Climate change, economic policy and technology choice of heterogeneous producers

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Abstract

This article introduces a new Hopenhayn-Melitz-type model of heterogeneous producers with decreasing returns to scale and different productivities. Different to previous models, it describes smallholder producers in rural areas of developing countries in the context of environment and development economics. The model enables a socially sensitive policy analysis considering poverty and distributional effects. In this model, the production input causes a negative environmental externality. External shocks, e.g., caused by climate change, and economic policies affect the producers' endogenous choice between market entry or exit and between simple or advanced technology. In the first step, various shocks and policies are analyzed theoretically. A novel type of the rebound effect (Jevons paradox) is identified for the production input that occurs when market entry is incentivized by productivity improvements. In the second step, the model is calibrated by applying it to coffee production in rural Vietnam. The simulation results show that secondary effects of the shocks, such as employment effects, can be substantially larger than the original impact. Moderate technology support is sufficient to induce the replacement of the simple by the advanced technology in the long-run. The support of market entry or of the advanced technology, however, creates adverse distributional effects.

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1 Introduction

Hopenhayn-Melitz-type models of heterogeneous producers have been widely used to analyze the behavior of firms engaged in international trade. Smallholder producers in developing countries, however, are among those who depend most on international markets and suffer most from global and local climate change impacts. Hence, a clearer theoretical picture of smallholder producers' behavior in the climate change context is required. Nonetheless, Hopenhayn-Melitz-type models have not yet been used to study the market entry and technology choice of smallholder producers and to derive socially sensitive policy solutions. To fill this gap, this article introduces a new Hopenhayn-Melitz-type model, tailored to the theoretical and numerical analysis of development policy. It addresses the question: how can policy makers support the technology adoption of smallholders in rural areas of developing countries facing (climate change-related) shocks in a sustainable and socially sensitive way?

Smallholders in the agricultural sector of developing countries face local and international competition and price pressure. At the same time, their economic activity is vulnerable to shocks and creates environmental externalities. The adoption of advanced technologies and corresponding policy support may resolve or at least mitigate this dilemma.

On the one hand, climate change will exacerbate economic pressure by extending and intensifying water shortages, floods and storms with repercussions on agricultural production and goods markets. On the other hand, agricultural production consumes scarce water, pollutes the ground water with fertilizers or pesticides and occasionally destroys forests. Consequently, this article attempts to resolve the dilemma of smallholders' vulnerability to climate change and negative environmental external effects of production by searching for feasible economic policy solutions.

Feasible economic policy solutions will likely draw on advanced technologies that produce a given output with reduced input and hence less environmental harm. Hence, this analysis particularly seeks new insights into the interaction between vulnerability to climate change and technology use as an adaptation measure. Often, advanced technologies exist but are not widely utilized in developing countries, especially among poor smallholders in remote rural areas, for example, because of poverty, financial barriers, lack of information or insufficient infrastructure. Similarly, smallholders often lack knowledge about the efficient use of technologies. Thus, the social benefits of technologies might be neither completely perceived nor completely exploited.

Against this background, this article investigates technology adoption and production of a homogeneous good by heterogeneous producers (smallholders) and the corresponding market equilibrium. Similar to Just and Zilberman (1988), the article evaluates policy options for supporting the utilization of advanced technologies and reducing inequality while reducing environmental externalities and the vulnerability to climate change as novel aspects. The policies under examination are an output subsidy, an eco-certificate, an environmental tax on the production input, a fixed subsidy for using the advanced technology, productivity-enhancing training for smallholders and a market entry subsidy. These policies are intended to improve smallholders' livelihood and reduce their vulnerability to climate change. They are expected to be relevant for decision makers located in developing countries as well as agencies located in industrialized countries providing foreign aid and technological assistance.

This endeavor requires a new economic model that can be applied to the analysis of technology adoption and economic policy in various contexts beyond the scope of this article. To this end, a new Hopenhayn-Melitz-type partial equilibrium model of heterogeneous producers (smallholders) using one of two available types of technology will be set up. Producers can choose one of three options: they can stay out of the market, enter the market and produce with a simple technology or produce with an advanced technology. The advanced technology features higher efficiency in terms of productivity and negative environmental effects than the simple technology. However, it also creates higher fixed costs. Climate change effects are represented in an aggregate way as changes in the world market output price or the available amount of the aggregate production input factor (including arable land and water) or in the output (yield). Similarly, the degree of negative external environmental effects (via water, fertilizer and pesticide use) is assumed to be proportional to the utilized amount of the production input factor.

The model merges three strands of model development. The first strand is the literature addressing agricultural production functions. The empirical literature debates whether there are increasing or decreasing returns to scale in agriculture. Empirical evidence is in favor of constant or decreasing returns to scale (Bardhan 1973; Townsend, Kirsten, and Vink 1998; Sheng et al. 2015). There is evidence from developing countries that the extension of the working force is constrained by the family size (Eastwood, Lipton, and Newell 2010; Bloom et al. 2013); thus, the employment of hired workers beyond the engagement of family members likely results in extraordinary costs and hence decreasing returns to scale. Another possible explanation for decreasing returns is the fragmentation of land together with a restricted land market (e.g., in Vietnam). As an advancement of this literature, the new model is able to explain the fragmentation of total production of a homogeneous good into a number of smallholders via decreasing returns to scale in the production of each smallholder.

The second strand in the literature describes the size distribution of producers (Sunding and Zilberman 2001). Threshold models of technology diffusion assume that producers (farmers) differ in their production size and that more advanced and more profitable technology creates fixed costs. As a result, a minimum farm size for the adoption of the more advanced technology will emerge. If the fixed costs decline or the profitability increases over time due to learning by doing, farmers will subsequently adopt the advanced technology, resulting in a typical S-shaped diffusion process (Sunding and Zilberman 2001). Different from this literature, the following analysis will derive technology adoption and the size distribution by drawing on models with heterogeneous firms (Hopenhayn 1992; Melitz 2003).

Thus, the third strand in the literature builds on Hopenhayn (1992) and Melitz (2003). Firm heterogeneity has been intensively used to study the effects of international trade, in particular, and market structure, in general (Berry and Reiss 2007; Foster, Haltiwanger, and

Syverson 2008; Syverson 2011). It has been combined with endogenous technical progress and technology diffusion to identify the effect of firm heterogeneity and international trade on economic growth (Baldwin and Robert-Nicoud 2008; Wu 2015; Sampson 2016). In agricultural economics, firm heterogeneity has been studied to identify drivers of trade (Kancs and Ciaian 2010) and to determine the optimal design of environmental regulation (Doole 2010). Different from this literature, the new Hopenhayn-Melitz model presented in the following describes producers' technology choice in the context of development policy and climate change.

Similar to previous Melitz models, our new model features an endogenous mass of heterogeneous producers (smallholders) that differ in their productivity. Previous models usually assume product differentiation and love-of-variety. This approach, however, provides an inadequate explanation for market fragmentation in the production of homogeneous agricultural goods in developing economies. Hence, as a new aspect introduced in our model, the combination of decreasing returns to scale and heterogeneity in producers' productivity explains the existence of a large number of producers with different economic sizes, despite the production of a homogeneous good. In contrast to previous models, producers choose one of the three abovementioned options depending on endogenously emerging productivity threshold points separating the three options. Consequently, climate change or economic policy alter not only endogenous prices and quantities but also these thresholds, which induces technology adoption or market exit and, hence, changes in the mass of producers utilizing the simple and the advanced technology. This fact allows us to study the effects of climate change and economic policy as well as their interaction.

The theoretical model solution derives new mechanisms. For the most productive smallholders (above an upper productivity threshold), the high fixed costs of the advanced technology pay off because they produce at a large scale. The least productive smallholders (below a lower productivity threshold) cannot operate profitably and thus leave the market. Smallholders with productivities between the two thresholds choose the simple technology with lower fixed costs and produce a smaller amount than the most productive producers.

The policy analysis does not derive the welfare-maximizing first-best optimum and the corresponding first-best instruments to remedy explicit market imperfections, because these mechanisms are well understood (e.g., how to set a Pigou tax). Instead, it disentangles the complex effects of climate change and economic policies to consult policy makers who strive for a balanced trade-off between conflictive social (distributional) and environmental (technological) outcomes within a realistic imperfect economy with insufficient empirical information about the magnitudes of social and environmental effects (and hence the first-best). The theoretical comparative static analysis demonstrates how the model equilibrium (including the thresholds) adjusts to external shocks and policies. It shows, for instance, that producer training incentivizes the adoption of the advanced technology and market entry. Consequently, total resource use increases despite reduced individual resource use.

The new model is applicable to different markets and technologies. For a first numerical application, we consider coffee production in Vietnam. Although Vietnam is a low-income country[1], it is the world's second largest coffee producer after Brazil. While coffee is a highly (though not completely) homogeneous good, coffee producers vary in size and productivity. Based on this fact, they invest particularly in irrigation technologies. A conventional irrigation system (surface/basin irrigation) can be installed at low cost but requires large amounts of water and fertilizer for coffee production, which causes relatively high input costs for the coffee producer and for society in terms of adverse environmental effects. An advanced irrigation system (drip irrigation) creates higher initial costs but enables more productive operation with less water and fertilizer use.

Few economic studies have analyzed coffee production in Vietnam to date. Luong and Tauer (2006) specify a real option model to identify coffee prices for the entry and exit of producers with specific variable and total costs. In an empirical study on the efficiency of

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[1] Referring to gross domestic products per capita in 2013, Vietnam is listed at position 137 of 184 countries (World Development Indicators, `http://data.worldbank.org/data-catalog/world-development-indicators`).

coffee production in Vietnam, Rios and Shively (2006) obtain two results with relevance for the following analysis: first, productivity is an important determinant of farm size, and second, the type of irrigation system installed is of crucial relevance for the success of the farm. Ha and Shively (2008) find econometrically that Vietnam's coffee producers react to falling coffee prices by changing input patterns and changing crops. They show that the reaction depends on the producer's business size because small businesses have limited adaptation possibilities. Consequently, a portfolio of policy instruments is required that can be adjusted to the specific characteristics of producer categories. The numerical model application presented in this article will build on these empirical insights.

The scenario simulation results show, for instance, that the employment effects of climate change can be substantially larger than the direct impact of climate change. They also show that moderate technology support is sufficient to induce the replacement of the simple by the advanced technology. Climate change effects and technology adoption processes, however, imply a long-run time perspective of the numerical model.

The article proceeds as follows. Section 2 sets up and analyzes the theoretical model. Based on this, Section 3 derives propositions about the effects of climate change and policy intervention. Section 4 calibrates the model to the Vietnamese coffee production sector and evaluates the previous propositions. Section 5 discusses the results. Section 6 concludes.

2 Model

This section details the theoretical model, motivates the assumption of decreasing returns to scale, defines the production factors and derives the scale of production. This section closes with the determination of the dynamic market equilibrium.

Let us consider a homogeneous (agricultural) good with a given price determined by the world market. In the economy under examination, the good is produced by a large number of small producers that are supposed to be smallholders, in other words, farmers owning a limited area of land and mainly relying on the family with respect to labor contributions (and capital ownership). Similar to Hopenhayn (1992) and Melitz (2003), we assume that the producers are heterogeneous in their productivity. The profitability of inputs depends on the productivity of each producer; thus, the amount of inputs used by the producer is a function of her/his productivity.

The decision process of the producer consists of two steps. In the first step, the producer decides on the relative shares of the inputs to employ. In the second step, she/he decides on the absolute quantity of the aggregate input bundle to employ. This division is meaningful since we assume the production to be homothetic. In the following, we will focus on the second step (in Section 2.3), while the Appendix details the first step.

2.1 Technology options

Ex ante, producers can choose between three options: They can decide to stay out of the market without producing. If they decide to produce, they need to choose one of two types of technology, a simple technology S or an advanced technology A. The technology choice has two implications. First, the advanced technology creates higher fixed costs than the simple technology, i.e., $f_A > f_S$. Second, the advanced technology provides a higher efficiency than the simple technology, i.e., $\eta_A > \eta_S$. Hence, A produces a given output quantity with a lower input quantity than S. Because the input causes environmental harm (proportional to the input volume), A also features better environmental efficiency than S (see Section 3.2).

2.2 Production function

In markets with product varieties, consumers are typically characterized by “love of variety.”[2] In the presence of product varieties, even very productive producers cannot monopolize the market because the varieties of other producers are valued (and purchased accordingly) for

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[2] They can overcome decreasing marginal utility of consumption by extending the scope of consumed goods, which creates a utility gain in addition to consuming larger quantities of each good.

their distinctness. Consumers' love of variety does not explain, however, why a homogeneous agricultural product such as coffee, wheat or rice is produced by a large number of small producers. If there are increasing returns to scale in such a market, the most productive producers would quickly capture the entire market. However, a large number of producers with different economic sizes can be explained by combining decreasing returns to scale with heterogeneity in producers' productivity. This approach will be chosen in the following.

Whether returns to scale in agricultural production are increasing, constant or decreasing appears to be difficult to prove with general validity (Assuncao and Braido 2007; Vollrath 2007). Nonetheless, empirical evidence points to constant or decreasing returns to scale (Bardhan 1973; Townsend, Kirsten, and Vink 1998; Sheng et al. 2015). In developing countries, one reason is the difficulty in hiring workers beyond family members (Bloom et al. 2013). In addition, "hired labor supervision costs tend to favor family farming" (Eastwood, Lipton, and Newell 2010). Another possible explanation is the fragmentation of the available land (Van Hung, MacAulay, and Marsh 2007). In Vietnam, for example, land cannot be owned, but land-use rights can be traded (Do and Iyer 2008), which implies that extending the farm size is difficult but possible. Empirical evidence confirms that whenever land is transferred, it is taken over by more productive farmers (Deininger and Jin 2008).

In our model, producers employ an aggregate production input factor l including labor, land, water and capital (see Appendix A for the rationale behind this aggregate). Let individual production output be given by the function

$$y_i = \eta_i \varphi l^{\theta} \ , \tag{1}$$

where η_i is the deterministic technology-specific efficiency, whereas φ is the probabilistic producer-specific productivity. $\theta < 1$ reflects decreasing returns to scale.

2.3 Producer optimization

Let us recall the continuum of small producers. Having entered the market, the producers first choose between the simple technology S and the advanced technology A. This decision determines the level of fixed costs and the production efficiency. The producers then choose the output quantity y_i. The optimal output quantity and the resulting total production costs will be determined via profit maximization.

Producers sell to the international market (via intermediate traders that are not explicitly modeled) at the international market price q. Because each producer has a negligible influence on q, q is treated as exogenous. Producers employ the input l, while the endogenous price for l is denoted p. Production with technology i creates technology-specific fixed costs f_i. Writing the profit function as $\Pi_i(\varphi) = qy_i - pl = q\eta_i\varphi l^\theta - f_i - pl$ for $i \in \{S, A\}$ and maximizing profits, $\max_l \Pi_i(\varphi)$, yields the optimal technology-specific amount of the input:

$$l_i^*(\varphi) = \left(\frac{q\eta_i\varphi\theta}{p}\right)^{\frac{1}{1-\theta}} \quad . \tag{2}$$

The optimal input amount $l_i^*(\varphi)$ depends positively on the output price, the efficiency of the technology and the producer's productivity. It depends negatively on the input price. By inserting $l_i^*(\varphi)$ into the production function, equation (1), we obtain the optimal output quantity y_i^*. By inserting it into the profit function, we obtain the maximum profit

$$\Pi_i^*(\varphi) = \left(\frac{q\eta_i\varphi}{p^\theta}\right)^{\frac{1}{1-\theta}} \tilde{\theta} - f_i \ , \tag{3}$$

where $\tilde{\theta} = \theta^{\frac{\theta}{1-\theta}} - \theta^{\frac{1}{1-\theta}} > 0$. With $\theta < 1$, profits increase more than proportionally in productivity φ. Intuitively, more productive producers employ more of the input l, i.e., they are larger, such that their absolute revenues $q\eta_i\varphi l^\theta$ are more than proportionally higher than those of less productive producers, while the fixed costs f_i are constant, and the input costs pl_i rise linearly in l.

2.4 Technology choice

Having determined the optimal input amount for a given technology, we can now compare the profits obtained from production with the two different technologies. First, we determine the level of productivity φ_i' at which producers make zero profits with technology i. From $\Pi_i^*(\varphi_i') = 0$, we obtain

$$\varphi_i' = \left(\frac{f_i}{\tilde{\theta}}\right)^{1-\theta} \frac{p^\theta}{q\eta_i} . \tag{4}$$

As long as $\varphi_S' \geq \varphi_A'$, it is never optimal to use the simple technology. We therefore assume that the difference in investment costs $f_A - f_S$ is so large that $\varphi_S' < \varphi_A'$. This restriction of the parameter values of f_A and f_S implies that there is at least one producer choosing the simple technology. Graphically, it means that the profit curve of the simple technology crosses the zero-profit line at a point φ_S' left of φ_A'; see Figure 1, where $\Pi_S(\varphi)$ depicts the profit curve of the simple technology and $\Pi_A(\varphi)$ of the advanced technology as a function of producers' productivity φ.

Let us define φ'' as the productivity level above which it is profitable to invest in the advanced technology. From $\Pi_A^*(\varphi'') = \Pi_S^*(\varphi'')$, we then obtain

$$\varphi'' = \frac{p^\theta}{q} \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{1-\theta} . \tag{5}$$

As shown in Figure 1, the threshold points are crucial for the technology choice of profit-maximizing producers. Producers with a productivity $\varphi < \varphi_S'$ do not produce at all because they would not be able to make (positive) profits. Producers with a productivity $\varphi_S' \leq \varphi < \varphi''$ choose the simple technology because it is more profitable than the advanced technology given their small business size and output quantity. The $\Pi_S(\varphi)$ curve is located above the $\Pi_A(\varphi)$ curve at small productivities φ. Producers with a productivity $\varphi'' \leq \varphi$, in contrast, choose the advanced technology because it is more profitable given their large business size and output quantity.

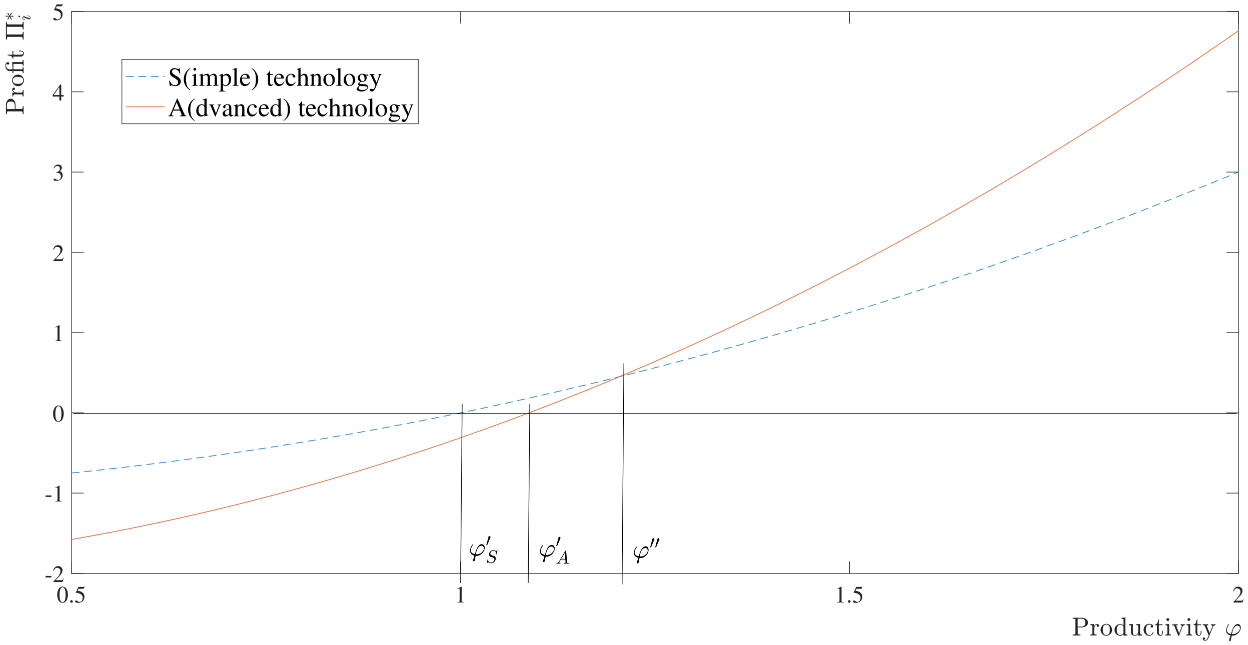

Figure 1: The maximum profit Π_i^* as a function of productivity φ and technology S/A (with $\eta_a = 1.3$, $f_A = 2$ and the remaining parameter values normalized to unity).

2.5 Market entry

To represent endogenous free market entry and exit based on producer heterogeneity, we follow Hopenhayn (1992) by assuming that firms draw their productivity level from a probability distribution after market entry. Ghironi and Melitz (2005) argue that the Pareto distribution is a suitable distribution because it generates an empirically plausible distribution of business sizes. We thus assume the following probability distribution:

$$g(\varphi) = k\frac{\varphi_m^k}{\varphi^{k+1}} \ . \tag{6}$$

where φ_m is the minimum of all possible productivity draws. For the shape parameter k, we assume that $k > \frac{1}{1-\theta}$; thus, the variance of business sizes is finite.

Based on the optimal strategies *after* market entry described previously (profit-maximizing choice of the technology, the input and output level), entrepreneurs decide whether to enter the market or not. Before entering the market, they do not know how productive they will actually be; therefore, they calculate expected profits based on the probability distribution of productivity and the threshold points for the technology choice derived in the previous section.

Expected profits can thus be expressed as

$$\begin{aligned} E[\Pi(\varphi, i(\varphi)] &= \int_{\varphi'_S}^{\varphi''} \Pi^*_S(\varphi) g(\varphi) d\varphi + \int_{\varphi''}^{\infty} \Pi^*_A(\varphi) g(\varphi) d\varphi \\ &= \left(\frac{p^\theta}{q}\right)^{-k} F_1(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m) \; . \end{aligned} \tag{7}$$

The expression $i(\varphi)$ simply reflects that the choice of technology i depends on productivity φ as described in Section 2.4. Appendix B.1 derives this expression in detail. Notice that

$$\begin{aligned} F_1(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m) &= \varphi_m^k k \left(1 - \frac{1-\theta}{1-(1-\theta)k}\right) \tilde{\theta}^{(1-\theta)k} \cdot \\ & \left[\frac{(f_A - f_S)^{1-(1-\theta)k}}{\left(\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}} + \frac{f_S^{1-(1-\theta)k}}{\left(\eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}} \right] \end{aligned} \tag{8}$$

is a function of parameters and does not contain any endogenous variable.

If expected profits exceed the market entry cost f_e, more entrepreneurs will enter the market until expected profits are exactly equal to the entry cost f_e,

$$E[\Pi(\varphi, i(\varphi)] = f_e \; . \tag{9}$$

By inserting (7) into (9), we obtain the equilibrium price of the aggregate input as

$$p = \left(\left(\frac{f_e}{F_1}\right)^{-\frac{1}{k}} q\right)^{\frac{1}{\theta}} \; . \tag{10}$$

2.6 Factor market clearance

We now turn to the market for the aggregate input factor. Equation (10) determines the equilibrium price paid by producers, where p is given as the gross input price paid by producers. As the input can be subject to taxes τ, the net price for the input $\tilde{p}$ can be written as $\tilde{p} = (1-\tau)p$. We assume that the supply of the total aggregate input increases in the input price with the elasticity $0 < \varepsilon$.

$$L = L_0 \tilde{p}^{\varepsilon} = L_0 \left((1-\tau)p\right)^{\varepsilon} \ , \tag{11}$$

where L_0 is the total benchmark amount of the input supplied at a net price of one.

Input demand is given by aggregate input use. To determine such demand, we first consider the distribution of productivity across those producers who stay in the market. Since only entrepreneurs with productivity $\varphi'_S < \varphi$ produce, the distribution of active producers will be given as

$$\mu(\varphi) = \begin{cases} \frac{g(\varphi)}{1-G(\varphi'_S)} & \text{if } \varphi \geq \varphi'_S \ , \\ 0 & \text{otherwise} \ . \end{cases} \tag{12}$$

The endogenous mass of actively operating incumbents (in short, the total mass of producers), similar to the number of firms in other Melitz-type models, will in the following be denoted as M.

The total aggregate input demand is thus given by

$$L = \int_{\varphi'_S}^{\varphi''} l^*_S(\varphi) M \mu(\varphi) d\varphi + \int_{\varphi''}^{\infty} l^*_A(\varphi) M \mu(\varphi) d\varphi \ . \tag{13}$$

As shown in Appendix B.2, we obtain

$$L = \frac{M}{p} F_2(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m) \ . \tag{14}$$

Notice that, similar to F_1,

$$F_2(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m) = \left(\frac{f_S}{\eta_S^{\frac{1}{1-\theta}}}\right)^{(1-\theta)k} k\frac{1-\theta}{(1-\theta)k-1}\frac{\theta^{\frac{1}{1-\theta}}}{\tilde{\theta}} \cdot \left[\frac{(f_A - f_S)^{1-(1-\theta)k}}{\left(\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}} + \frac{f_S^{1-(1-\theta)k}}{\left(\eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}}\right] \quad (15)$$

is a function of parameters and does not contain any endogenous variable.

By equalizing demand and supply, we obtain

$$M = L_0 p^{1+\varepsilon}(1-\tau)^{\varepsilon} F_2^{-1} \; . \quad (16)$$

The mass of producers using the simple technology is given by

$$M_S = \frac{1}{1-G(\varphi'_S)}\int_{\varphi'_S}^{\varphi''} Mg(\varphi)d\varphi = M\frac{G(\varphi'') - G(\varphi'_S)}{1-G(\varphi'_S)} \; . \quad (17)$$

Similarly, the mass of producers using the advanced technology is given by

$$M_A = M\frac{1-G(\varphi'')}{1-G(\varphi'_S)} \; . \quad (18)$$

Because M_S and M_A are not relevant for the following analysis, their calculations are not further detailed.

As shown in Appendix B.3, the total output of the economy reads

$$Y = \frac{M}{q}\theta^{\theta} F_2(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m) \; . \quad (19)$$

Inserting (10) into (16) and (16) into (19) yields

$$Y = L_0 \theta^{\theta} (1-\tau)^{\varepsilon} \left(\frac{f_e}{F_1} \right)^{-\frac{1+\varepsilon}{k\theta}} q^{\frac{1+\varepsilon}{\theta}-1} \; . \tag{20}$$

2.7 Model equilibrium

The described model consists of an equation system with eight endogenous variables: first, at the economy-wide level, the input price p, the productivity threshold for entering the market φ'_S and the productivity threshold for adopting the advanced technology φ''; second, at the individual producer level, the optimal input quantity l_i^*, the corresponding optimal output quantity y_i^* and the resulting maximum profit π_i^*; and third, at the aggregate economy-wide level, the total mass of producers M, the total input factor quantity L and the corresponding total output quantity Y.

The central equation of the model is the free-entry condition, equation (10), which yields the input price. Inserting the input price into the market clearing condition (16), the equilibrium conditions for the thresholds, equations (4) and (5), and the producers' optimality condition (2) yields the remaining key variables. While equations (1) and (3) provide the optimal individual output quantity and the maximum profit, the total input and output quantities are obtained from equations (14) and (20).

Based on this model solution, additional variables can be derived. For example, using the two thresholds and the total mass of producers, the mass of producers using the simple technology and the mass of producers using the advanced technology can be calculated with equations (17) and (18).

3 Analysis

Having solved the model, we are now able to analyze the effects of climate change, economic policies and their interactions in a comparative static analysis.

3.1 Climate change

Climate change is expected to affect worldwide production negatively via weather extremes, especially in developing regions near the equator. In the following, we will consider three cases. For mathematical clarity and tractability, we treat the three considered cases separately. In reality, the considered cases can coincide. To represent this fact, the effects of the three cases need to be considered jointly. The overall net effect will then depend on the relative strength of the three subeffects. We assume that the producers anticipate these exogenous climate change damages in their profit maximization calculus as expected values.

Price change

Weather shocks will reduce production and drive up the world market price of the affected production good.[3] If the producers considered in the model are not affected while other world regions are affected, the producers under consideration will benefit from the higher world market price for their output good. This case is analyzed first.

Proposition 1 *An increase in the world market price for the output* q *causes an increase in the input price,* $\frac{dp}{dq} > 0$*, the mass of producers,* $\frac{dM}{dq} > 0$*, total output,* $\frac{dY}{dq} > 0$*, and total input,* $\frac{dL}{dq} > 0$*. Individual producers use less input,* $\frac{dl_i^*}{dq} < 0$*. The technology choice and individual profits remain unaffected,* $\frac{d\varphi_S'}{dq} = \frac{d\varphi''}{dq} = \frac{d\Pi_i^*}{dq} = 0$*.*

Proof: The result for total output follows from equation (20). The result for the input price follows directly from equation (10). Inserting this into equations (2), (4), (5), (11) and

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[3] Even though such shocks occur occasionally, they will affect the average price observed over a longer period of time, such as one year.

(16) yields the remaining results. Inserting (10) into (3) shows that the effect of higher input prices and higher output prices cancel out; thus, individual profits remain stable. □

The increase in the world market price causes more producers to enter the market. This increases the demand for the input and thus raises the input price. Market incumbents react to the higher input price by lowering their production. For incumbents, the effects of higher input and output prices thus cancel out; thus, profits remain constant. The market entrants, however, overcompensate the production loss of the incumbents; therefore, total output increases.

Corollary 1 *Let the input supply be inelastic to price changes,* $0 < \varepsilon < 1$*. Then, the total absolute output* Y *increase due to a rising output price* q *(i) decreases in taxation,* $\frac{d\frac{dY}{dq}}{d\tau} < 0$*, (ii) decreases in the cost of the advanced technology,* $\frac{d\frac{dY}{dq}}{df_A} < 0$*, (iii) increases in the productivity of the advanced technology,* $\frac{d\frac{dY}{dq}}{d\eta_A} > 0$*, and (iv) decreases in the market entry cost,* $\frac{d\frac{dY}{dq}}{df_e} < 0$.

Proof: We know from equation (20) that $\frac{dY}{dq} = L_0\theta^\theta(1-\tau)^\varepsilon \left(\frac{f_e}{F_1}\right)^{-\frac{1+\varepsilon}{k\theta}} \left(\frac{1+\varepsilon}{\theta}-1\right) q^{\frac{1+\varepsilon}{\theta}-2} > 0$. (i) follows directly from $\frac{dY}{dq}$. (ii) Because of $\frac{1}{1-\theta} < k$, we know that $\frac{dF_1}{df_A} < 0$. Using $\frac{d\frac{dY}{dq}}{dF_1} > 0$, the result follows. (iii) From equation (8), we obtain $\frac{dF_1}{d\eta_A} > 0$. Again, using $\frac{d\frac{dY}{dq}}{dF_1} > 0$, the result follows. (iv) follows directly from $\frac{dY}{dq}$. □

An economy with less taxation τ, a lower market entry cost f_e, lower fixed costs of the advanced technology f_A or a higher productivity of the advanced technology η_A produces more output such that the variation in the output price has a larger effect.

Input reduction

In the second case, climate change-related weather shocks cause detrimental domestic effects, such that the producers considered in the model are negatively affected, while the world market price stays stable because the domestic producers have no international market power.

Extreme weather events can affect producers, particularly farmers (smallholders), in various ways. Droughts or floods can – at least temporarily – destroy part of the arable land. Droughts can exacerbate water scarcity, and water is essential for farming. Floods and storms can damage production facilities and so forth. In the model, we summarize these effects as a reduction in the total available amount of the aggregate input factor L_0 including land, water and other inputs that are effectively available for production.[4]

Proposition 2 *A decrease in the total available amount of the aggregate input* L_0 *decreases the equilibrium amount of inputs used,* $\frac{dL}{dL_0} > 0$*. Further, it causes the mass of producers and total output to decrease,* $\frac{dM}{dL_0} > 0$ *and* $\frac{dY}{dL_0} > 0$*. The input price, individual profits, the input of individual producers and the technology threshold points remain unaffected,* $\frac{dp}{dL_0} = \frac{d\Pi_i^*}{dL_0} = \frac{dl_i^*}{dL_0} = \frac{d\varphi_S'}{dL_0} = \frac{d\varphi''}{dL_0} = 0$.

Proof: The result for the mass M directly follows from equations (16). Equation (10) shows that the input price is not affected. Given the unchanged input price, we obtain the result for output Y directly from (20). Because L and M do not influence equations (3), (9), (2), (4) and (5), the respective variables do not change. □

Intuitively, in the short term, a decreasing input supply causes a rising input price. In the long term, the increasing input price forces producers to leave the market, which in turn decreases the input price until the former price level has been restored.

Corollary 2 *Let the input supply be inelastic to price changes,* $0 < \varepsilon < 1$*. Then, the absolute decrease in total output* Y *due to a decline in the total aggregate input* L_0 *(i) decreases in taxation,* $\frac{d\frac{dY}{dq}}{d\tau} < 0$*, (ii) decreases in the cost of the advanced technology,* $\frac{d\frac{dY}{dL_0}}{df_A} < 0$*, (iii) increases in the productivity of the advanced technology,* $\frac{d\frac{dY}{dL_0}}{d\eta_A} > 0$*, (iv) decreases in the market entry cost,* $\frac{d\frac{dY}{dL_0}}{df_e} < 0$*, and (v) increases in the (world market) output price,* $\frac{d\frac{dY}{dL_0}}{dq} > 0$.

Proof: We know from equation (20) that $\frac{dY}{dL_0} = \theta^\theta(1-\tau)^\varepsilon \left(\frac{f_e}{F_1}\right)^{-\frac{1+\varepsilon}{k\theta}} q^{\frac{1+\varepsilon}{\theta}-1} > 0$. (i) follows directly from $\frac{dY}{dL_0}$. (ii) From equation (8), we obtain $\frac{dF_1}{d\eta_A} > 0$. Using $\frac{d\frac{dY}{dL_0}}{dF_1} > 0$, the

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[4] The exogenous parameter L_0 reflects the general availability of inputs used at a net price of one ($\tilde{p} = 1$), while the endogenous variable L is the aggregate input amount used in equilibrium.

result follows. (iii) Because of $\frac{1}{1-\theta} < k$, we know that $\frac{dF_1}{df_A} < 0$. Again, using $\frac{d\frac{dY}{dL_0}}{dF_1} > 0$, the result follows. (iv) follows directly from $\frac{dY}{dL_0}$. (v) follows from $\frac{dY}{dL_0}$ with $\varepsilon > 0$ and $\theta < 1$. $\square$

As in Corollary 1, in an economy producing more output, any input reduction causes a larger absolute output loss.

Output reduction

In the third case, climate change-related weather shocks cause again detrimental domestic effects, such that the producers under consideration are negatively affected, while the world market price stays constant.

Extreme weather events such as droughts or floods may also destroy part of the output, particularly part of the harvest. Different from the second case, now, we keep the aggregate input constant, i.e., we assume that production inputs and facilities are not affected by climate change. Let us further assume that producers anticipate climate change damages at an expected rate α; thus, for example, 40% of the harvest is deemed to be destroyed. Without geographic heterogeneity[5] of producers or heterogeneous adaptation to climate change, all producers will ex ante expect the same damage rate α at the individual level. While in equation (1), y_i is endogenous, η_i is exogenous and thus varied by α.

Proposition 3 *Let both productivities η_A and η_S change by the same factor $\alpha < 1$. Then, the input price, the total input, the total output and the mass of producers will decrease, $\widehat{p} < 0$, $\widehat{L} < 0$, $\widehat{Y} < 0$ and $\widehat{M} < 0$. Individual inputs increase, $\widehat{l_i^*} > 0$. The thresholds and profits remain unaffected, $\widehat{\varphi_i'} = \widehat{\varphi''} = \widehat{\Pi_i^*} = 0$.*

Proof: Consider a decrease in productivity from an initial level of η_A and η_S to $\bar{\eta}_S = \alpha\eta_S$ and η_A to $\bar{\eta}_A = \alpha\eta_A$ with $\alpha < 1$. Then, we obtain $F_1(\bar{\eta}_S, \bar{\eta}_A) = \alpha^k F_1(\eta_S, \eta_A)$ from (8) and $F_2(\bar{\eta}_S, \bar{\eta}_A) = F_2(\eta_S, \eta_A)$ from (15). Using (10), it follows that $p(\bar{\eta}_S, \bar{\eta}_A) = \alpha^{\frac{1}{\theta}} p(\eta_S, \eta_A)$. Since $\alpha < 1$ and $\frac{1}{\theta} > 1$, we have $p(\bar{\eta}_S, \bar{\eta}_A) < p(\eta_S, \eta_A)$. Using the result for the input price, the

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[5] With geographic heterogeneity, for example, those residing at a river would face a higher risk of flooding.

results for individual inputs, profits and total input use follow directly from (2), (3) and (11), respectively. Using (20), it follows that $Y(\bar{\eta}_S, \bar{\eta}_A) = \alpha^{\frac{1+\varepsilon}{\theta}} Y(\eta_S, \eta_A)$, and using (16), we find $M(\bar{\eta}_S, \bar{\eta}_A) = \alpha^{\frac{1+\varepsilon}{\theta}} M(\eta_S, \eta_A)$. Since the exponents of α are larger than one, Y and M will decrease. Again, using the input price, we obtain $\varphi_i'(\bar{\eta}_S, \bar{\eta}_A) = \varphi_i'(\eta_S, \eta_A)$ from (4) and $\varphi''(\bar{\eta}_S, \bar{\eta}_A) = \varphi''(\eta_S, \eta_A)$ from (5). $\square$

The expected climate change damage reduces the attractiveness of production. As a result, less producers enter the market ex ante, while those that are in the market produce less with reduced input use. This drives down the input price, which is beneficial for the surviving companies: they purchase more of the input and make higher profits. The relative attractiveness of the two technologies remains unchanged such that the thresholds stay as they were previously.

Corollary 3 *Let the input supply be inelastic to price changes,* $0 < \varepsilon < 1$. *Then, the total absolute output* Y *decrease due to a decline in productivity (i) decreases in taxation,* $\frac{d\widehat{Y}}{d\tau} < 0$, *(ii) decreases in the cost of the advanced technology,* $\frac{d\widehat{Y}}{df_A} < 0$, *(iii) increases in the productivity of the advanced technology,* $\frac{d\widehat{Y}}{d\eta_A} > 0$, *and (iv) decreases in the market entry cost,* $\frac{d\widehat{Y}}{df_e} < 0$.

Proof: From (20), we have $\frac{dY}{d\tau} < 0$ and $\frac{dY}{df_e} < 0$. The results (i) and (iv) follow. Further, we have $\frac{dY}{dF_1} > 0$. Using $\frac{dF_1}{df_A} < 0$, result (ii) follows. Using $\frac{dF_1}{d\eta_A} > 0$, result (iii) follows. $\square$

Following the same intuition as before, favorable economic conditions enhance total output, which increases the total damage caused by climate change.

3.2 Economic policy

In a situation of poverty and insufficient technology adoption, climate change can increase the pressure on the government for policy intervention. Let us assume that (agricultural) production creates negative environmental externalities; for example, it consumes scarce water, pollutes the water with fertilizers or pesticides and occasionally destroys forests. To address this market failure, an environmental (Pigouvian) input tax will be applied.

A government considering poverty and rural development (or the next election), however, may not want to create a tax burden too heavy for producers, especially poor farmers. Thus, it may prefer to subsidize output or market entry, support the use of the more productive advanced technology or raise productivity via producer training. The government may consider that the use of the advanced technology or producer training increase the output-to-input ratio and hence the ratio of the output to environmental harm.

In this respect, let us assume that the advanced technology exists but is insufficiently used by the producers, for example, because of poverty, financial barriers, lack of information or insufficient infrastructure. Let us furthermore assume that the producers lack knowledge about the efficient use of either the advanced or both technologies and have insufficient access to information.

The subsidies create negative budgetary effects for the government and hence a tax burden to finance them, whereas the taxes create revenues and hence positive budgetary effects. The budgetary effects of the policies will be summarized in Table 1 and discussed in Section 5.1 together with other social and environmental effects.

Input tax

First, the government intends to internalize, or at least reduce, the negative environmental effects caused by the production input via an environmental (Pigouvian) tax on the aggregate input l at the rate τ as introduced previously. Let us further assume that the total social damage is proportional to l at the individual producer level and to L at the economy-wide level, which implies that we neglect changes of the input structure within the aggregate input bundle l such that the aggregate input is homogeneous regarding its environmental effects. The choice of a technology i affects l but does not cause other environmental effects. Assuming that the marginal damage created by l is δ, then in the absence of other market imperfections the socially optimal (Pigouvian) tax rate will be $\tau^* = \delta$. Without loss of generality, one can assume that the tax rates examined in the following analysis fulfill this condition.

By imposing $\tau > 0$, the government may also introduce a (shadow) price for scarce resources included in L, for example, water is insufficiently priced, or forests are cleared to obtain land. A possible contribution of L to climate change is assumed to be negligible.

Proposition 4 *An increase in the input tax τ causes the mass of producers, the total supply of the aggregate input and total output to decrease, $\frac{dM}{d\tau} < 0$, $\frac{dL}{d\tau} < 0$ and $\frac{dY}{d\tau} < 0$. The input price, the input of individual producers, profits, and the thresholds remain unaffected, $\frac{dp}{d\tau} = \frac{dl_i^*}{d\tau} = \frac{d\Pi_i^*}{d\tau} = \frac{d\varphi_S'}{d\tau} = \frac{d\varphi''}{d\tau} = 0$.*

Proof: The results for L, M and Y follow directly from equations (11), (16) and (20), respectively. As τ and M do not influence equations (2), (3), (4) and (5) and (9), the respective variables do not change. $\square$

The tax raises production costs. As a consequence, a smaller number of producers are able to operate with positive profits, which reduces the total input quantity, although the individual input demands stay constant.

Output subsidy

A straightforward method of governmental support for producers (that may not be theoretically justified but follow a political calculus) is a subsidy for the output of all producers.

Corollary 4 *An output subsidy for both types of producers causes the input price to rise, $\frac{dp}{dq} > 0$, individual producers to decrease their input, $\frac{dl_i^*}{dq} < 0$, and more producers to enter the market, $\frac{dM}{dq} > 0$. The total output and input increase, $\frac{dY}{dq} > 0$ and $\frac{dL}{dq} > 0$. The technology choice and individual profits remain unaffected, $\frac{d\varphi_S'}{dq} = \frac{d\varphi''}{dq} = \frac{d\Pi_i^*}{dq} = 0$.*

Proof: An output subsidy increases the price perceived by each producer in the same way as an increase in the world market price. The proof is thus identical to that of Proposition 1. $\square$

Technology subsidy

Let us now assume that the government actively promotes the advanced technology. To this end, the government pays a subsidy for part of the technology-specific fixed costs f_A, either in the form of a grant or by providing a credit. Another option is the provision of information about the advanced technology, because lack of information is a typical problem in rural areas of developing countries that hinders technology adoption. Like the subsidy, this option creates costs for the government but reduces f_A, in this case by reducing the producers' information search costs. Without loss of generality, one can assume that f_A perceived by the producer exceeds the true (efficient) f_A^* because of investment or information barriers. Then, the socially optimal subsidy/support (i.e., the reduction of f_A) in the absence of other market imperfections will be equal to $f_A - f_A^*$. The following proposition, however, is valid for any extent of f_A's reduction.

Proposition 5 *A decrease in the fixed costs of producing with the advanced technology* f_A *causes the input price, the threshold point for the simple technology, the total output and input to increase,* $\frac{dp}{df_A} < 0$, $\frac{d\varphi'_S}{df_A} < 0$, $\frac{dY}{df_A} < 0$ *and* $\frac{dL}{df_A} < 0$. *It causes producers, who do not switch technology, to decrease their input,* $\frac{dl_i^*}{df_A} > 0$. *The profits of producers with the simple technology decrease,* $\frac{d\Pi_S(\varphi)}{df_A} > 0$. *The effects on the mass of producers* M*, the threshold between technologies* φ'' *and profits of producers with the advanced technology depend on the specific parameter values.*

Proof: Because of $\frac{1}{1-\theta} < k$, it is $\frac{dF_1}{df_A} < 0$. With equation (10), $\frac{dp}{df_A} < 0$ follows directly. Inserting this into equations (2), (3) and (4) yields $\frac{dl_i^*}{df_A} > 0$, $\frac{d\Pi_S(\varphi)}{df_A} > 0$ and $\frac{d\varphi'_S}{df_A} < 0$, respectively. Concerning M, consider equation (16), and note that $\frac{dF_2}{df_A} < 0$. Further, we have $\frac{\partial M}{\partial F_2} < 0$ and $\frac{\partial M}{\partial p} < 0$; thus, either effect could dominate. The same two effects in opposite directions occur for φ''. With $\frac{dF_1}{df_A} < 0$ and equation (20), we have $\frac{dY}{df_A} < 0$. $\frac{dL}{df_A} < 0$ follows from (11) with increasing p. From equation (3), it is clear that the price effect and the direct effect on technology cost go in different directions for technology A. $\square$

Figure 2 (b) in Appendix D illustrates the changes in the profits and the thresholds of both types of producers for the calibration introduced in Section 4.2 (Appendix C). The dashed lines depict the postpolicy situation.

A decrease in the fixed cost of installing the advanced technology eases the use of the advanced technology and hence raises overall productivity and production. This increases input demand and causes the input price to rise. Simple technology users suffer from this cost increase and the resulting intensified productivity pressure. As a consequence, some of them leave the market. The direction of the shift of the threshold between the technologies, however, is ambiguous. Advanced technology users benefit from the lower investment costs but suffer from the higher input price.

Producer training

We first consider the training of producers using the advanced technology. The socially optimal extent of training would equate the marginal cost of training and its social marginal benefit.

Proposition 6 *An increase in the productivity of the advanced technology* η_A *raises the input price, the total input, the threshold for producing with the simple technology technology and total output,* $\frac{dp}{d\eta_A} > 0$, $\frac{dL}{d\eta_A} > 0$, $\frac{d\varphi'_S}{d\eta_A} > 0$ *and* $\frac{dY}{d\eta_A} > 0$. *Producers using the simple technology demand less* $\frac{dl_S(\varphi)^*}{d\eta_A} < 0$ *and make lower profits* $\frac{d\Pi_S(\varphi)^*}{d\eta_A} < 0$. *For the mass of producers,* M, *the input of advanced producers* $l_A(\varphi)^*$, *profits of advanced producers,* $\Pi_A(\varphi)$ *and the threshold between technologies,* φ'', *the effects depend on the (relative) parameter values.*

Proof: Note that $\frac{dF_1}{d\eta_A} > 0$ and $\frac{dF_2}{d\eta_A} > 0$. With these inequalities, the results for total output and the input price follow directly from equations (10) and (20), respectively. Using the result for the input price, the outcomes for the input of simple producers, profits of simple producers, the total input and the threshold of the simple technology follow from (2), (3), (11) and (4), respectively. For the advanced producers, equations (2) and (3) show again the price effect and the direct effect going in opposite directions. By inserting (10) and (15) into equation (16), we see that the direct effect (via F_2) and the price effect work in opposite directions. $\square$

Figure 2 (c) in Appendix D illustrates the effects. The direct effect of an increase in η_A is to make the advanced technology more attractive, which reduces its threshold productivity. Yet, the larger input demand of advanced technology producers causes upward pressure on the input price, which renders the advanced technology less attractive, increasing its threshold. The net effect can point in either direction.

Despite the higher productivity, not only the total output but also the total input demand increases, which raises the input price and induces more input supply. This implies a Jevons paradox as studied by Schwerhoff and Wehkamp (2018) (see the explanations below).

Now, let all producers (incumbents and entrants) using either type of technology participate in the same type of training.

Corollary 5 *Let the input supply be inelastic to price changes,* $0 < \varepsilon < 1$, *and let both productivities* η_A *and* η_S *increase by the same factor* α. *Then, the input price, the total input, the output and the mass of producers will increase,* $\widehat{p} > 0$, $\widehat{L} > 0$, $\widehat{Y} > 0$ *and* $\widehat{M} > 0$. *Individual inputs decrease,* $\widehat{l_i^*} < 0$. *The thresholds and profits remain unaffected,* $\widehat{\varphi_i'} = \widehat{\varphi''} = \widehat{\Pi_i^*} = 0$.

Proof: The proof follows that of Proposition 3 with reversed signs. $\square$

Because of the higher productivity, more producers enter the market. Individually, they demand less input such that the input intensity of production decreases. Overall, the larger number of producers, however, demands more of the input, which raises the input price and induces additional input supply. This is a typical example of Jevons paradox (Schwerhoff and Wehkamp 2018), i.e., a rebound effect exceeding 100%, which implies a novel type of rebound effect via increased employment (activity) at the aggregate level. The higher input price also reduces individual profits. The productivities of the technologies relative to each other remain unchanged; thus, the thresholds stay as they were previously.

Eco-certificate

Next, we consider the effect of an eco-certificate. As the advanced technology uses inputs more efficiently than the simple technology, the amount of environmental harm (such as water pollution) per unit of production is lower. Eco-certification makes the improved environmental footprint transparent to consumers and allows for charging a higher price than for a corresponding conventionally produced good. Now the socially optimal price premium would reflect the marginal social benefit of the good produced with the advanced technology compared to the good produced with the simple technology.

Corollary 6 *The introduction of an eco-certificate, which provides a higher output price* $q_A = \beta q$ *with* $\beta > 1$ *for producers using the advanced technology, has exactly the same effect as an increase in* η_A *(see Proposition 6).*

Proof: Consider the profit function of a producer with the advanced technology given a technology-specific price q_A. It is $\Pi_A(\varphi) = q_A \eta_A \varphi l_A^\theta - f_A - pl = \beta q \eta_A \varphi l^\theta - f_A - pl = q \tilde{\eta}_A \varphi l_A^\theta - f_A - pl_A$, where $\tilde{\eta}_A = \beta \eta_A$. As the profit function is the basis for all decisions of the producers, the price increase has an identical effect to that of an increase in productivity. $\square$

Hence, the effects of eco-certification are described by Proposition 6.

Entry subsidy

Another policy option is financial support for reducing the market entry cost f_e to encourage more prospective producers to begin production. Another option is the provision of information about general production and management techniques that are required in this sector. Thus, without loss of generality, let us again assume that f_e perceived by the producers exceeds the true (efficient) f_e^* because of investment or information barriers. Then, the socially optimal subsidy (i.e., the reduction of f_e) in the absence of other market imperfections will be equal to $f_e - f_e^*$.

Proposition 7 *A decrease in the market entry cost f_e increases the input price, the mass of producers, the thresholds, the total output and the total input, $\frac{dp}{df_e} < 0$, $\frac{dM}{df_e} < 0$, $\frac{d\varphi'_S}{df_e} < 0$, $\frac{d\varphi''}{df_e} < 0$, $\frac{dY}{df_e} < 0$, $\frac{dL}{df_e} < 0$, while individual producers decrease their input, $\frac{dl_i^*}{df_e} > 0$ and profits, $\frac{d\Pi_i^*}{df_e} > 0$.*

Proof: The result for total output follows directly from equation (20). The result for the input price follows directly from equation (10). Inserting this into equations (2), (3), (4), (5), (16) and (11) yields the remaining results. □

Figure 2 (d) in Appendix D depicts the mechanism. A decrease in the cost of market entry makes market entry more attractive. The mass of producers and subsequently the output quantity expand. Hence, the demand for the input also increases so that the input price adjusts upwards. The higher input price incentivizes producers with low productivity to leave the market, because they cannot cover the higher (marginal) production costs anymore, and producers on the edge between technologies to switch to the simple technology.

3.3 Summary

Table 1 summarizes the climate change and policy effects and their interactions qualitatively. Changes in the climate change impact ($\frac{d\widehat{Y}}{d\Psi}$) are defined as changes in climate change-induced total output deviations ($d\widehat{Y}$) caused by policy intervention ($d\Psi$), as described by Corollaries 1 to 3. Changes in the state budget are caused by subsidy payments or tax revenues.

Table 1: Summary of climate change and policy effects

Prop./ Corol.	Policy/ shock	Param. change	Y	M	L	l_S^*	l_A^*	π_S^*	π_A^*	Climate impact	State budget
Climate change:											
P1	out. price	$q \uparrow$	+	+	+	−	−	=	=	/	=
P2	input	$L_0 \downarrow$	−	−	(−)	=	=	=	=	/	=
P3	output	$\eta_{A/S} \downarrow$	(−)	−	−	+	+	=	=	/	=
Environmental externality:											
P4	input price	$\tau \uparrow$	−	−	−	=	=	=	=	−	+
Total production:											
C4	out. price	$q \uparrow$	+	+	+	−	−	=	=	+	−
C5	training	$\eta_{A/S} \uparrow$	+	+	+	−	−	=	=	+	=/−
P7	entry	$f_e \downarrow$	+	+	+	−	−	−	−	+	=/−
Advanced technology:											
C6	eco-certif.	$q_A \uparrow$	+	+/=/−	+	−	−	−	+/=/−	+	=
P6	training	$\eta_A \uparrow$	+	+/=/−	+	−	−	−	+/=/−	+	=/−
P5	fixed cost	$f_A \downarrow$	+	+/=/−	+	(−)	(−)	−	+/=/−	+	=/−

Y denotes the total output value, M denotes the mass of producers, and L denotes the total input value. l_i^* and π_i^* denote the optimal individual input value and the maximum profit of producers using the simple technology S or the advanced technology A, respectively. In the results, + indicates an increase, − indicates a decrease, and = indicates no change.

4 Application

To illustrate the economic mechanisms, we apply the model to coffee production in Vietnam. The following descriptions show that our model framework is suitable for this application. The subsequent simulation results illustrate the theoretical results and indicate possible (relative) magnitudes of climate change and policy effects.

4.1 Vietnamese coffee

Coffee is a very water-intensive traded good. According to an estimate, a cup of coffee implicitly contains 140 liters of water, which are consumed during production.[6] Furthermore, coffee production requires scarce land and uses fertilizers and pesticides that pollute the ground water and reduce soil fertility. Similar to other traded goods, coffee price is determined on the international market and varies over time (ICO 2018; Marsh 2007). In the 1990s, weather shocks in Brazil led to coffee price hikes (World Bank 2004); in 2005/6, a drought in Vietnam caused "unprecedented volatility in Robusta futures markets" (p. 10) and water shortages (IDH 2013). Hence, coffee production is susceptible to the effects of climate change (Haggar and Schepp 2012).

While Brazil is the world's largest coffee exporter specialized in Arabica, Vietnam has become the second largest exporter specialized in Robusta coffee because of favorable climatic conditions for growing this sort. Between 90% and 95% of Vietnam's coffee production are exported (p. 15) (ICO 2019). The main importers of Vietnamese coffee are Germany, the USA and Italy (Marsh 2007). In Vietnam, coffee is mainly grown in the Central Highlands near the border to Cambodia, particularly in Dak Lak Province, followed by Lam Dong Province (Marsh 2007). The coffee is grown by a large number of smallholder farmers with different sizes and productivities (ICO 2019; TVSEP 2018) and then collected by large companies. Coffee production helped Vietnam considerably reduce poverty during the last two

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[6] See Ridoutt and Pfister (2010) for a critical discussion of this estimate.

decades (Summers 2014). More than 40,500 officially certified farmers produce more than 50% of Dak Lak's annual coffee output, i.e., 226,000 tonnes of coffee beans on an area of 65,000 hectares (VOV 2017). The certified farmers have been trained, including watering and fertilizing, to minimize negative environmental effects (VOV 2017).

"From 1986 to 2016, coffee production in Vietnam has increased nearly 100-fold" (p. 15) (ICO 2019). To achieve this, the Vietnamese government has supported coffee producers, for example, via subsidies, for centuries (Marsh 2007). These policies have created profit incentives and granted access to the market, capital, agricultural inputs and technologies (Marsh 2007). "Harnessing technologies such as irrigation and understanding Robusta coffee physiology has enabled the Vietnamese farmers to become the most productive[7] Robusta coffee growers in the world" (p. xii) (Marsh 2007). Currently, the Vietnamese government supports investments in machinery, equipment and facilities, particularly water-saving irrigation systems, training and agricultural extension as well as certification with the aim to increase farmers' income and to make production sustainable (Vietnam 2018). In accordance with our model, empirical evidence from Vietnam shows that rental market transactions transfer cropland from less to more productive farmers (Huy and Nguyen 2019). Irrigation and fertilization are the key to achieve high productivity (Marsh 2007). The downside is that overuse of water and fertilizers is common among Vietnamese coffee producers (Cheesman, Bennett, and Son 2008; Amarasinghe et al. 2015). Often, water is freely or cheaply available such that farmers use on average "more than double the amount of water required" (p. 9) (IDH 2013). Furthermore, forests have been cleared to obtain land for production (World Bank 2004). One challenge of Vietnamese coffee farmers is limited access to financial resources. Other challenges are the lack of technical information and risk aversion that hinders investments (Marsh 2007; Cheesman, Bennett, and Son 2008).

Robusta production is water-intensive because the per-area yield is increased via more intensive irrigation during the dry season. For this purpose, different irrigation technologies can be used. Conventional basin (surface) irrigation involves the lowest investment costs of

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[7] With an average coffee yield of 2.3t/ha, many farmers producing over 3.5t/ha (ICO 2019).

the irrigation device and the installation (corresponding to the simple technology, denoted S). The more advanced sprinkler irrigation method and particularly the most advanced drip irrigation method involve higher investment costs but reduce variable costs and detrimental environmental effects by raising productivity and improving water efficiency (corresponding to the advanced technology, denoted A). Currently, the less efficient basin irrigation method is still common in Vietnam (Cheesman, Bennett, and Son 2008).

Whereas water scarcity is already a challenge today, climate change will put additional pressure on coffee production and smallholders' livelihoods in the future (Morton 2007). Baker and Haggar (2007) argue that rising temperature will negatively affect coffee production. Production areas need to migrate to higher altitudes or northern latitudes. Due to restricted geographic options, the above authors predict higher geographic concentration of coffee production. This concentration together with higher weather variability will likely increase the volatility of coffee production and prices.[8] Baker and Haggar (2007) argue further that reduced rainfall together with more frequent inundations and fertilizer use will increase the pressure on groundwater reservoirs.

Regarding Vietnamese coffee production, the World Bank (2004) notes that "the unbridled push to increase agricultural productivity and production has had outcomes that are positive and some that are negative" and that it is inevitable to obtain insights in the market mechanisms to identify a suitable policy strategy. Against this background, we calibrate the model and study the effects of climate change and policy intervention discussed in the previous sections numerically to derive policy implications for Vietnamese coffee production. The policies accord with the current policy support initiatives by the Vietnamese government discussed above (Vietnam 2018), recommendations by the World Bank (2004), such as technical training, finance or even policy (p. 16), and by the industry (IDH 2013), such as training for all coffee farmers, incentives for the adoption of sustainable practices, eco-certification, input cost savings, sustainable (ground) water use, conserving soil fertility

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[8] Whereas technical progress might increase productivity and create downward pressure on the coffee price, the growing world population together with rising income create upward pressure.

or reducing vulnerability to coffee price volatility.

4.2 Scenario simulations

Model calibration

Table 3 in Appendix C details the parameter values and their sources followed by further explanations. Following De Pelsmacker et al. (2006), we assume price premia for eco-certified coffee of 25%. Referring to Vietnam (2018), we consider a subsidy covering 50% of the entry cost, another subsidy covering 40% of the fixed cost of the advanced technology and a 10% output subsidy. The 5% productivity increase via producer training is conservative compared to the tremendous historical productivity gains reported by (ICO 2019) and slightly below the 7% productivity gain from agricultural extension estimated by (Feder and Slade 1986) for India. It reflects the remaining potential of productivity gains in Vietnamese coffee production in the short-run (a couple of years) that remain in the long-run (20–50 years). We further assume a 10% input tax (Rodi, Schlegelmilch, and Mehling 2012). In the climate change scenarios, the coffee price is assumed to vary by 50%, and the total input and output (represented by productivities) are assumed to vary by 35%, which accords with the variation in the empirical data (ICO 2018) and estimated damages of extreme weather events (Gamage, Pearson, and Hanna 2016).

Additionally, we search for the extent of support – producer training or fixed cost subsidy – for the advanced technology that leads to the *complete replacement* of the simple technology by the advanced technology, denoted by η_A^* and f_A^*. In either situation, the threshold productivities φ_S', φ_A' and φ'' (depicted in Figure 1) will coincide. Stronger policy support will reverse the order of the thresholds and thus displace the simple technology.

Table 2: Quantification of climate change and policy effects

Prop./ Corol.	Policy/ shock	Param. change	Y	M	L	l_S^*	l_A^*	π_S^*	π_A^*	Climate damage
Climate change:										
P1	out. price	$1.50q$	+91.3	+187.0	+27.6	–55.6	–55.6	0.0	0.0	/
P2	input	$0.65L_0$	–35.0	–35.0	(–35.0)	0.0	0.0	0.0	0.0	/
P3	output	$0.65\eta_{A/S}$	(–67.4)	–67.4	– 22.8	+136.7	+136.7	0.0	0.0	/
Environmental externality:										
P4	inp. price	$\tau = 0.10$	–3.1	–3.1	–3.1	0.0	0.0	0.0	0.0	–3.1
Total production:										
C4	out. price	$1.50q$	+91.3	+187.0	+27.6	–55.6	–55.6	0.0	0.0	+91.3
C5	training	$1.05\eta_{A/S}$	+13.5	+13.5	+3.0	–9.3	–9.3	0.0	0.0	+13.5
P7	entry	$0.50f_e$	+82.3	+82.3	+14.9	–60.3	–60.3	–63.4	–60.2	+82.3
Advanced technology:										
C6	eco-certif.	$1.25q_A$	+80.1	–8.7	+14.5	–59.6	–36.8	–62.4	–1.0	+80.1
P6	training	$1.05\eta_A$	+12.5	–1.8	+2.8	–16.6	–8.0	–14.8	+1.1	+12.5
	replace S	$1.0878...\eta_A$	+23.1	–3.2	+4.9	–27.4	–14.1	–25.3	+1.4	+23.1
P5	fixed cost	$0.60f_A$	+38.0	–4.8	+7.7	–39.1	–39.1	–37.6	–10.7	+38.0
	replace S	$0.845f_A$	+6.4	–1.0	+1.5	–9.1	–9.1	–8.0	+2.1	+6.4

Y denotes the total output value, M denotes the mass of producers, and L denotes the total input value. l_i^* and π_i^* denote the optimal individual input value and the maximum profit of producers using the simple technology S or the advanced technology A, respectively. The results are reported as percentage changes in the variables compared to the situation without any shock or policy.

Simulation results

Evaluating the propositions and corollaries, Table 2 replicates Table 1 quantitatively. The results for producers using the simple technology are reported for a given producer with a fixed productivity φ above φ'_S, while the results for producers using the advanced technology are reported for a given producer with a fixed productivity φ above φ''. The right column reports the percentage change of the climate change damage of total output caused by the introduction of the policy instrument considered in the corresponding row (see Corollary 3). Changes in the state budget not only depend on the specific way of financing each policy but are also difficult to quantify in some cases and are therefore left out.

The detected productivity increase of the advanced technology that exactly causes complete replacement of the simple by the advanced technology amounts to approximately 8.78% of the initial productivity, i.e., $\eta_A^* = 1.0878... \cdot \eta_A$. The corresponding subsidy for the fixed cost of the advanced technology that causes complete replacement amounts to 15.5%, i.e., $f_A^* = 0.845 \cdot f_A$.

According to the simulation results, the annual economic effects of policy measures imposed on coffee production in Dak Lak/Vietnam at conservative rates (5%) are moderate; whereas due to the assumed significant climate change impacts (35–50%) based on VOV (2017) and Gamage, Pearson, and Hanna (2016) or policy measures at higher rates (40–50%) the resulting economic effects are substantial.

Expressed as absolute numbers referring to Dak Lak/Vietnam in 2017 (VOV 2017; Quan 2018; ICO 2019), the percentage simulation results yield a total output (Y) change with annual magnitudes of approximately 56,250 tonnes of coffee beans (12.5% of 450,000 tonnes) to 410,850 tonnes (91.3%) caused by the different policies. The policy-induced change in the number of producers (represented by M) varies between –8,700 and 187,000 (–8.7% and 187% of 100,000).[9] The corresponding policy-induced land use change (a major component of L) varies between 5,600 hectares and 55,200 hectares (2.8% and 27.6% of 200,000 hectares).

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[9] Rounded medium assumption based on VOV (2017) and survey data from Dak Lak.

According to the same calculus, the possible long-term climate change-related annual output change varies between –303,300 (–67.4%) and 410,850 tonnes (91.3%), the change in the number of farmers between –67,400 (–67.4%) and 187,000 (187.0%) and the land use change between –70,000 hectares (–35.0%) and 55,200 hectares (27.6%).

5 Discussion

This section interprets the qualitative and quantitative results reported in Tables 1 and 2 with regard to poverty, employment, environmental, distributional and budgetary effects; it also discusses the effects of the policies on climate change damages as well as policy substitution possibilities. Finally, it provides a sensitivity analysis and a discussion of model limitations.

5.1 Scenario results

According to the simulation results, a 9% productivity increase of the advanced irrigation technology or a 16% investment subsidy would suffice to replace the simple old-fashioned technology by the advanced technology. The numerical results presented in Table 2, however, represent a long-run perspective (20–50 years), because technology adoption processes require time to emerge and climate change impacts will become more severe in the future.

Poverty effects

Poverty effects are reflected by changes in total income Y. By assumption, climate change reduces income when it occurs in the local economy (here the Central Highlands of Vietnam). It can, however, also raise income via an increasing world market price (of coffee) when it occurs abroad. The only policy that reduces total income is the input tax; all other examined policies raise it.

Employment effects

An increase in the mass of producers M represents positive employment effects, or in other words, an increasing number of active (coffee) producers. In the results, positive/negative income effects of climate change correspond to positive/negative employment effects.

Among the policy instruments, only the input tax reduces employment. The policies enhancing total production also increase employment. The policies enhancing the advanced technology induce a switch of medium-productivity producers (with productivities slightly below φ'') to the advanced technology but do not induce the entry of new producers, i.e., they are employment-neutral.

The numerical results indicate that the climate change impacts on employment (and to a lesser extent, on output and the input price) can be significantly larger than the extent of the original shock.

Environmental effects

An increase in the total input L reflects higher negative environmental effects and more resource exploitation. Input changes point in the same direction as output (income) changes.

The input tax reduces the total input as intended. Notably, all other policies increase the total input L, even though the individual inputs l_i^* decrease. There are three reasons for this finding: The policies enhancing total production induce more producers to enter the market (and to use the simple technology), which increases output and input demand. The policies supporting the advanced technology induce a switch of medium-productivity producers to the advanced technology with a higher productivity than the previous simple technology, which also raises output and input. In either case, the input supply increases.

Compared to the relative input changes, the relative output changes, however, are approximately threefold. Hence, the input intensity of production L/Y declines whenever a policy other than the input tax is introduced. The input tax, in contrast, reduces the total output, employment and input to the same extent; consequently, L/Y stays constant.

Eco-certification and training of advanced-technology users lead to a stronger input reduction of simple- than advanced-technology users. This happens because the advanced-technology users increase their input demand, which drives up the input price, such that the simple-technology users with lower productivities downscale their production.

Distributional effects

Distributional effects are represented by changes in the profits of the two types of producers, i.e., π_A^* and π_S^* together with employment M. The policies supporting the advanced technology increase the profits of the advanced-technology users but decrease the profits of the simple-technology users. Numerically, the profit losses of the latter are much larger than the profit gains of the former. Thus, assuming that advanced-technology users are more productive and richer than simple-technology users, these policies increase inequality within the (coffee) production sector under scrutiny.

The reduction of the market entry barrier (via a subsidy or credit) reduces the profits of both advanced- and simple-technology users, numerically, to a larger extent those of the simple-productivity users. Hence, it increases inequality among the active producers in this sector. In contrast, such a reduction helps inactive producers to enter the (coffee) market and to find a base of living in smallholder (coffee) production. Hence, this policy reduces inequality among active and inactive producers in this sector if the incumbents (or active producers) are richer than the entrants (or inactive producers). Incumbents, however, might oppose such a policy. Regarding economic efficiency, this policy is nevertheless advisable if a market failure hindering market entry exists. As a lower market entry barrier and fiercer competition are likely to stimulate innovation, benefits may occur outside the scope of the model. These considerations show the complexity of policies supporting market entry.

Budgetary effects

Changes in the state budget, i.e., in public expenses, as reported in the right column of Table 1, depend on the way of financing the policies. They have distributional implications and are a key criterion for policy decisions. The output subsidy clearly requires public expenditures, whereas training can be financed by the government, the farmers in the form of participation fees or by foreign aid donors in the form of international technical cooperation. Similarly, market entry or technology support can be financed by the government or foreign donors in the form of subsidies or (zero/low interest rate) credits together with guarantees. Eco-certification has the advantage to create no or low costs for the government because (foreign) consumers pay for the sustainability premium. The environmental tax has the advantage of creating tax revenues that can, for example, be used to finance the discussed subsidies.

Climate interactions

The effect of the policies under scrutiny on climate change damages refers to Corollary 3 and is reported in the right column of Table 2. The interpretation is straightforward: when a policy increases total output by $\gamma\%$ in absolute terms, climate change impacts will affect a corroding surface, which is $\gamma\%$ larger. Thus, the climate change-induced output reduction will be $\gamma\%$ larger as well. Other characteristics of the current state of the economy, such as technology shares or input intensities, are not relevant for this relationship.

Policy substitution

Apart from their costs, the advanced-technology-supporting policy instruments (eco-certificate, technology-specific training and technology support) can replace each other regarding their economic effects. Similarly, the subsidy for the entire (coffee) production and training for all producers can replace each other. The input tax and market entry support, in contrast, cause specific economic effects and thus cannot be replaced. Although technology support increases environmental efficiency, it causes a rebound effect with entry of new producers that eliminates the efficiency gain and renders it a poor substitute for the input tax.

Ignoring policy costs, climate change damages affecting the output (such as coffee) can be compensated by a corresponding output subsidy or training for all producers. Climate change damages affecting the input (such as land or water) can be compensated by lowering the input tax. The latter policy, however, has the drawback of increasing the negative effects on the environment and sustainable resource use.

5.2 Sensitivity analysis

The sensitivity analysis refers to the policy scenario with training for users of the advanced technology A described by Proposition 6 and reported in Table 2 (or eco-certificates with a price premium of 10% versus 5%, referring to Corollary 6). The sensitivity results are reported in Table 4 in Appendix D.

When the extent of the policy is doubled ($1.10\eta_A$ instead of $1.05\eta_A$), the aggregate variables (Y, M, and L) will react more than proportionally, while the individual variables (l_i^* and φ_i^*) react less than proportionally; the influence on technology A users' profits is particularly small.

When the model parameter values of θ or k are varied by ±10%, the change in the effect of technology A support on individual profits φ_i^* (deviations of 55–93% compared to the benchmark effects reported in Table 2) will be much larger than the change in its effect on the aggregate variables (deviations of 2–5%). In accordance with Proposition 6, alternative choices of θ, ε or k result in positive or negative policy effects on M. A 10% variation in ε causes a 10% change in the policy effect on the total input L but has no influence on the individual variables. In contrast, a 10% reduction in f_e exacerbates the profit drop for technology S users by nearly 250% but has no influence on other variables.

Variation in the benchmark amount of the input L_0 or the output price q does not alter the policy effects measured in relative terms.

5.3 Model limitations

The model analysis is, however, subject to limitations. Because the rest of the world is not relevant for this analysis, the world market price for the output (coffee) is taken as given, which determines the (coffee) production and consumption side and rules out power on the international market. The world market price is varied exogenously to mimic climate change-related price variation. Besides climate change, there are also other possible reasons for world market price variations and shocks, such as financial crises, conflicts or natural disasters. Thus, the analysis can also be applied to such aspects. Endogenous effects on the world market price are not relevant for this producer level analysis, because even the largest smallholder producers have no significant power on the international market.

Similarly, other sectors, alternative (cash) crops or further business or employment opportunities of farmers and their households are not relevant for the analysis and hence not represented explicitly. The model is static, ruling out forward-looking planning, for example, regarding perennial crops.

Having derived the optimal input aggregate, the input aggregate is used in the analysis to simplify the exposition. The policy-induced substitution of inputs is well known and hence not further analyzed, especially because in our model application the input water (and fertilizer) can hardly be replaced. If climate change- or policy-induced changes in the input structure are of further interest, the aggregate should be split into single inputs.

Finally, the policy costs and benefits (state budget, reduced environmental externalities, poverty and inequality) are difficult to quantify and therefore analyzed qualitatively.

6 Conclusion

The adoption of new technologies and corresponding technology support are sometimes deemed to be a one-fits-all solution for the adaptation to climate change, the reduction of environmental pollution and the alleviation of poverty. Our results do not support this view. They confirm the relevance of the classic Pigou tax by identifying a novel rebound effect via market entry of producers. Technology support induces this rebound effect whereas the Pigou tax avoids it. To see these effects, we have introduced a new Hopenhayn-Melitz type model of heterogeneous producers and endogenous technology adoption.

According to our simulation results, a 9% productivity increase of the advanced irrigation technology or a 16% investment subsidy would suffice to induce the replacement of the simple old-fashioned technology by the advanced one in the long-run. Technology support, however, can also create unintended distributional effects by supporting primarily the more productive producers with higher income. Output subsidies may also be inconsistent with World Trade Organization law. By contrast, the reduction of market entry barriers has the advantage of reduced inequality among active and inactive producers if the incumbents (or active producers) are richer than the entrants (or inactive producers). Training for all producers is a recommendable policy because it increases total income and hence reduces poverty, avoids detrimental distributional effects and can be financed by foreign aid (technical assistance) or participation fees. The quantitative results indicate that secondary economic effects, such as changes in the number of producers, can be considerably larger than the original magnitude of the shock. The results are in favor of local policies and foreign aid (technical assistance) supporting the adoption of advanced technologies. This includes precision farming and digitization of farming as future options. However, the environmental and distributional policy insights derived in this article and the discussed limitations should be considered.

Coffee production in Vietnam has been studied as a suitable model application. However, the model is applicable to many other geographic and technological fields, especially, but not only, within the agricultural sector in developing countries. Cacao production is one example. Future model extensions may introduce trade between two or N identical or distinct economies that differ, for example, by size or technology. They may also add a dynamic perspective, which will enable the analysis of technology choice under changing yields of perennial crops. Provided that data are available for the topic, country and sector under study, the model could be parameterized with a structural estimation approach.

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Appendix

The following supplementary (online) appendix derives the optimal production factor input in part A and several complex terms in part B. It provides the parameter values of the model calibration in part C. It presents a sensitivity analysis and illustrations of selected propositions in part D.

A Production factors

Our approach derives the implicit generic input that Melitz (2003) denotes "labor" explicitly. The producer employs a vector $[l_1, l_2, ..., l_n]$ of n different types of inputs, including labor, land and capital, to produce an intermediate good l. The production function is given by $l = \prod_{j=1}^{n}(l_j)^{\alpha_j}$ with $\sum_{j=1}^{n}\alpha_j = 1$. The inputs are available at exogenous prices represented by the vector $[p_1, p_2, ..., p_n]$. Notice that the aggregate, l, and the price for this aggregate, p, are defined as scalars.

The cost minimization problem for producing one unit of the intermediate good is given by $\min_{l_j}\sum_{j=1}^{n} l_j p_j$ such that $1 = \prod_{j=1}^{n}(l_j)^{\alpha_j}$. The corresponding Lagrangian reads $\mathfrak{L} = \sum_{j=1}^{n} l_j p_j + \lambda[1 - \prod_{j=1}^{n}(l_j)^{\alpha_j}]$. The first-order condition for the optimal input of production factor l_j with $j = \{1..n\}$ given by $p_j - \lambda\alpha_j\frac{1}{l_j} = 0$; thus, $l_j = \frac{\lambda\alpha_j}{p_j}$. By inserting this in the minimization problem above, we obtain $1 = \prod_{j=1}^{n}\left(\frac{\lambda\alpha_j}{p_j}\right)^{\alpha_j} = \lambda\prod_{j=1}^{n}\left(\frac{\alpha_j}{p_j}\right)^{\alpha_j}$; therefore, $\lambda = \left[\prod_{j=1}^{n}\left(\frac{\alpha_j}{p_j}\right)^{\alpha_j}\right]^{-1}$. From this expression, we obtain the share of the factor l_j in production to be $l_j = \frac{\alpha_j}{p_j}\left[\prod_{j=1}^{n}\left(\frac{\alpha_j}{p_j}\right)^{\alpha_j}\right]^{-1}$. The cost of producing one unit of l is given by $p = \sum_{j=1}^{n} l_j p_j = \sum_{j=1}^{n}\frac{\alpha_j}{p_j}\left[\prod_{j=1}^{n}\left(\frac{\alpha_j}{p_j}\right)^{\alpha_j}\right]^{-1} p_j = \left[\prod_{j=1}^{n}\left(\frac{\alpha_j}{p_j}\right)^{\alpha_j}\right]^{-1}$.

The resulting optimal aggregate l_i^* is thus a combination of inputs, which are available at the aggregate per unit price p. All individual optimal inputs are fixed shares of l_i^*.

B Derivations

B.1 Derivation of equation (7)

To make the mathematical exposition explicit, in the following expressions, we write individual profits and inputs as a function of productivity and technology.

$$\begin{aligned}
E[\Pi(\varphi, i(\varphi)] &= \int_{\varphi'_S}^{\varphi''} \Pi^*(\varphi, S) g(\varphi) d\varphi + \int_{\varphi''}^{\infty} \Pi^*(\varphi, A) g(\varphi) d\varphi \\
&= \int_{\varphi'_S}^{\varphi''} \left(\left(\frac{q\eta_S \varphi}{p^\theta} \right)^{\frac{1}{1-\theta}} \tilde{\theta} - f_S \right) k \frac{\varphi_m^k}{\varphi^{k+1}} d\varphi \\
&\quad + \int_{\varphi''}^{\infty} \left(\left(\frac{q\eta_A \varphi}{p^\theta} \right)^{\frac{1}{1-\theta}} \tilde{\theta} - f_A \right) k \frac{\varphi_m^k}{\varphi^{k+1}} d\varphi \\
&= \left(\frac{q\eta_S}{p^\theta} \right)^{\frac{1}{1-\theta}} \tilde{\theta} k \varphi_m^k \frac{1-\theta}{1-k(1-\theta)} \left((\varphi'')^{\frac{1}{1-\theta}-k} - (\varphi'_S)^{\frac{1}{1-\theta}-k} \right) \\
&\quad + \left(\frac{q\eta_A}{p^\theta} \right)^{\frac{1}{1-\theta}} \tilde{\theta} k \varphi_m^k \frac{1-\theta}{1-k(1-\theta)} \left(-(\varphi'')^{\frac{1}{1-\theta}-k} \right) \\
&\quad - k\varphi_m^k f_S \left((\varphi'')^{-k} - (\varphi'_S)^{-k} \right) - k\varphi_m^k f_A \left(-(\varphi'')^{-k} \right)
\end{aligned}$$

$$
\begin{aligned}
= \quad & \left(\frac{q\eta_S}{p^\theta}\right)^{\frac{1}{1-\theta}} \tilde{\theta} k \varphi_m^k \frac{1-\theta}{1-k(1-\theta)} \\
& \Biggl(\left(\frac{p^\theta}{q} \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{1-\theta} \right)^{\frac{1}{1-\theta}-k} - \left(\left(\frac{f_S}{\tilde{\theta}} \right)^{1-\theta} \frac{p^\theta}{q\eta_S} \right)^{\frac{1}{1-\theta}-k} \Biggr) \\
& + \left(\frac{q\eta_A}{p^\theta}\right)^{\frac{1}{1-\theta}} \tilde{\theta} k \varphi_m^k \frac{1-\theta}{1-k(1-\theta)} \\
& \Biggl(- \left(\frac{p^\theta}{q} \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{1-\theta} \right)^{\frac{1}{1-\theta}-k} \Biggr) \\
& -k\varphi_m^k f_S \Biggl(\left(\frac{p^\theta}{q} \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{1-\theta} \right)^{-k} - \left(\left(\frac{f_S}{\tilde{\theta}} \right)^{1-\theta} \frac{p^\theta}{q\eta_S} \right)^{-k} \Biggr) \\
& -k\varphi_m^k f_A \Biggl(- \left(\frac{p^\theta}{q} \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{1-\theta} \right)^{-k} \Biggr) \\
= \quad & \left(\frac{p^\theta}{q}\right)^{-k} \varphi_m^k k \Biggl(\eta_S^{\frac{1}{1-\theta}} \tilde{\theta} \frac{1-\theta}{1-k(1-\theta)} \Biggl(\left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{1-(1-\theta)k} - \left(\left(\frac{f_S}{\tilde{\theta}} \right)^{1-\theta} \frac{1}{\eta_S} \right)^{\frac{1}{1-\theta}-k} \Biggr) \\
& -\eta_A^{\frac{1}{1-\theta}} \tilde{\theta} \frac{1-\theta}{1-k(1-\theta)} \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{1-(1-\theta)k} \\
& -f_S \Biggl(\left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{-k(1-\theta)} - \left(\left(\frac{f_S}{\tilde{\theta}} \right)^{1-\theta} \frac{1}{\eta_S} \right)^{-k} \Biggr) \\
& +f_A \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}} \right)^{-(1-\theta)k} \Biggr)
\end{aligned}
$$

$$
\begin{aligned}
&= \left(\frac{p^{\theta}}{q}\right)^{-k} \varphi_m^k k \left(1 - \frac{1-\theta}{1-k(1-\theta)}\right)\left(\frac{1}{\tilde{\theta}}\right)^{-(1-\theta)k} \cdot \\
&\quad \left[\frac{(f_A - f_S)^{1-(1-\theta)k}}{\left(\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}} + \frac{f_S^{1-(1-\theta)k}}{\left(\eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}}\right] \\
&= \left(\frac{p^{\theta}}{q}\right)^{-k} F_1(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m)
\end{aligned}
$$

$F_1(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m)$ is an auxiliary function implicitly defined in the last two lines. Recall that $f_A > f_S$, $\eta_A > \eta_S$, $\theta < 1$ and $\frac{1}{1-\theta} < k$. From the last of these inequalities, it follows that $1 - \frac{1-\theta}{1-k(1-\theta)} > 0$; thus, $F_1(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m) > 0$.

B.2 Derivation of equation (14)

$$
\begin{aligned}
L &= \int_{\varphi'_S}^{\varphi''} l^*(\varphi,S)M\mu(\varphi)d\varphi + \int_{\varphi''}^{\infty} l^*(\varphi,A)M\mu(\varphi)d\varphi \\
&= M\frac{1}{1-\left(1-\left(\frac{\varphi_m}{\varphi'_S}\right)^k\right)}\left[\int_{\varphi'_S}^{\varphi''}\left(\frac{q\eta_S\varphi\theta}{p}\right)^{\frac{1}{1-\theta}} k\frac{\varphi_m^k}{\varphi^{k+1}}d\varphi + \int_{\varphi''}^{\infty}\left(\frac{q\eta_A\varphi\theta}{p}\right)^{\frac{1}{1-\theta}} k\frac{\varphi_m^k}{\varphi^{k+1}}d\varphi\right] \\
&= M\left(\frac{\varphi'_S}{\varphi_m}\right)^k \Bigg[\left(\frac{q\eta_S\theta}{p}\right)^{\frac{1}{1-\theta}} k\varphi_m^k\frac{1-\theta}{1-k(1-\theta)}\left((\varphi'')^{\frac{1}{1-\theta}-k}-(\varphi'_S)^{\frac{1}{1-\theta}-k}\right) \\
&\quad + \left(\frac{q\eta_A\theta}{p}\right)^{\frac{1}{1-\theta}} k\varphi_m^k\frac{1-\theta}{1-k(1-\theta)}\left(-(\varphi'')^{\frac{1}{1-\theta}-k}\right)\Bigg] \\
&= \frac{M}{p}\left(\left(\frac{f_S}{\tilde{\theta}}\right)^{1-\theta}\frac{1}{\varphi_m\eta_S}\right)^k\Bigg[(\eta_S\theta)^{\frac{1}{1-\theta}} k\varphi_m^k\frac{1-\theta}{1-k(1-\theta)} \\
&\quad \left(\left(\frac{1}{\tilde{\theta}}\frac{f_A-f_S}{\eta_A^{\frac{1}{1-\theta}}-\eta_S^{\frac{1}{1-\theta}}}\right)^{1-(1-\theta)k} - \left(\left(\frac{f_S}{\tilde{\theta}}\right)^{1-\theta}\frac{1}{\eta_S}\right)^{\frac{1}{1-\theta}-k}\right) \\
&\quad - (\eta_A\theta)^{\frac{1}{1-\theta}} k\varphi_m^k\frac{1-\theta}{1-k(1-\theta)}\left(\frac{1}{\tilde{\theta}}\frac{f_A-f_S}{\eta_A^{\frac{1}{1-\theta}}-\eta_S^{\frac{1}{1-\theta}}}\right)^{1-(1-\theta)k}\Bigg] \\
&= \frac{M}{p}\left(\frac{f_S}{\eta_S^{\frac{1}{1-\theta}}}\right)^{(1-\theta)k} k\frac{1-\theta}{k(1-\theta)-1}\frac{\theta^{\frac{1}{1-\theta}}}{\tilde{\theta}} \\
&\quad \left[\frac{(f_A-f_S)^{1-(1-\theta)k}}{\left(\eta_A^{\frac{1}{1-\theta}}-\eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}} + \frac{f_S^{1-(1-\theta)k}}{\left(\eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}}\right] \\
&= \frac{M}{p}F_2(\eta_S,\eta_A,f_S,f_A,\theta,k,\varphi_m)
\end{aligned}
$$

$F_2(\eta_S,\eta_A,f_S,f_A,\theta,k,\varphi_m)$ is an auxiliary function implicitly defined in the last two lines. Note that $\frac{1}{1-\theta} < k$; thus, $k(1-\theta)-1>0$ and $F_2>0$.

B.3 Derivation of equation (19)

$$
\begin{aligned}
Y &= \int_{\varphi'_S}^{\varphi''} y(\varphi, S) M\mu(\varphi) d\varphi + \int_{\varphi''}^{\infty} y(\varphi, A) M\mu(\varphi) d\varphi \\
&= M \frac{1}{1 - \left(1 - \left(\frac{\varphi_m}{\varphi'_S}\right)^k\right)} \left[\int_{\varphi'_S}^{\varphi''} \eta_S \varphi \left(\frac{q\eta_S\varphi\theta}{p}\right)^{\frac{\theta}{1-\theta}} k\frac{\varphi_m^k}{\varphi^{k+1}} d\varphi + \int_{\varphi''}^{\infty} \eta_a \varphi \left(\frac{q\eta_A\varphi\theta}{p}\right)^{\frac{\theta}{1-\theta}} k\frac{\varphi_m^k}{\varphi^{k+1}} d\varphi\right] \\
&= M \left(\frac{\varphi'_S}{\varphi_m}\right)^k \left[\left(\frac{q\theta}{p}\right)^{\frac{\theta}{1-\theta}} \eta_S^{\frac{1}{1-\theta}} k\varphi_m^k \frac{1-\theta}{1-k(1-\theta)} \left((\varphi'')^{\frac{1}{1-\theta}-k} - (\varphi'_S)^{\frac{1}{1-\theta}-k}\right)\right. \\
&\quad \left. + \left(\frac{q\theta}{p}\right)^{\frac{\theta}{1-\theta}} \eta_A^{\frac{1}{1-\theta}} k\varphi_m^k \frac{1-\theta}{1-k(1-\theta)} \left(-(\varphi'')^{\frac{1}{1-\theta}-k}\right)\right] \\
&= \frac{M}{q} \left(\left(\frac{f_S}{\tilde{\theta}}\right)^{1-\theta} \frac{1}{\varphi_m \eta_S}\right)^k \left[\eta_S^{\frac{1}{1-\theta}} \theta^{\frac{\theta}{1-\theta}} k\varphi_m^k \frac{1-\theta}{1-k(1-\theta)}\right. \\
&\quad \left(\left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}}\right)^{1-(1-\theta)k} - \left(\left(\frac{f_S}{\tilde{\theta}}\right)^{1-\theta} \frac{1}{\eta_S}\right)^{\frac{1}{1-\theta}-k}\right) \\
&\quad \left. -\eta_A^{\frac{1}{1-\theta}} \theta^{\frac{\theta}{1-\theta}} k\varphi_m^k \frac{1-\theta}{1-k(1-\theta)} \left(\frac{1}{\tilde{\theta}} \frac{f_A - f_S}{\eta_A^{\frac{1}{1-\theta}} - \eta_S^{\frac{1}{1-\theta}}}\right)^{1-(1-\theta)k}\right] \\
&= \frac{M}{q} \left(\frac{f_S}{\eta_S^{\frac{1}{1-\theta}}}\right)^{(1-\theta)k} k\frac{1-\theta}{k(1-\theta)-1} \frac{\theta^{\frac{\theta}{1-\theta}}}{\tilde{\theta}} \\
&\quad \left[\frac{(f_A - f_S)^{1-(1-\theta)k}}{\left(\eta_A^{\frac{1}{1-\theta}} + \eta_S^{\frac{1}{1-\theta}}\right)^{1-(1-\theta)k}} + \frac{f_S^{1-(1-\theta)k}}{\left(\eta_S^{\frac{1}{1-\theta}}\right)^{-(1-\theta)k}}\right] \\
&= \frac{M}{q} \theta^\theta F_2(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m)
\end{aligned}
$$

$F_2(\eta_S, \eta_A, f_S, f_A, \theta, k, \varphi_m)$ is the same auxiliary function as was used previously.

C Parameter values

Table 3: Benchmark parameter values of the calibrated model

Parameter	Symbol	Value	Source/calibration
Invariant:			
Decr. returns	θ	0.5	median of the possible range
Elast. inp. sup.	ε	0.3	following Griliches (1959)
Shape param.	k	3.0	following Melitz and Ottaviano (2008)
Min. product.	φ_m	0.2	in t/ha, Chi et al. (2005), D'haeze et al. (2007)
Policy-dependent:			
Productivities	η_S, η_A	1.0, 1.3	relative productivities: D'haeze et al. (2007)
Fixed costs	f_S, f_A	1.0, 2.0	relative costs: Chi et al. (2005)
Entry cost	f_e	0.009435	adjusted such that $L = p = 1.0$, $\varphi'_S = 2.0$
Bench. input	L_0	1.0	normalized, 35% reduction: ICO (2018), Gamage, Pearson, and Hanna (2016)
Output price	q	1.0	normalized, 50% variation: ICO (2018)
Input tax	τ	0.0	no tax in the benchmark, 10% variation assumed: Rodi, Schlegelmilch, and Mehling (2012)

The calibration of exogenous invariant and exogenous policy dependent parameter values draws on (a) general theory-based and empirical assumptions and (b) specific data sources about coffee production in Dak Lak/Vietnam.

(a) θ is first set to the median value of 0.5 within the theoretically feasible range and then varied in the sensitivity analysis (Section 5.2) by ±10%. $\varepsilon = 0.3$ follows Griliches (1959) regarding his estimate of the implied aggregate farm supply elasticity. $k = 3$ is taken from Melitz and Ottaviano (2008). ε and k are also varied by ±10%. f_e is exogenously adjusted such that the total aggregate input L and the input price p are normalized to one and φ'_S is normalized to two in the benchmark situation. L, p and φ'_S are endogenous variables that display relative changes in the counterfactual scenarios. Similarly, L_0 and q are normalized to one in the benchmark and varied exogenously in the counterfactual scenarios. The variation of L_0 by 35% and of p by 35% accord with the variation in the data of ICO

(2018) and estimated damages caused by extreme weather events of Gamage, Pearson, and Hanna (2016). The benchmark value of τ is zero.

(b) The productivity distribution among coffee producers in Vietnam and the minimum productivity of $\varphi_m = 0.2$t/ha are based on Chi et al. (2005), D'haeze et al. (2007) and TVSEP (2018). The calibration of the productivity $\eta_A = 1.3$ relative to $\eta_S = 1.0$ additionally draws on personal correspondence with Dr. Dave A. D'haeze referring to coffee production in Dak Lak/Vietnam and the more general study of Postel et al. (2001). The values of $\eta_A = 1.3$ and $\eta_S = 1$ in combination with the values of the fixed costs result in well-defined theory-consistent profit functions as displayed in Figure 1. The value of $f_A = 2.0$ for the fixed costs of the advanced irrigation technology relative to $f_S = 1.0$ for the simple technology is derived from Chi et al. (2005) studying coffee production in Dak Lak/Vietnam.

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For the remaining sources see the main text's reference list.

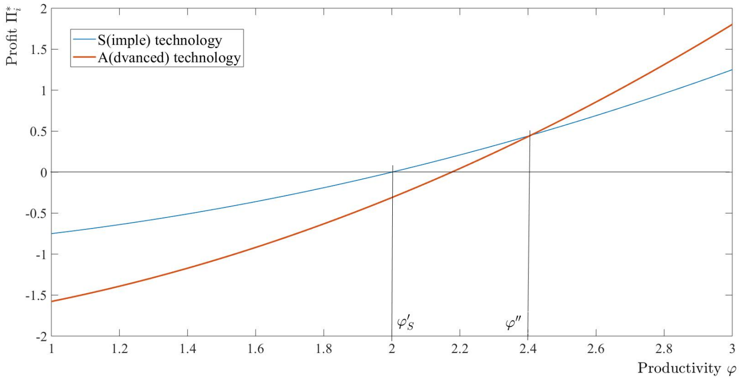
D Sensitivity & illustrations

Table 4: Sensitivity analysis under training or eco-certification for advanced technology users

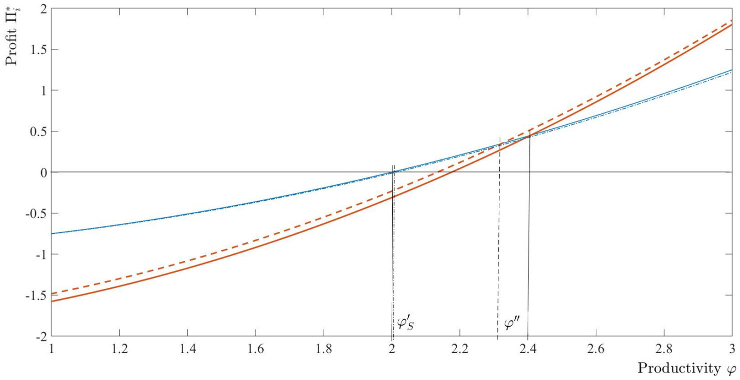
Scenario name	Parameter change	Y	M	L	l_S^*	l_A^*	π_S^*	π_A^*
B(enchmark)	$1.05\eta_A$	+14.5	0.0	+4.6	–16.6	–8.0	–93.4	+2.9
D(ouble pol.)	$1.10\eta_A$	+31.5	0.0	+9.6	–30.6	–16.0	–179.8	+3.4
rel. to B		*+116.3*	*0.0*	*+106.5*	*+84.6*	*+99.6*	*+92.6*	*+17.5*
Low θ	0.9θ	+15.0	+1.4	+4.8	–15.5	–7.7	–42.5	+5.0
rel. to B		*+2.8*	*+inf*	*+2.7*	*–6.2*	*–3.8*	*–54.5*	*+74.9*
High θ	1.1θ	+13.9	–1.3	+4.4	–17.5	–8.1	–160.3	+1.2
rel. to B		*–4.5*	*–inf*	*–4.3*	*+5.9*	*+1.0*	*+71.7*	*–58.5*
Low ε	0.9ε	+14.0	–0.5	+4.2	–16.6	–8.0	–93.4	+2.9
rel. to B		*–3.6*	*–inf*	*–10.2*	*0.0*	*0.0*	*0.0*	*0.0*
High ε	1.1ε	+15.1	+0.5	+5.1	–16.6	–8.0	–93.4	+2.9
rel. to B		*+3.6*	*+inf*	*+10.3*	*0.0*	*0.0*	*0.0*	*0.0*
High k	$1.1k$	+14.2	–1.3	4.5	–16.2	–7.6	–20.2	+1.8
rel. to B		*–2.4*	*–inf*	*–2.3*	*–2.1*	*–4.8*	*–78.4*	*–38.3*
Low f_e	$0.9f_e$	+14.5	0.0	+4.6	–16.6	–8.0	–324.3	+3.7
rel. to B		*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*+247.3*	*+28.5*
High f_e	$1.1f_e$	+14.5	0.0	+4.6	–16.6	–8.0	–58.3	+2.4
rel. to B		*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*–37.6*	*–15.8*

Y denotes the total output value, M denotes the mass of producers, and L denotes the total input value. l_i^* and π_i^* denote the optimal individual input value and the maximum profit of producers using the simple technology S or the advanced technology A, respectively. The results are reported as percentage changes in the variables compared to the situation without any shock or policy and in italic letters as percentage changes compared to the benchmark (B) policy scenario with support for the technology A, as described by Proposition 5 and Corollary 6 and reported in Table 2. The low k case is left out because it results in negative profits.

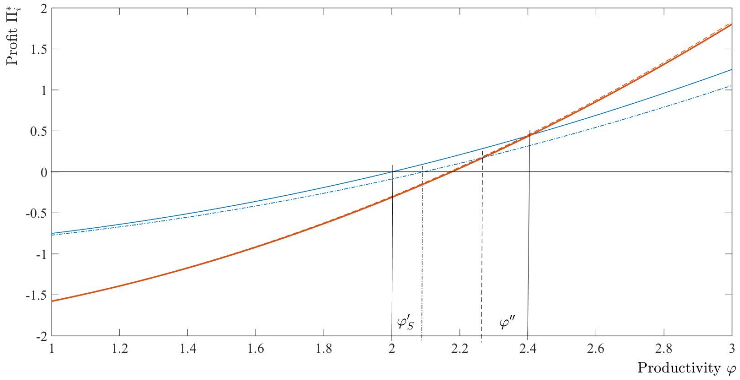
Figure 2: Policy effects (dashed lines) based on the calibration of Appendix C



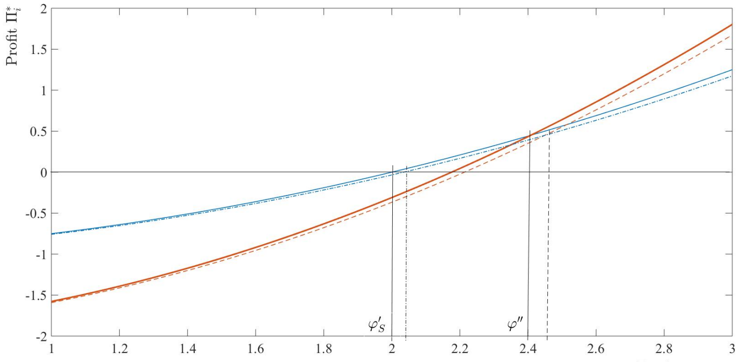
(a) Benchmark calibration



(b) Prop. 5: Lower costs of the advanced technology f_A



(c) Prop. 6: Higher productivity of the advanced technology η_A



(d) Prop. 7: Lower market entry cost f_e