the θ term is completely arbitrary, and affords us the opportunity to use the DODF for further estimation. With that in mind, we set $\theta = -q$. Based on this parameterization which includes one desirable ($M = 1$) and one undesirable ($L = 1$), the DODF can be written as

$$
\begin{aligned}
\vec{D}_o(x_i,(q_i+\theta),(b_i+\theta),1,-1) &\stackrel{!}{=} \vec{D}_o(x_i,q_i,b_i,1,-1)-\theta \\
&= \alpha_0 + \sum_{k=1}^{K}\alpha_k x_{i,k} + \sum_{m=1}^{M}\beta_m(q_{i,m}+\theta_i) + \sum_{l=1}^{L}\gamma_l(b_{i,l}+\theta_i) \\
&+ \frac{1}{2}\sum_{i=1}^{K}\sum_{k=1}^{K}\alpha_{kk'}x_{i,k}x_{i,k'} + \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M}\beta_{mm'}(q_{i,m}+\theta_i)(q_{m,m'}+\theta_i) \\
&+ \frac{1}{2}\sum_{l=1}^{L}\sum_{l'=1}^{L}\gamma_{l,l'}(b_{i,l}+\theta_i)(b_{l,l'}+\theta_i) \\
&+ \sum_{k=1}^{K}\sum_{m=1}^{M}\nu_{km}x_{i,k}(q_{i,m}+\theta_i) + \sum_{k=1}^{K}\sum_{l=1}^{L}\rho_{kl}x_{i,k}(b_{i,l}+\theta_i) \\
&+ \sum_{m=1}^{M}\sum_{l=1}^{L}(q_{i,m}+\theta_i)(b_{i,l}+\theta_i) \\
&\qquad \theta \in \Re
\end{aligned}
\tag{7}
$$

2.3 Data

This research relies on two combined surveys: one is a socio-economic household survey including 600 smallholders of Jambi Province on Sumatra, Indonesia, conducted by another sub-project of the CRC 990[2], while the second survey covers the environmental data and includes a sub-sample from the household survey of 135 smallholder rubber farmers.

The household survey, conducted at the end of 2012, covers five regions (Sarolangun, Batanghari, Muara Jambi, Tebo, and Bungo) in the province of Jambi. A stratified sampling approach seemed the best fit to mirror geographical and regional disparities, which are stretched out through the province. Forty villages were selected in a two-step random selection, equally distributed over four sub-regions in each of the five regions. To account for dissimilarities in terms of village population size, an adjusted amount of farmers were randomly selected as opposed to using constant sampling numbers. Thus, the randomly selected villages were categorized by size in four quarters: 6, 12, 18, and 24 households were then randomly selected, depending on their category (Faust et al., 2013).

For the environmental data-set, one third of the previously sampled households from the household survey were re-sampled to extract information on the state of biological diversity and plant abundance. From each sub-sampled farmer, we collected vegetation data relating to the major plantation site. To that end, a sampling site was established in the form of a 5x5 meter plot on which the understory vegetation of the plantation in question was adequately represented. Within the plot, all plants were counted and identified.

The descriptive statistics of all the relevant variables evolving from the data-set are summarized in Table 1, where we include rubber production per plot for the last year (q) and invasive plants[3] per plot (b) for the production function as the desired and undesired output. We also include the following inputs: size of the plot (*x1*), hours of labor per plot (*x2*), plantation age (*x3*), and cost of all chemicals (fertilizer, herbicides, soil amends) (*x4*). Each input and output was normalized by its mean prior to the estimation.

[2]The household survey covering a variety of socio-economic and consumption data is further described in the publications of Euler et al. (2015); Drescher et al. (2016); Faust et al. (2013)

[3]Names and abundance in percentage of invasive plants on the plot are presented in the appendix in Figure 3

Table 1: Descriptive statistics

Variable	Unit	Mean	Std.dev.	Min	Max
Rubber	kg	3045	2966	240	24000
Invasive Plants	plant	217	307	0	1750
Plot size	ha	2.1	1.8	.02	10
Labor	hours	1649	1595	71	15000
Plantation Age	years	19.2	8.4	5	55
TC. Chemicals	.000 Ruphia	676	1764	0	16225.5

3 Results and Discussion

We applied a variety of directional vectors in order to capture the effect of the different directions. Even though the proportional relationship of the efficiencies and other economic characteristics of the farm will not change, the absolute values will be strongly affected by the choice of the directional vector. A range of angles, between 25°, the smallest possible angle concerning convergence, and 89°, the largest angle including a reduction in the undesired output, were applied in the model. After evaluating the results of the grid of directional vectors using the Akaike Information Criterion (AIC), the smallest feasible vector was shown to be the correct choice. Nevertheless, estimation with a 25° vector is less meaningful for most of the coefficients. Moreover, a vector of 25° would imply a stronger focus on the reduction in the undesired output, which may be controversial to the average producers, who are more likely to operate under the logic of profit maximization. Therefore, we follow the example of Färe et al. (2005) and set $g = (g_y, -g_b) = (1, -1)$, representing an angle of 45°. This choice reflects a compromise between the number of violations and a low AIC and the equal reduction of environmental disturbance and economic output.

Prior to evaluating the estimation of the DODF in its empirical specification, we ran tests for the general inclusion of the non-negative inefficiency component in the model through the LR-test, where the null hypothesis is set as $\sigma_u^2 = 0$. Since this null hypothesis lies on the boundary of the parameter feasible space, the LR statistics follows a mixed chi-squared distribution $(1/2)\chi_0^2 + (1/2)\chi_1^2$ (Coelli, 1995). The test results show a rejection of the null hypothesis at a 1% significance level (Table 2). For further model specifications concerning the production function, LR-tests were used to exclude the non-relevant variables. The coefficients of the estimated DODF are listed in the appendix in Table 7. Two out of the

Table 2: LR-test results for testing the presence of inefficiency

LL_{OLS}	-57.39	
LL_{SFA}	-35.06	
	LR Value	44.66
	critical value 0.01 df(8)	19.384

five first order coefficients are significant at a 10% level, and three out of five are equally significant as second order coefficients. The special interest in this estimation lies in the coefficient of the bad output, $bstar = (b_i - (\theta_i g_b)$, which is significant at the 10% level in the first order and highly significant as a second order term. The only significant input in our production function is plot size, even though all inputs tested positive for their relevance in the model through the LR-test. Second order coefficients, next to plot size and hours of labor, are also significant in addition to an interaction with the bad output and plantation age.

The curvature of the frontier is likely to be concave, since the second order coefficient of q, represented by the coefficient *bstarsq* due to the translation property, is negative. The monotonicity assumptions were violated in 4% or 6 out of the 135 cases regarding the elasticity of the bad output with respect to the good output. In 7 out of the 135 observations, the condition $\vec{D}_o(x, y, b, 1, -1) \geq 0$ was not satisfied, leading to a 5.2% violation of the null-jointness condition.

In order to gain better insight into the underlying relationship between inputs and outputs in smallholder rubber production, interpretation of the input elasticities with respect to the distance is helpful. All of the input elasticities listed in Table 3 are positive at the mean, indicating an increase in the distance through enhancing the frontier and therefore the overall production. The highest effect on the frontier emanates from the input plot size, x_1, with 0.514, representing a 0.51% increase in the distance for a one percent increase in the input use. The elasticity of labor, $\mathcal{E}_{Labor}$ is the second highest coefficient with 0.28%, indicating a moderate increase in output with an increase in labor. After summing up all input

Table 3: Summary of the elasticities

Variable	Mean	Std. Dev.	25%	75%	Number of obs.
$\mathcal{E}_b$	0.340	0.195	.249	.449	135
$\mathcal{E}_{Size}$	0.514	0.293	0.410	0.633	135
$\mathcal{E}_{Labor}$	0.282	0.354	0.061	0.345	135
$\mathcal{E}_{Pl.age}$	0.170	0.249	0.022	0.271	135
$\mathcal{E}_{TC.Chemical}$	0.022	0.065	-.014	0.038	135
RTS	0.818	0.454	0.535	0.952	135

elasticities, a scale elasticity of 0.818 at the mean is obtained, revealing decreasing returns to scale, *ceteris paribus*. Regarding the economic interpretation, decreasing returns to scale hint at an input increase with a less than proportional output increase. These are mostly found in smaller and more labor-intensive farms, where smaller volumes of production are also efficiently feasible. This suits the considered rubber production, which is relatively small in size and volume, especially in smallholder productions.

3.1 Technical efficiency of the production

From the estimation of the DODF, efficiency values for each individual can be derived, the subsequent distribution values of which are reported in Table 4. The counter value of the estimated efficiency – inefficiency – can be seen as the maximum possible desired output expansion and the maximum undesired output contradiction to reach the frontier. Values greater than zero indicate an inefficiency in the production, while a value of $\vec{D}_o(x, y, b, 1, -1) = 0$ signifies total efficiency.

Table 4: Distribution of the efficiencies

Quantile	Number of obs.	Mean	Std. Dev.	25%	75%
$\vec{D}_o(x, y, b, 1, -1)$	135	0.7521	0.2334	0.671	0.910
$\vec{D}_o(x, y, b, 1, -1) < .25$	10	0.1671	0.059	0.135	0.211
$\vec{D}_o(x, y, b, 1, -1)$ .25 -.75	36	0.578	0.142	0.483	0.718
$\vec{D}_o(x, y, b, 1, -1) >.75$	89	0.888	0.067	0.842	0.944

The estimation results report a mean efficiency of 0.75, corresponding to an inefficiency of 0.25. This relates to a possible expansion in production by 755 kg of rubber per year and the equivalent reduction of 54 invasive plants per plot considering the normalized data and the directional vector of $\vec{D}_o(x, y, b, 1, -1)$. Even though the biggest share of observations lies above an efficiency of 0.75, the mean reflects substantial inefficiencies in the production. Low values tend to indicate a less competitive and less specialized market

with low pressure for producers (Kumbhakar and Lovell, 2000). From our field observations, this coincides with smallholder rubber markets in Sumatra, where the only controllable feature is the quality of the raw product, and both traders and producers do not pay too much attention to this.
Plotting the individual efficiencies against the number of invasive plants on the respective sites, a slight linear increase of invasive plants with decreasing efficiencies can be discerned (Figure 1). Hence, plots with higher occurrences of exotic plants tend to be less efficient in overall terms, reinforcing our hypothesis that exotic plants which are a disturbance to the ecosystem also can affect the output level in terms of inefficiency. However, plotting the yearly yield against the efficiency reveals no such pattern.

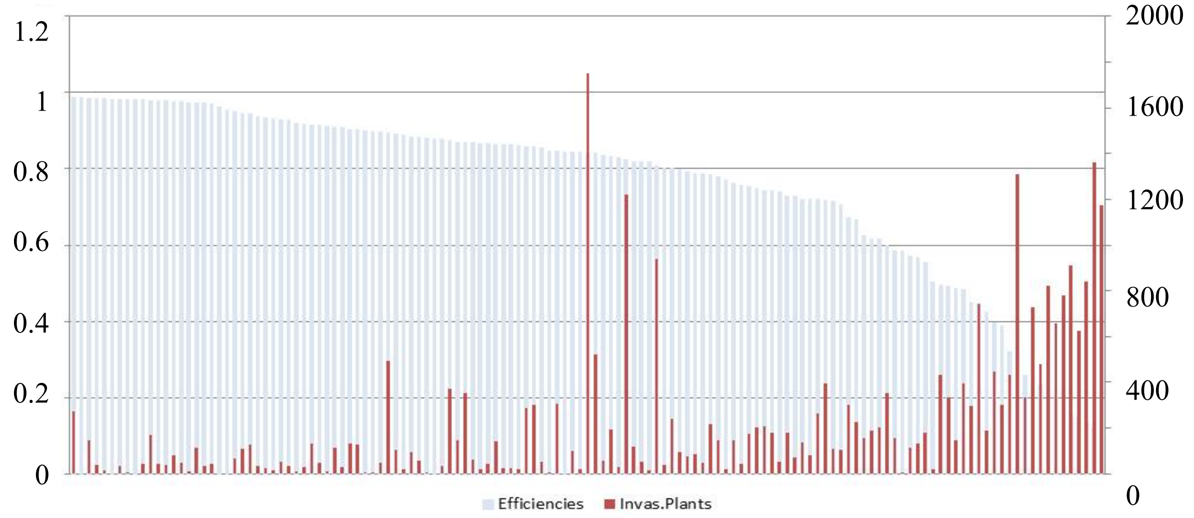

Figure 1: Efficiencies over invasive plants

After comparing efficiency groups on the basis of the relevant variables, some notable differences come to light. In correspondence with the preceding findings, producers with low efficiencies have, as the hypothesis suggested, the highest number of invasive plants, followed by the intermediate group and the high efficiency group.
The DODF is simulated with the inputs at the sample mean in Figure 2; the resultant shape fits our results when keeping the chosen directional vector of $g = (1, -1)$ in mind. It shows an increase in the undesired output of invasive plants, while at the same time exhibiting an increase in the desired output of rubber in kg. As a result, a clear outward-bending trade-off between the desired and undesired output underlies the production. Other criteria such as allocation of labor is lowest in the highest efficiency group, signifying a more efficient use of the available labor force. Furthermore, the efficiency distributions show a higher level of efficiency in producers with smaller plots at the mean.

We allow the systematic inefficiency component u to be heteroscedastic by modeling a multiplicative relationship between the variables accounting for heteroscedasticity, such as farm characteristics, and the distribution parameter of the systematic inefficiency component σ_u.
After including all collected covariates, both the significance and relevance of the variables were checked through LR-testing. Thus, the variables under consideration are plot size, (x_1), chemical weeding, application of gylphosate, participation in a transmigrant support program (TSP), contractual arrangements, years of education, and burning as a clearing method. The estimated coefficients and the corresponding marginal effects are listed in Table 5. Out of the seven covariates, five are at least significant at the 5% level.

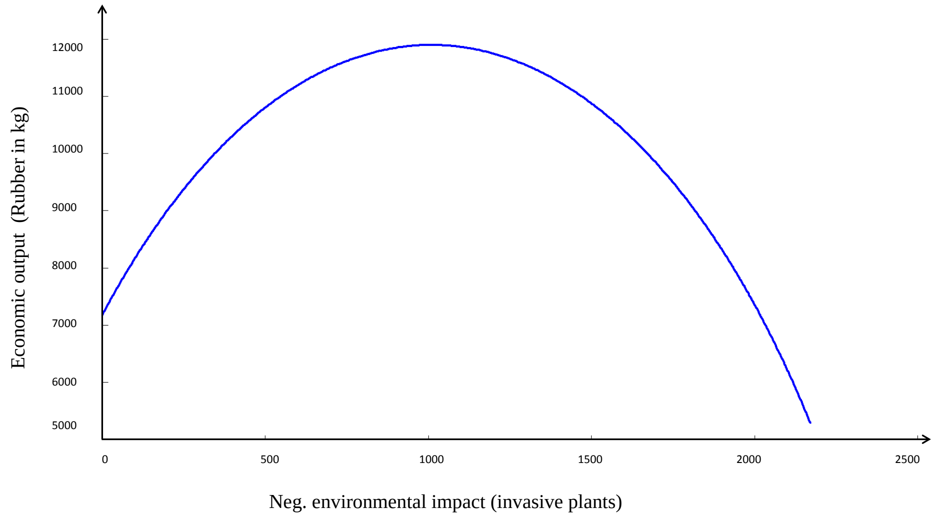

Figure 2: Interaction of invasive plants and the economic output

The largest effect on the distance, and thus inefficiency, reveals the completion of a marketing contract. A contractual linkage to a trader or a factory will increase the efficiency by 1.06%. This effect might be slightly over-estimated since only five of our farmers entered into such an agreement; this result should therefore be considered with due care.

Table 5: Estimation results of the covariates and the corresponding marginal effects

	Estimation Results		Marginal Effects			
Variable	Coefficient	t-value	Mean	Std. Dev.	25%	75%
Size	0.972***	3.80	0.58	1.76	0.11	0.43
Chem. Weeding	-0.639***	-3.22	-0.38	1.15	-0.28	-0.08
Glyphosate	0.651***	2.74	0.39	1.18	0.08	0.29
TSP	-2.300	-0.67	-1.37	4.17	-1.02	-0.28
Contract	-1.780*	-2.10	-1.06	3.22	-0.79	-0.22
Education	-0.447**	-2.17	-0.26	0.80	0.20	-0.05
Burning	-0.373**	-2.28	-0.22	0.67	-0.16	-0.05
Constant	-0.852***	-2.87				

***Estimate is significant at 1% level of significance
**Estimate is significant at 5% level of significance
*Estimate is significant at 10% level of significance

Even though the size of the rubber plot is also part of the production function, an effect on the efficiency is salient in terms of the p-value. The coefficient shows an elongating effect on the distance to the frontier with a marginal effect of 0.58. Thus, a 1% increase in the plot size would increase the distance to the frontier by 0.58%, amplifying the inefficiency as a result. This effect on the efficiency seems reasonable, since the larger the plot the more difficult it is to control the weeds between the trees, especially in smallholder production and with daily tapping. These effects coincide with the preceding findings concerning the efficiency distributions. The application of glyphosate also increases the inefficiency, and was included as a dummy variable. The utilization of glyphosate prolongs the vector by 0.39% , while other active ingredients of numerous herbicides did not show any effect. Decreasing effects on the distance, and thus the inefficiency, are further indicated through general weeding with chemical herbicides, increasing the level of education, and the practice of burning to eradicate undergrowth, as well as plantation establishment. The range of the reduction varies from 0.22% if burning is used as an eradication technique, to a 0.26% decrease, when years of education are extended by 1%, up to a maximum of 0.38% for the application of chemicals for weeding. The variable TSP represents the participation in the governmental transmigrant support program; this tested positive for inclusion in the model, although it was not found to be significant.

The contradictory effects of herbicide application in general and the specific use of glyphosate are rather exceptional and may be explained in a number of ways. Glyphosate is the only systematic herbicide used by farmers that affects not only the leaves it contacts, but also inhibits growth in roots, intentionally eradicating the complete plant. Upon closer inspection of plots and farmers using glyphosate, an elevated abundance of one specific invasive plant – *Asystasia gangetica* – was revealed. After linking the results with this information, the following conclusion can be made. The specific type of herbicide and the nature of invasive plants allows them to recover faster than local plants, giving them a competitive advantage in the environment, especially when their strength lies in fast germinating seeds, as in the case of *Asystasia gangetica* (Othman, 1993).

3.2 Shadow price calculation

As part of understanding the trade-off between the desired and undesired outputs a monetary quantification of the trade-off is required. Since markets for the undesired output in our specification are not existent we estimate the shadow price, based on our specified DODF with the vector $g = (1, -1)$ and the corresponding revenue function. In combination with the price of the desired output we can derive the absolute price for the undesired output.
The price information for the desired output states the yearly aggregated rubber price per kg over the last four years, given by the association of rubber enterprises "Gabungan Perusahaan Karet Indonesia" (Gapkindo). The computation of the undesired output's price is solved by the following equation Färe et al. (2005):

$$q = -p * \frac{\partial \vec{D}_o(x,y,b,1,-1)/\partial b}{\partial \vec{D}_o(x,y,b,1,-1)/\partial y} * \frac{\mu q}{\mu b} \tag{8}$$

Due to the normalization of our variables, we need to multiply the derivatives from the equation by the ratio of means of the good output to the bad output to receive real values. The interpretation of the multiplied derivatives, the shadow price of invasive plants, describes the amount of production that must be relinquished in order to reduce the undesired output by one unit moving along the efficient points on the frontier. Thus, from the estimation results, the price for one invasive plant lies between 134,921 IDR in 2012 and 76,706 IDR in 2015 at the mean, as listed in Table 6. The drop of global rubber prices is also reflected in the diminishing shadow price. Due to violations of monotonicity, six observations of the shadow price estimation were dropped in order to avoid scaling in the reverse direction on the frontier (Färe et al., 2005). The relation between the shadow price and the abundance of invasive plants bestows further insight on the shape of our trade off function. It seems that plots with a low abundance of invasive plants are linked to higher shadow prices as opposed to plots with a high abundance. This arouses the suspicion of a steeper slope in the area of low abundance, coinciding with the concave curve.

Plotting the individual shadow prices against producers' characteristics such as plot size and labor input does not reveal any strong patterns, which could lead to any further conclusion (Appendix Figure 4 and 5).

Table 6: Shadow price calculated for 2012-2015 by average rubber prices (in .000 IDR)

Year	Obs	Mean	Std. Dev.	25%	75%
2012	129	134.92	90.13	80.93	163.58
2013	129	107.21	71.61	64.31	129.98
2014	129	83.10	55.51	49.85	100.75
2015	129	76.71	51.24	46.01	92.10

3.3 Efficiencies and shadow price over different groups

Smallholder rubber production in Sumatra can be separated into extensive and intensive cultivation. Both are differentiated by the intensification of management and the plantation establishment. Due to differences in management, it can be stated that a more extensive cultivation quantifies a more sustainable production, which is therefore more environmentally efficient. The t-tests on the estimated efficiencies reveal a significant variation in the efficiencies at the mean of 5%. The extensive production results in a mean efficiency of 0.642 (n=19) and the more intensive production yields 0.769 (n=116).

The differentiation in shadow price by the grade of intensification – extensive and intensive – results in a lower shadow price of 60,976 IDR for the extensive producers, while intensive producers would have to forgo 79,256 IDR for an invasive plant, taking the prices of 2015 into account. This relates to 8 kg of rubber in extensive production and 10 kg of rubber in intensive production for the eradication of one invasive plant.

Considering these results, the stated hypothesis of higher environmental efficiency on account of the invasive plants cannot be supported. The lower output combined with the higher amount of invasive plants on the extensive plots places the producers even further away from the best-practice frontier. This highlights a broader potential to increase the output of extensive production and reduce the invasive plants on the plot with the given production inputs. The lower shadow price displayed in the extensive production indicates a more shallow segment of the trade-off curve, coinciding with the larger amount of invasive plants on extensively cultivated plots and the outward-bending concave trade-off curve. Therefore, at an efficient point of extensive production the desired reduction in the invasive plants is coupled with a smaller output decrease than in intensive productions.

4 Conclusion

This study aims to look at the underlying trade-off between smallholder rubber production – one of the main cash crops in Sumatra – and the surrounding ecosystem, and to investigate the determinants of technical and environmental efficiency within the production. With the application of a DODF including a desired output, rubber, and an undesired output, the amount of invasive plants on a plot site, we allow for the reduction of the latter variable and the simultaneous increase in the desired output. The unique data set, resulting from a household and environment survey conducted in 2012, allows for a plot-level analysis for 135 producers.

We find a concave trade-off curve between the desired output and the undesired output, indicating an increase in invasive plants and therefore a higher disturbance in the natural ecosystem with an increase in the desired output. On account of this trade-off curve, intensification of the plots would result in a higher level of ecosystem service degradation. Furthermore, the prediction shows substantial inefficiencies, leaving room for amelioration of the production processes by moving towards a higher rubber output level and reducing the number of undesired invasive plants. By calculating the shadow price of the undesired output, we give a monetary value to the reduction of the invasive plant output by one unit, which constitutes a substantial part of the yearly yield, after exploiting all potential output ameliorations.

The determination of drivers of inefficiency – the potential economic output losses and environmental disturbance – due to systematic shortfalls, reveals three major results showing the potential for sustainable development which could help to shape future policies. First, smaller plots in the estimation presented overall higher efficiencies, reinforcing the ongoing smallholder participation. Second, the contractual linkages increased the efficiency of production, most likely through creating secure distribution channels. Third, the application of glyphosate increased, in contradiction to the general usage of herbicide, the inefficiency of production. This combined with the indirect effect of invasive plants stated by Lupwayi et al. (2009) and Widenfalk (2005) suggests that the industry should re-think the strongly promoted application of glyphosate, especially without accurate training. Next to these three main findings, the different effects of farm characteristics show that, through management and institutional settings, low efficiency can be positively influenced.

Contrary to our hypothesis, extensive production did not result in lower ecosystem disturbance, as shown by lower overall efficiencies. For future research, an application of the by-production approach might be informative to some extent, since the environmental and technical efficiency can be analyzed separately; this was not possible in our case given the definition of the DDF over a combined output vector.

As an overall result, the impact on the environment and the disturbance of the natural ecosystem could be reduced without a big loss to profits, if productions were leveled up to higher efficiencies.

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Appendix

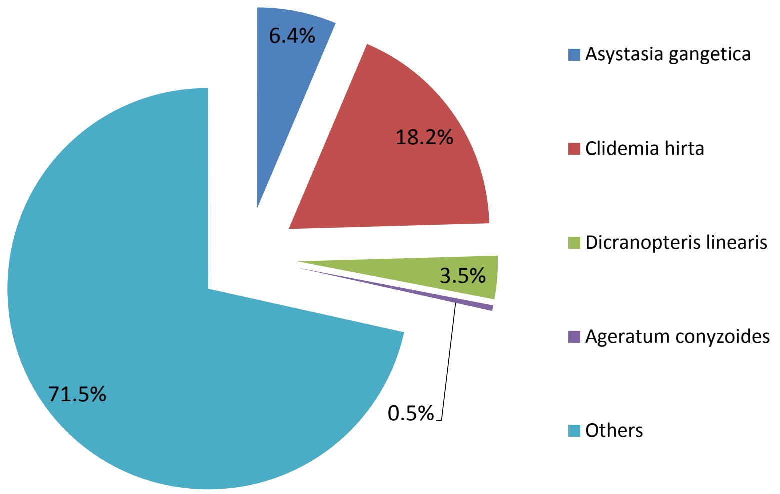

Figure 3: Distribution of invasive plant and non-invasive plants on average on the sampled plots

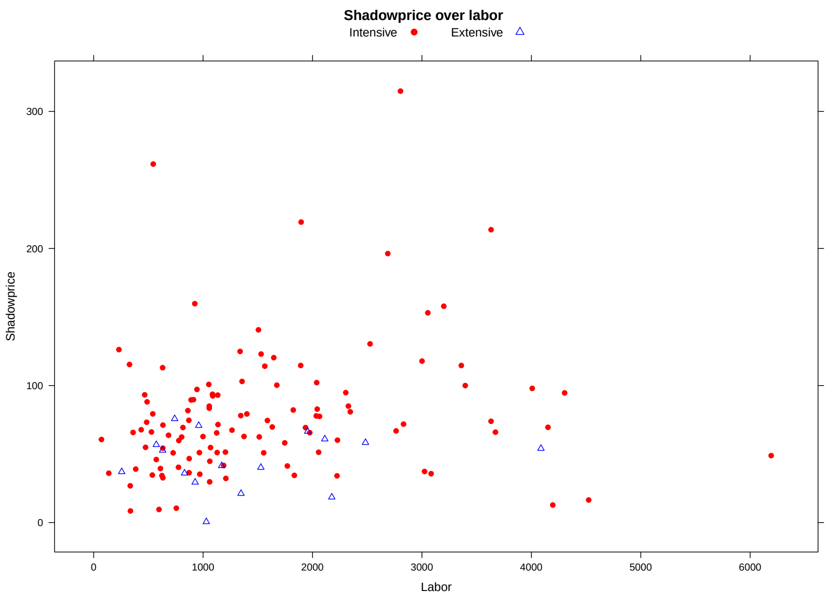

Figure 4: Scatterplot of the individual shadowprice against the labor input over both management intensity (red dots = intensive , blue triangle = extensive)

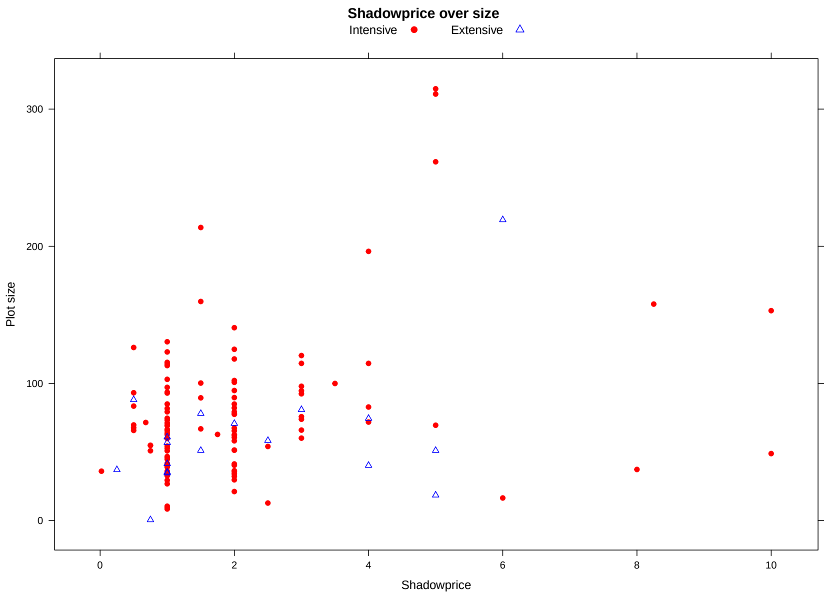

Figure 5: Scatterplot of the individual shadowprice against the size input over both management intensity (red dots = intensive , blue triangle = extensive)

Table 7: STATA output of the directional output distance function including the z-variables; size of the plot (*Size*), hours of labor per plot (*Labor*), plantation age (*Pl. Age*), cost of all chemicals (*TC. Chemicals*), and the bad output times the directional vector and the translation value θ , ($bstar = (b_i - \theta_i g_b)$).

Variable	**Coefficient**	**(Std. Err.)**
Equation 1 : n_theta		
b_star	0.166*	(0.098)
Size	0.565***	(0.212)
Labor	0.055	(0.169)
Pl. Age	0.363	(0.281)
TC. Chemicals	-0.066	(0.085)
Dummy Chemicals	-0.017	(0.056)
b_star^2	-0.129***	(0.019)
Size^2	-0.443**	(0.204)
Labor^2	-0.138**	(0.058)
Pl. Age^2	-0.319	(0.205)
TC. Chemicals^2	-0.004	(0.007)
b_star*Size	0.133**	(0.056)
b_star*Labor	0.138***	(0.041)
b_star*Pl. Age	0.150*	(0.084)
b_star*TC. Chemicals	0.009	(0.018)
Size*Labor	0.178	(0.145)
Size*Pl. Age	-0.048	(0.206)
Size*TC. Chemicals	-0.004	(0.039)
Labor*Pl. Age	-0.147	(0.171)
Labor*TC. Chemicals	0.057	(0.035)
Pl. Age*TC. Chemicals	0.020	(0.081)
Intercept	0.055	(0.185)
Equation 2 : lnsig2v		
Intercept	-3.462***	(0.212)
Equation 3 : lnsig2u		
Size	1.945***	(0.389)
Chem. Weeding	-1.277***	(0.451)
Glyphosat	1.302***	(0.498)
TSP	-4.602	(5.300)
Contract Supp.	-3.561*	(1.901)
Education	-0.119**	(0.059)
Burning	-0.745**	(0.372)
Intercept	-1.703***	(0.640)

***Estimate is significant at 1% level of significance

**Estimate is significant at 5% level of significance

*Estimate is significant at 10% level of significance