Welfare Impact of Adopting a High-Yield Cocoa Tree in West African Countries

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Abstract

In this paper we estimate the benefit of adopting a high-yield cocoa tree in West African countries using a temporal and spatial equilibrium model that accounts for international trade with the Rest of the World. Because Ivory Coast and Ghana supply more than 55% of the world supply of cocoa, adoption of high-yield cocoa trees can disrupt the international price affecting smallholders in these countries. In this paper, we show that adoption of a high yield tree while allocating part of the land previously on cocoa to an alternative crop can be a solution. Our results indicate that considering maize as an alternative crop while transitioning land out of cocoa due to the increase in yield result in an increase of $2.61 billion in profits for these two countries over thirty-five years.
Keywords: *adoption; cocoa; land allocation; West African countries.*

1 Introduction

Cocoa production is essential to West Africa's economy. It generated more than 55% of world cocoa supply in 2018 (Food and Agricultural Organization – FAO, 2021) in addition to more than 60% of West African smallholders' income (XXX). However, West African smallholders' yields are among the lowest in the world, averaging half ton per hectare per year while with some management practices the potential yield is the quadruple of this rate (Gockowski et al., 2011). Yields are also higher in different countries such as Peru and Colombia, which together produced less than 5% of the world supply and have yields that are almost twice larger than West African countries. The low cocoa yields in West Africa are due to a variety of factors, including diseases such as the Cacao Swollen-Shoot Virus, which can destroy up to 30% of total production. The adverse impacts of low cocoa productivity are reflected not only in the incomes of impoverished smallholders but also in the environment. Since cocoa production can only take place in West Africa's forest agro-ecological zone, large areas of forest cover have been lost to cocoa production due to rising demand for cocoa on the world market.

The cocoa market is unique among agricultural commodities. In 2018, ten countries produced together 93% of the world supply, exported (imported) 94% (81%) of the world exports (imports) in 2018 (FAO, 2021). However, among the top producers, Brazil exported less than 1% of what it produced. On the other hand, Ivory Coast and Ghana exported 71% and 93% of their production in 2018, respectively. A few countries with no or small production are in the list of major exporters (e.g. Netherlands and Belgium) and of large importers. Some of the countries are known for their chocolate production, such as the Netherlands, Belgium, United States, Germany and France. Ivory Coast exports to the Netherlands (25% of the exports), United States (17%), Germany (9%), Belgium (8%), Malaysia (8%), and Indonesia (5%). Ghana's exports have similar destinations: Brazil (23%), Netherlands (18%), Malaysia (14%), United States (7%), Japan (5%), and Spain (5%). These trade links indicate that drastic changes in the Ivory Coast and Ghana domestic markets affect the rest of the world.

The wide adoption of a high-yield technology or management practices can disrupt the international price and affect farmers in these countries. An alternative could be to encourage smallholders to adopt new high-yielding cocoa varieties while at the same time reallocating a proportion of their cocoa land to other food staples, palm oil and other crops. Not only would this approach diversify smallholders' incomes and make them more resilient to shocks, but it would also stabilize cocoa supply and prices. The market disruption can be more severe if adopted by larger exporters such as Ivory Coast and Ghana. The increase in quantity supplied driven by adoption of a technology that quadruples yield can substantially decrease the international price. A simple estimate of the effect of adoption of a technology such as in Gockowski et al. (2011), that quadruples yield, in only these two countries would result in a world price decrease of 59%. This simple estimate reinforces the fear of countries and institutions such as the Cocoa Board that rely on exports. However, the price change can be averted, at least partially, with changes in land allocation.

In this paper we develop a temporal spatial equilibrium to estimate the benefits of adopting a high-yield cocoa variety while reallocating the land to maize for Ivory Coast, Ghana and Rest of the World over 35 years. Using a straightforward and simplified spatial model, the main goal of the paper is to demonstrate that policies incentivizing adoption of high-yield cocoa have the potential to increase these countries welfare. We adapt Samuelson (1952) and Takayma and Judge's (1964, 1971) model of spatial equilibrium based on Busdieker-Jesse et al. (2016) study of disease on apples, to incorporate current cocoa practices, potential cocoa and maize over time. This model allows us to evaluate the impact of adopting a high-yield cocoa while considering international trade and accounting for the dynamic cocoa tree characteristics instead of using a static one-period model. Land reallocation occurs among current and potential cocoa and maize endogenously in our model. For instance, it implies that a policy that leads to a slow and steady adoption of 1% per year reaching 35% of the area under current practices 35 years later, will yield an increase in the area producing maize driven by market factors. Our results indicate that considering maize as an alternative crop while transitioning land out of cocoa due to the increase in yield results in an increase of $2.61 billion in profits for these two countries over thirty-five years.

In these countries, large areas of agricultural production are used for staple foods. Cocoa beans rank in the top ten crops in terms of production value in Ghana and Ivory Coast, along with cassava, yams, plantains, rice, palm oil and maize. Altogether, these crops represent 82% (82%) and 91% (77%) of the value of production (area harvested) in 2018 for Ivory Coast and Ghana, respectively. Cocoa, alone, generates 28% and 8% of the value of production in 2018 for these two countries. Maize was produced in 520 thousand and 1.179 million hectares in

Ivory Coast and Ghana, generating together almost US$ 1 billion in 2018, or US$ 608/ha and US$ 526/ha , respectively. Land allocation is much more complex at the farm level. The environmental/soil characteristics also play a role on the crop decision. There have been studies that investigate cocoa production in consortium with other crops such as Gockowski et al. (2011), which analyzes cocoa production along plantains and cocoyams for Ghana.

Several factors can impact the success of a crop substitution in cocoa farms while adopting high-yield cocoa. A public policy incentivizing a land partition between a yield-enhancing cocoa variety and an alternative crop could be implemented regionally based on socioeconomic and agro-climatic factors. Several socioeconomic reasons might drive the choice of the alternative crop. Because cocoa is a tree that does not generate revenues in its first few years and is a long life-cycle crop, an annual crop might be the chosen alternative because it would allow farmers to react to market changes on a year-to-year basis. Some of these crops are considered staple foods in these countries, which could help mitigating malnutrition and provide a steady food source during unexpected downturn years in the cocoa market. For this reason, in our model we use maize as alternative crop.

In the next section, we briefly discuss the agricultural economy of West African countries and the economic literature relevant to our analysis. Then, we introduce the model used to estimate the benefit of adopting a high-yield technology while reallocating land from cocoa to an alternative crop. Results are presented next. Lastly, we discuss the results in light of the current discussion on adoption.

2 Literature

The value of agricultural production in the three West Africa countries of Ghana, Ivory Coast, and Nigeria is mainly generated by cocoa, yam, palm oil, cassava, maize, rice, plantains and okra (FAO, 2018). Cocoa represented 21% of the total value of production in Ivory Coast in 2016, 10% of the Ghanaian and less than

1% of Nigerian total value of production (FAO, 2018). While Ghana and Ivory Coast exports are cocoa dependent, Nigeria does not rely solely on one commodity export (Abbott, 2013). Several perennial crops are produced in these countries, such as cocoa, palm oil and timber/firewood. Smoot et al. (2015) asserted that the average household income in Ivory Coast is 67% from cocoa production, 15% from coffee, 1% from palm oil, and 17% from other crops. They argued that coffee production has declined, and rubber production has increased since 2002.

Agriculture in West Africa countries structurally changed during the mid-1980s due to the Structural Adjustment Programs imposed by the World Bank and the International Monetary Fund (Tsiboe et al., 2016). After privatization occurred because of these changes, Ghana and Nigeria initially relied on private entities to market their commodities, while Ivory Coast heavily regulated private entities (Abbott, 2007; Abbott, 2013). It is logical that the government may have a stake in determining the price and is interested in keeping the price stable and as high as possible. Tsiboe et al. (2016) argued that heavy taxation, absence of input subsides, and farm training are all partially responsible for the declining yields in these countries.

As mentioned before, several programs sought to tackle the issue of poverty in these countries by targeting the lack of training and credit. The Vision for Change (V4C) is a program supported by Mars that seeks to boost cocoa yields in Africa. The project is in its initial phase performing on-farm research with different cultivars, investigating farmers' fertilizer use and other management practices, and establishing Cocoa Development Centres (CDC) in this region (Smoot et al., 2015). Another well-established program is the Cocoa Livelihood Program (CLP). It is a project by the World Cocoa Foundation and funded by the Bill and Melinda Gates Foundation that seeks to improve the livelihood of cocoa producers by providing training and other tools (Tsiboe et al., 2016). These programs' existence are key to our analysis. They could help to disseminate new varieties to farmers. We discuss the impact of these programs in more details in the next paragraphs.

Cocoa production in West African countries can differ for several reasons, such as the set of production management practices used and edaphoclimatic characteristics. The wide distribution of cocoa yields is mainly driven by different farm and smallholders' characteristics such as access to credit and input use (Gockowski et al., 2010; Guya et al., 2014; Smooth et al., 2015; Tsiboe et al., 2018a; Tsiboe et al., 2018b). The Ghanaian Ministry of Food and Agriculture reported a current yield of 500 kg/ha and argued that the potential yield is 1000 kg/ha (SRID, 2015). Norton and Nalley (2013) also found a wide distribution, reporting a yield range in Ghana from 213 kg/ha to 855 kg/ha.

The nature of the cocoa production requires a dynamic analysis of the impact of technology adoption on farmer welfare. As suggested by Mahrizal et al. (2014), cocoa production has four stages: no yield, increasing yield at increasing rate, increasing yield at a decreasing rate, and declining in yield. This yield behavior affects the income stream from cocoa production. Several papers have used net present value to analyze the impact of programs, such as the Cocoa Livelihood Program, on cocoa producer's income (Victor et al., 2010; Gockowski et al. 2011; Norton and Lanier, 2013; Oseni et al., 2013; Mahrizal et al., 2014).

Mahrizal et al. (2014) estimated the optimal replacement rate (ORR) and initial replacement year (IRY) of cocoa trees given production practices in West Africa countries. They used a deterministic dynamic model based on maximization of NPV during two production cycles (over 50 years). Three cocoa-tree input-output management schemes were considered in their analysis based on Gockowski et al. (2009). In addition to the baseline, they modeled five scenarios with changes in cocoa price (increase of 3% annually), fertilizer price (increase of 5% annually), labor price (increase of 5% annually), and two levels of yield loss due to black pod outbreak. They found the optimum ORR and IRY to vary across cocoa-tree input-output management. For the Low Input, Landrace Cocoa (LILC) cocoa-tree input-output management and the baseline scenario, the optimum ORR and IYR range from 5% to 7% per year and 5 to 9 years, respectively. An increase in cocoa price lowers the initial replacement year in order to capture higher profits from a higher price, while an increase in fertilizer price increases the IYR. They found that profit increases between 5.57% and 14.67% under different scenarios compared to the status quo for different cocoa-tree input-output managements. Mahrizal et al. (2014) also argue that Ghana still does not have a fully liberal marketing system, as the market is controlled by the Ghana Cocoa Board (COCOBOD). The COCOBOD determines the share of the international price (FOB) received by farms, which fluctuates around 70%. Mahrizal et al. (2014) used a share of 76.04% based on information in 2012 (Delmas, 2011).

Gyau et al. (2014) and Smoot et al. (2015) analyzed the impact of the V4C program on cocoa supply in Ivory Coast, using a quantitative survey of 400 producers conducted in 2013 and other data sources. Tsiboe et al. (2016) also investigated the impact of the Cocoa Livelihood Program (CLP) under a broader context. They used data on 2048 cocoa producers pre and post-CLP from Ghana, Ivory Coast, Nigeria and Cameron. To do so, they first estimated the change in yields using a difference-in-difference approach and, then, use the outcome in a NPV analysis over 25 years.

Norton and Nalley (2013) investigated the 2009-2014 Bill and Melinda Gates/World Cocoa Foundation (WCF) training program given to Ghanaian cocoa producers using a survey of 183 farmers. They used Mahrizal et al's (2014) approach and parameters but incorporated the gain in yields from the program from a regression analysis. The average farm size in their sample was 3.2 hectares and the average yield was 562 kg/ha, ranging from 213 kg/ha in Atwima Nwabiagya to 855 kg/ha in Sefwi Wiawso. They found that fertilizer and insecticide use increased yields by 54% and 34%, respectively. Out of the three training programs, only one increased yield s (statistically), the input promoter, by 75%. The NPV analysis found that this yield increase would increase farm income by 90% considering the estimated ORR and IYR of 6% per year and 9 years, respectively.

Tsiboe et al. (2018a) focus on labor heterogeneity in Ghanaian cocoa production and extensively describe cocoa production and smallholders' characteristics. They used the Ghana Cocoa Farmers Surveys of 2004, 2006, 2008 and 2010 in their analysis. In their data, an average farm was 2.8 ha, used 58 kg/ha of fertilizer and yielded 635 kg of cocoa beans per ha. Around 53% of the farmers had planted new trees and 25% had access to credit. The majority of the labor used on cocoa production was provided by the household (55%). They found that these households simultaneously make decisions on the production process and in-house consumption. Also relevant to our paper, their estimated production function suggested an inverse relationship between yield and farm size (elasticity of -0.51) and credit (-0.089), a direct relationship between yield and fertilizer (0.021), out-of-household labor (0.039), and in-household labor (0.053). While other inputs such as insecticide and fungicide had no impact on yield, they found that the planting of new trees led to a decrease in yield (-0.129) and that the trend, which could be a measure of technical change, led to an increase in yields (0.029). Although the paper does not explicitly define, it seems to assume a demand elasticity of -0.9 and a supply elasticity of 0.62 (see their Table 6). In another paper, Tsiboe et al. (2018b) also used a demand elasticity of -0.9, obtained from ICCO (2008). ICCO (2008) also reports a long-run price elasticity of cocoa export demand of 0.9 for Ghana and a price elasticity of 0.96 for the world.

3 Model

A simple country analysis calculating country supply as the sum over all farmers can shed light on the problem faced by these countries. The simplest estimate is $Q_t^S = Nq_{i,t}$. Here, N represents the fixed number of cocoa farmers and $q_{i,t} = y_t^O l_t(1-\gamma_t) + y_t^N \beta l_t \gamma_t$. y_t^O represents current yield, l_t is land in hectares in period t, γ_t represents the speed of transition (with $0 \leq \gamma_t \leq 1$ and $\gamma_t \geq \gamma_{t-1}$), y_t^N is the yield of potential cocoa, and β represents the land allocation to high-yield cocoa. This is the same as treating the country as a farm, and calculating the country supply as $Q_t^S = q_t^O L_0(1-\gamma_t) + q_t^N \beta L_t \gamma_t$ where q_t^O and q_t^N are country yields, L_0 is the total country land planted in cocoa in $t = 0$, and β is defined as before but for the country level.

Each country will maximize welfare over time while accounting for price changes in the international markets for cocoa and the alternative crop. In this scenario, these countries will determine the land allocation, specifically, β, such that producer and consumer surpluses in both markets increases. These changes would result in higher (or the same) farm income. To add complexity to this scenario, one could account for land allocation $1-\beta$ to an alternative crop, as is done in the next section. This would also generate additional income to farmers. Next, we present the non-linear optimization in which the social planner maximizes the welfare.

3.1 Model Description

The literature on the impact of adoption of high-yield technologies is large (Takahashi et al., 2019; cite a few meta-analysis studies). To estimate the impact of adopting a yield-enhancing technology in cocoa while accounting for land allocation to an alternative crop, we use a temporal and spatial partial equilibrium. We assume that countries maximize their welfare over time while trading the commodities with other countries. As in Busdieker et al. (2016), we modify the model discussed in Samuelson (1952) and Takayama and Judge (1964, 1971) to account for time.

We assume that each market has a linear demand and supply except for Ivory Coast and Ghana, which have a total cost function instead of a supply curve. The inverse demand and supply for country i in period t and commodity c are $P_{i,t,c} = \alpha_{i,c} + \beta_{i,c} Q^D_{i,t,c}$ and $P_{i,t,c} = d_{i,c} + e_{i,c} Q^S_{i,t,c}$, where $\beta_{i,c} < 0$ and $e_{i,c} > 0$. We use the demand and supply elasticity estimates to find the parameters for the demand and supply. There are three countries/regions, $i = 1$ for Ivory Coast, $i = 2$ for Ghana and $i = 3$ for the rest of the world. In the model there are 2 different crops, $c = 1, 2$, cocoa and maize with three different varieties $v = 1, 2, 3$, current cocoa, new cocoa and alternative crop, respectively. To capture the change in the Ivory Coast and Ghana supplies because of adoption of a high-yield cocoa we represent their supply using a cost structure, as in Busdieker et al. (2016). The objective function is

$$\max_{Q^D_{i,t,c},Q^S_{i,t,c},E_{i,i',t,c},L_{i,t,c}} W = \sum_t \delta \sum_i \sum_c \Big[Q^D_{i,t,c}(\alpha_{i,c} + 0.5\beta_{i,c}Q^D_{i,t,c}) - Q^{S*}_{3,t,c}(d_{i,c} + 0.5e_{i,c}Q^S_{i,t,c}) - TC_{i,t,c} - \sum_{i,i'} tc_{i,i'}E_{i,i',t,c} \Big] + \sum_{i=1}^{2} FTV_{i,c=1,a} \tag{1}$$

where δ represents a discount factor, $Q^D_{i,t,c}$ represents the quantity demanded for time t, country/region i and crop c, $Q^{S*}_{3,t,c}$ represents the quantity supply for the rest of the world given that supply for Ivory Coast and Ghana for both crops is represented using a cost structure as Busdieker et al (2016), $TC_{i,t,c}$ represents the total cost structure for countries $i = 1, 2$ discussed below, $tc_{i,i'}$ represents the transportation cost from country i to country i' of one unit of output. $E_{i,i',t,c}$ represents the quantity exchanged between countries in period t for commodity c.

The total cost function for Ivory Coast and Ghana are represented as $\sum_\omega mc_{i,c}L_{i,t,c}$, a function of the marginal cost per hectare $(mc_{i,c,v,a})$ to produce cocoa $(c = 1)$ and for other crops $(c = 3)$ over different technologies $(v = 1, 2, 3)$ and different tree ages (a). $mc_{i,c,v,a}$ varies by country (i), crop (c), technology (v) and age (a). rc represents the constant removal cost of a tree and $RA_{i,t,c=1,v,a}$ represents the hectares of cocoa $(c = 1)$ that were removed in country $i = 1, 2$ in period t of technology v and age a. This cost structure allows us to capture the increase in the cost associated with the new technology. $FTV_{i,c}$ represents the final total value of the standing crop (Busdieker et al. (2016)) for $c = 1$ (cocoa trees) for country $i = 1, 2$, which depends on the year in which the tree is at the terminal point T, as is shown below.

$$TC_{c,t} = \sum_a mc_{i,c,v,a} L_{i,t,c,v,a} + \sum_a rcRA_{i,t,c=1,v,a} \tag{2a}$$

$$FTV_{i,c=1,a} = L_{i,T,c,v,a} \sum_{T+\tau} \delta \left[py_{i,c=1,v,a} - mc_{i,t,c,a} \right] \tag{2b}$$

where $L_{i,T,c,v,a}$ allocated to each tree crop $(c = 1)$ and technology $(v = 1, 2)$, p is the optimal price in the terminal year, and the summation is over the tree life-cycle post-terminal point. We follow Busdieker et al (2016) and use an iterative process to obtain the optimal price in the terminal year. First the model is run using the price in $t = 0$. Price is then recovered and used in the next iteration. This process is repeated until the expected price in T and the price obtained in the previous iteration converge. $y_{i,c=1,v,a}$ represents the yield in country $i = 1, 2$, commodity $c = 1$, technology $v = 1, 2$ over age $a = 1, \ldots, 35$.

The maximization is constrained by equilibrium conditions (eqs. 3, 4 and 5), land restriction (eqs. 6, 7 and 8) and the cocoa tree dynamics (eq. 9). Equation (3) represents the usual market equilibrium that domestic demand is equal to supply minus exports plus imports for non-adopters for both crops $(c = 1, 3)$. Equations (4) and (5) state the market equilibrium for adopters for cocoa $(c = 1, 2)$ and alternative crop $(c = 3)$, respectively. Note that in equation (5) we are adding the land in the alternative crop in period $t = 0$ $(L_{i,0,3})$ to the additional land allocated out from cocoa $(L_{i,t,3})$. We assume that these countries will not reduce area harvested of this crop. The land constraint states that at time t the sum of the land allocated to the three crops (c) in a country i has to be equal of lower than the initial land allocated to these crops. Equation (7) imposes that land devoted to cocoa cannot increase. Equation (8) imposes that land allocated to the alternative crop should be equal to or greater than land in period $t = 0$. Equation (9) captures the nature of the cocoa tree. One hectare of cocoa tree of age a in period t is equal to a hectare of age $a-1$ in period $t-1$ subtracting what was removed in period t of age a.

$$Q^D_{i,t,1} + \sum_i E_{i,i',t,1} = Q^S_{i,t,1} + \sum_i E_{i',i,t,1} \tag{3}$$

$$Q^D_{i,t,1} + \sum_i E_{i,i',t,1} = \sum_{v=1}^{2} \sum_a y_{i,t,1,v} L_{i,t,1,v,a} + \sum_i E_{i',i,t,1} \tag{4}$$

$$Q^D_{i,t,c} + \sum_i E_{i,i',t,c} = y_{i,t,2,3} L_{i,t,2,3} + \sum_i E_{i',i,t,c} \tag{5}$$

$$\sum_c \sum_a L_{i,t,c,v,a} \leq \sum_c \sum_a L_{i,t=0,c,v,a} \tag{6}$$

$$\sum_{v=1}^{2} \sum_a L_{i,t,c,v,a} \leq \sum_a L_{i,t=0,c=1,v=1,a} \tag{7}$$

$$L_{i,t,2,3} \geq L_{i,0,2,3} \tag{8}$$

$$L_{i,t,1,v,a} = L_{i,t-1,1,v,a-1} + RA_{i,t,1,v,a} \tag{9}$$

New technology adoption

Adoption of new technologies or management practices depend on several factors such as availability to potential adopters, financial constraints, knowledge, and (internal and external) acceptability. To model adoption, we consider a 3 scenarios. Busdieker et al. (2016) assume an exogenous adoption with 1% rate per year , where ar is equal to $0.01t$, which implies that adoption would increase at rate of 1% per year over the 35 years, reaching 35% of the land planted of current cocoa in $t = 35$ (see eq. 10). Note that adoption of the new variety is a percentage of the current variety at $age = 1$. It implies that the new variety will be adopted only after the trees under current variety reach the removal age and are replanted. It assumes that productive trees will not be removed to plant new variety trees.

$$L_{i,t,c=1,v=2,a=1} \leq ar L_{i,t,c=1,v=1,a=1} \tag{10}$$

This constraint only imposes what trees should be replaced. It does not imply that land devoted to cocoa has to decrease. Adoption of a high-yield variety without land substitution can yield high production and low prices. On the other hand, a policy that also constraints land devoted to cocoa can potentially result in higher profits. Equation (11) says that land on current and new cocoa has to lower or equal to the initial land devoted to cocoa. For sake of simplicity, the rate of adoption is used as the transition rate, rate in which cocoa is replaced by an alternative crop. The transition rate has to be selected accordingly with the increase in yield of the new variety so supply is not affected. We add a ϕ factor to the equation to demonstrate how this transition rate affects the result of the policy.

$$\sum_{v=1}^{2} \sum_{a} L_{i,t,c=1,v,a} \leq (1 - ar_t \phi) \sum_{a} L_{i,t=0,c=1,v=1,a} \tag{11}$$

A third scenario is suggested by Busdieker et al. (2016), where none of the two constraints are included in the model. They find that without adoption constraints, land devoted to apple decreases considerably compared to the scenario with the restriction. This was expected, since increase in yield makes up for the decrease in land. They also find that profits increase under this scenario. However, they argue that this scenario does not take into account the limit producer and consumer acceptance of the new technology (genetically modified apples). Therefore, they focus on the results with the restriction. Our results are in line with theirs. This model was estimated using GAMS MINOS.

3.2 Data

To account for transportation cost between these countries, transportation cost per ton is calculated as the difference between prices in the two countries using FAO data based on implicit exports prices and importing prices . This approach was taken, instead of using producer prices as in Busdieker et al. (2016), because only a few countries produce cocoa. In the model, we use FAO data on quantity produced as the supply quantity for both cocoa and maize. We calculated the demand quantity as quantity produced minus exports plus imports. These quantities along with demand and supply elasticities are used to calculate the intercept and slope of the linear demand and supply curves.

Based on the literature, we assume that the demand elasticity for Ivory Coast, Ghana and Rest of the World for cocoa are -0.2, -0.2 and -0.6, respectively. The supply elasticity assumed for these three regions are 0.2, 0.2 and 0.3, respectively. We also collected information on domestic price (value of production divided by quantity produced) and export and import prices. The current technology yield (t/ha) and area harvested (ha) are also from FAO. Estimates for these parameters are not available for all countries. See Table 1 for the key parameters used in the model.

There is no information about the current age distribution of the cocoa trees in these countries. Therefore, we proceed by assuming that each age between 2 and 30 have the same number of hectares. Based on the average yield (FAO, 2021), we create a yield curve that starts with 0.141 t/ha at age 2 reaches 0.772 and 0.990 for IVC and GHA in age 7 and declines to 0.3 t/ha in age 24. The yield between these three values are calculated using a geometric average. The average of these yield curves results in approximately the FAO average of 0.467 and 0.535 for IVC and GHA, respectively. Yield curve times land distribution results in the quantity reported in FAO.

New cocoa tree In the last decades, we have seen the development of varieties that are disease resistant, drought resistant or other issues for several commodities. The development of gene editing techniques such as CRISPR has strengthen the search for such varieties. There are some scientists and institutions in pursue of disease-resistant cacao such as the Innovative Genomics Institute (IGI) from the University of California, Berkeley. They are focusing on Cacao swollen shoot virus (CSSV), which can reduce considerably yield. Gyau et al. (2014) reported that 32% of the smallholders in Ivory Coast faced cocoa swollen shoot virus (CSSV). This variety has the potential to reduce or eliminate these losses while preserving other important characteristics of the cacao tree and fruit. However, because this is an on-going scientific study, yield and cost information is not available.

To overcome this limitation, we consider a few scenarios. First, we use data from World Cocoa Foundation to model the yield curve. The results of this scenario are displayed in here. We use the best possible yield in the Farm Economic Model and its cost information. Yield can reach up to 1.5 t/ha, three times the current average. Note that this yield curve is possible to obtain with existent management practices. It represents a lower bound of potential gains from an introduction of a disease resistant variety. Second, we use Gockowski et al. (2011) data on different management practices to highlight the potential gains from adopting disease-resistant variety. Gockowski et al. (2011) report yields four times higher at the peak of the yield curve than the average reported in Table 1 for West African countries. Third, because such yield gains might be unrealistic at the country level , we model costs as in Gockowski et al. (2011) but with a lower yield (75% of the reported yield). It implies that Ivory Coast yield is 0.94 t/ha.

4 Results

In this section, we will focus in three scenarios. First, we will discuss the scenario with both adoption restrictions (eq. 10 and 11). Then, we will discuss the results of the scenario with only the first restriction (eq. 10). Lastly, we will discuss the scenario without the restrictions. Before analyzing the scenarios discussed in the previous section, we first analyze the industry without the adoption of the new technology. The main results are in table 2. Busdieker et al. (2016) report both the present value for profits over the 35 years and the total profit and the remaining value of the trees planted. We will also report both but focus on the present value of the profit. The average yearly profit is $2,787 and $1,476 million for Ivory Coast and Ghana. The present value of the profit over the thirty-five years for the baseline scenario (no adoption) is $54.63 and $30.45 billion for Ivory Coast and Ghana.

Scenario 1 imposes that adoption only occurs when tree productivity decreases enough that is profitable to replace for a new tree. It also imposes that some of the land devoted to cocoa must be allocated to maize. Figure 1 displays (top panel) the results of this scenario. While for Ivory Coast, all initial land is used among the two varieties of cocoa and maize, for Ghana land use decreases over time. The temporal and spatial market equilibrium yields a lower number of acres for Ghana. This is probably driven by the limited domestic demand for maize in Ghana. In the model solution, only ROW and Ivory Coast participate in the international market. The average yearly profit for cocoa for Ivory Coast and Ghana under this scenario is \$2,973 and \$1,523 million (table 2). The per hectare yearly average profit with cocoa is \$805.20 and \$1,114.89 for both countries, respectively. Under scenario 1, the net present value of profit over the 35 years and the value of the trees planted at year 35 is \$56.59 and \$31.10 billion for Ivory Coast and Ghana.

In Scenario 2, land allocated to these two crops, cocoa and maize, is the same throughout the entire time because equation (11) was dropped from the model. This change resulted in a few different results. First, maize production does not increase in these countries. Second, country supply increases along with a decrease in prices (see Fig. 2). These changes yield a lower net present value of the profit, \$48.61 and \$30.78 billion for Ivory Coast and Ghana, respectively. This result indicates that the land allocation constraint, represented by eq. (11), results in higher benefits for the countries.

The third scenario yields striking but expected results. Busdieker et al. (2016) report similar results when analyzing adoption in the US apple market. An unrestricted adoption scenario yields fast adoption of the new variety. The entire country would be producing under new variety before year 10. This is mainly driven by the superiority of the new variety here modeled. Even though costs are higher under this variety, the gain in yields more than compensate for them. The land devoted to the alternative crop varies by year for Ivory Coast while it does not as much for Ghana. The tree age and market prices play an important role on this result. As in scenario 1, Ghana does not trade maize, which results in a more stable production of maize in this country.

This scenario also yields a significant increase on the countries' supply of cocoa (fig 2). This occurs because land devoted to cocoa every year is mostly the same as in the first year but now enjoys a much higher yield. This significantly reduces prices of cocoa in these countries, resulting in a big loss compared to the other scenarios. The net present value for Ivory Coast and Ghana under this scenario is \$16.86 and \$15.27 billion. These numbers suggest that a slower and steadier rate of adoption with land reallocation to alternative crops is the best approach to increase profit per hectare when adopting a high yield technology.

Robustness check – alternative scenarios In Equation (11), $\phi = 1$, which implies that the rate in which each country shift out from cocoa to maize is proportional to the adoption rate. As a robustness check, we also calculate the results for $\phi = (0.5, 0.9, 1.1, 1.4)$. Results are displayed in table 3. A higher ϕ implies that the rate of land devoted to cocoa in the country decreases faster than the scenario 1 presented above and land devoted to cocoa at year 35 is lower. For instance, in scenario 1 presented above, 75% or lower of the initial land on cocoa will be devoted to cocoa in year 35. For $\phi = 1.4$, only 51% $(1 - 0.35 * 1.4)$ or lower of the initial land on cocoa will be devoted to cocoa. We find that Ivory Coast would benefit the most under a scenario where the land devoted to cocoa in year 35 is 61.5%, while Ghana would benefit the most under a scenario with land on cocoa equal to 68.5% in year 35. These numbers are considering the remaining of value of the trees at year 35. However, if we only consider the profit over the thirty-five years in the model, $\phi = 1.4$ is the best factor for Ivory Coast, while $\phi = 1.0$ is still the best factor for Ghana.

Relevant concerns regarding the policy on adoption of a high-yield variety while relocating land to an alternative crop is the uncertainty regarding adoption, the transition rate and their interaction. One might argue that a high (and unexpected) adoption rate (60% in year 35) jointly with a low reallocation (transition) rate (20% in year 35) can disrupt the world supply affecting international price and smallholders' income. The same can be said about the opposite scenario, a low adoption rate (10% at year 35) with a high reallocation rate (50%). For the first scenario, the net present value for the profit over the 35 years is $52.97 and $29.77 billion for Ivory Coast and Ghana, respectively. The latter scenario yields a profit of $56.68 and $30.69 billion for Ivory Coast and Ghana, respectively. While the first scenario results in lower profits compared to the baseline scenario (no adoption), the second scenario results in $2.29 billion in benefits for these two countries. Even though these scenarios can occur, they are very unlikely.

The demand and supply elasticities can also affect the results considerably. Based on Tsiboe et al. (2018a) estimates for demand and supply elasticities at -0.9 and 0.6, we calculate the results for the baseline and scenario 1 using those elasticities for Ivory Coast and Ghana and kept the elasticities for ROW unchanged. For the baseline model, we find profits of $51.53 and $29.11 billion for Ivory Coast and Ghana, respectively. For scenario 1, we find $54.11 and $29.99 billion for the same countries. Therefore, the increase in profits due to a slow and steady adoption while reallocating 35% of the initial cocoa land to maize yields a benefit of $3.46 billion over the 35 years studied.

5 Conclusion

While researchers have been working on a successful application of the gene-editing tool CRISPR-Cas9 in a cocoa variety, which has the potential to create a disease resistant tree which could generate yield increases of up to 30%, there are concerns about the downward pressure these yield increases could put on prices and subsequently on smallholders' incomes. There are also concerns about its consumer and political acceptability. In particular, the Ghana Cocoa Board (COCOBOD), which seeks to stabilize smallholders' income by fixing the buying price for cocoa in Ghana, fears that a supply shock from the introduction of a high-yield technology in the market would push down the international price.

This raises the question of whether and how programs can be designed to increase cocoa productivity while at the same time improving the economic well-being of the smallholders. Results from the previous section indicate that the concern regarding supply disruption can be mostly disregarded. A policy that incentivizes slow adoption of a high-yield cocoa tree while enforcing land reallocation between cocoa and an alternative crop can increase generate benefits for these countries.

Parameter	Description	Value
η	Demand Elasticity (IVC,GHA,ROW)	-0.2, -0.2 and -0.6
ε	Supply Elasticity (IVC,GHA,ROW)	0.2, 0.2 and 0.3
$Q_{i,1,1}^{S}$	Initial Quantity supplied for cocoa in 2018 (FAO, 2021) (IVC,GHA,ROW) in million tons	2.154, 0.905, and 2.514
$Q_{i,1,1}^{D}$	Initial Quantity demanded for cocoa in 2018 (FAO, 2021) (IVC,GHA,ROW) in million tons	0.628, 0.061, and 4.887
$Q_{i,1,2}^{S}$	Initial Quantity supplied for maize in 2018 (FAO, 2021) (IVC,GHA,ROW) in million tons	1.0.6, 2.31, and 1.121
$Q_{i,1,2}^{D}$	Initial Quantity demanded for maize in 2018 (FAO, 2021) (IVC,GHA,ROW) in million tons	1.07, 2.38, and 1,114
$p_{i,t=1,c=1}$	Initial price for cocoa (IVC,GHA,ROW) per ton	1,984.70, 1,677.10, and 2,778.00
$p_{i,t=1,c=2}$	Initial price for maize (IVC,GHA,ROW) per ton	315.00, 340.80, and 274.41
pc	Planting cost for IVC and GHA	
$mc_{a,1,v}$	Maintenance cost for cocoa for IVC and GHA	Varies by crop and age (see supplementary material)
rc	Removal cost for IVC and GHA	
$mc_{1,2,3}$	Maintenance cost for maize for IVC and GHA (represents the year cost)	

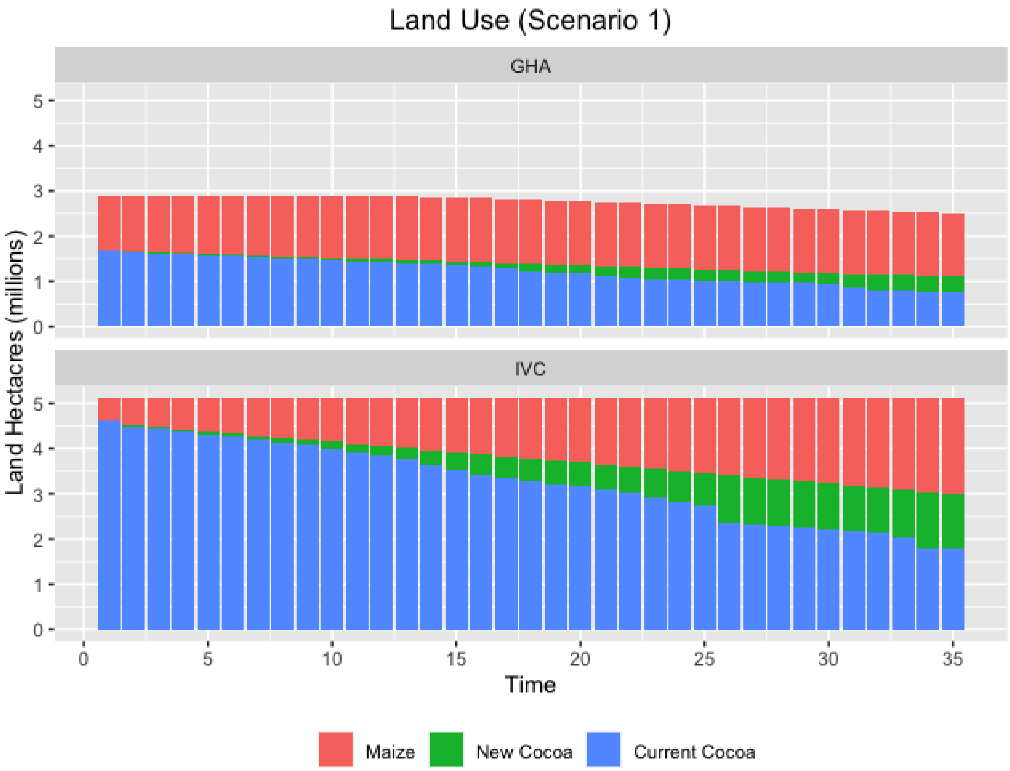
Table 1: Parameters used in the model

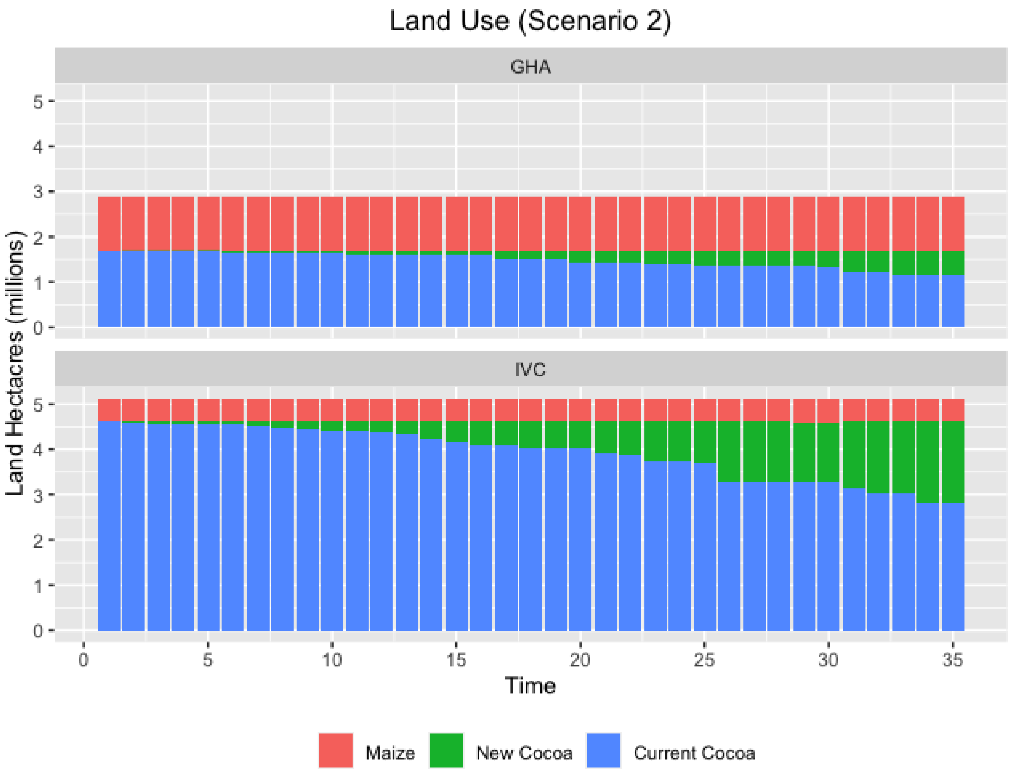
	No Adoption		Scenario 1		Scenario 2		Scenario 3	
	IVC	*GHA*	*IVC*	*GHA*	*IVC*	*GHA*	*IVC*	*GHA*
Av. Yearly Profit - cocoa	2787.01	1476.96	2973.82	1523.60	2361.79	1300.11	618.32	483.36
PV of Profit (NPV)	54.63	30.45	56.59	31.10	48.61	30.78	16.86	15.27
PV of Remain trees	16.49	7.96	19.85	8.00	15.63	6.87	7.69	4.47
Total profit (NPV)	71.12	38.41	76.44	39.10	64.24	37.66	24.55	19.74

Table 2: Average Profit and Net Present Value of profits for Ivory Coast and Ghana under the three scenarios.

	Average Yearly Profit for cocoa	Present Profit (NPV)	PV of Remaining trees	Total profit (NPV)
		$\boldsymbol{\phi = 0.5}$		
IVC	2730.75	52.7	19.47	72.18
GHA	1444.16	31.09	8.03	39.12
		$\boldsymbol{\phi = 0.9}$		
IVC	2934.48	55.93	20.03	75.97
GHA	1513.3	31.08	8.08	39.16
		$\boldsymbol{\phi = 1.1}$		
IVC	3011.39	57.2	19.42	76.63
GHA	1528.78	31.09	7.86	38.95
		$\boldsymbol{\phi = 1.4}$		
IVC	3091.86	58.67	17.58	76.26
GHA	1541.25	31.03	7.15	38.18

Table 3: Results for Scenario 3 under different values of ϕ, transition rate parameter.


Land Use (Scenario 1)
GHA
IVC
Land Hectacres (millions)
Time
Maize
New Cocoa
Current Cocoa


Land Use (Scenario 2)
GHA
IVC
Land Hectacres (millions)
Time
Maize
New Cocoa
Current Cocoa

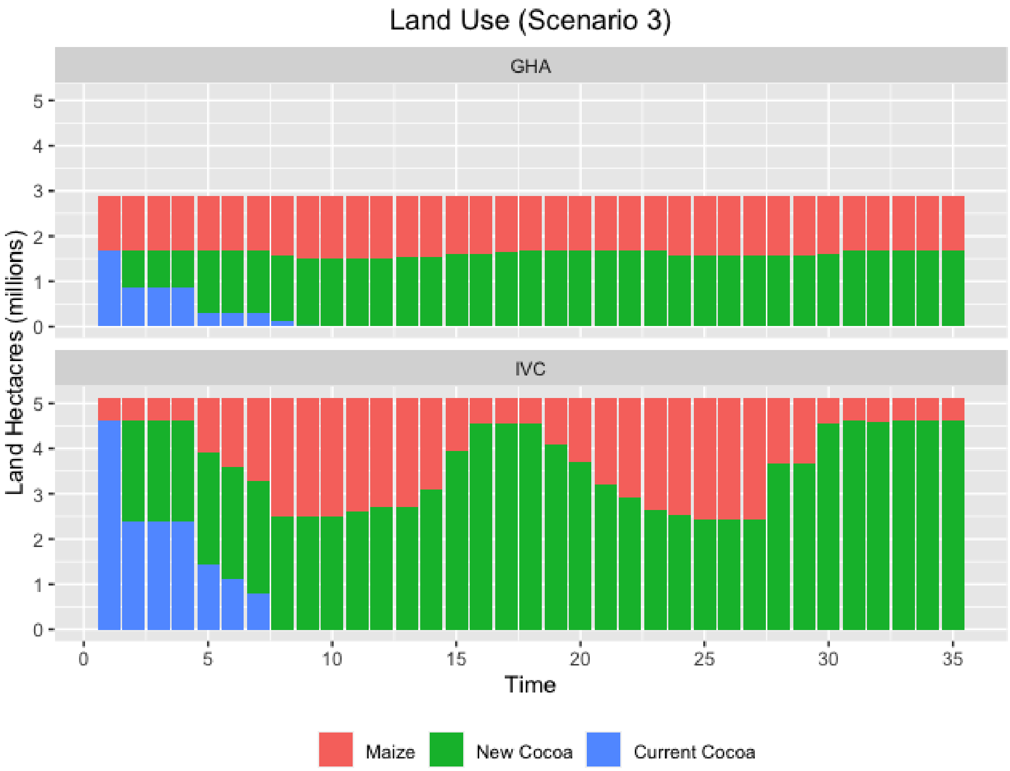
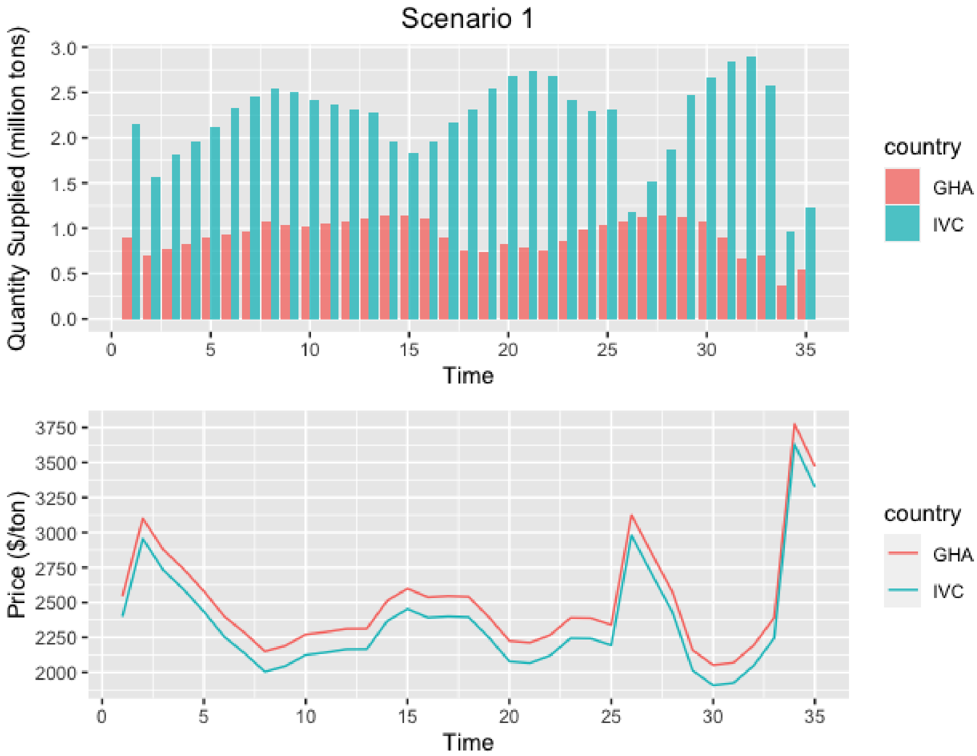
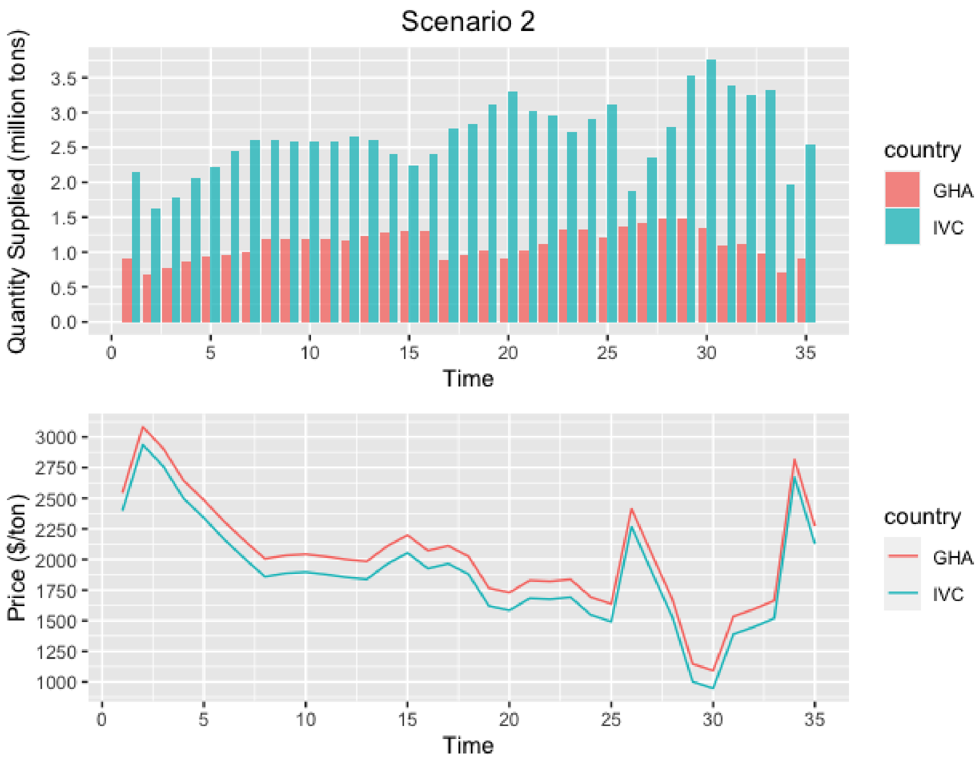


Figure 1: Land use for Ivory Coast and Ghana under three different scenarios over 35 years and with maize as alternative crop: (i) both adoption constraints, (ii) only one adoption constraint (eq. 10), (iii) none of the constraints.


Scenario 1
Quantity Supplied (million tons)
Time
Price ($/ton)
Time
country
GHA
IVC


Scenario 2
Quantity Supplied (million tons)
Time
Price ($/ton)
Time
country
GHA
IVC

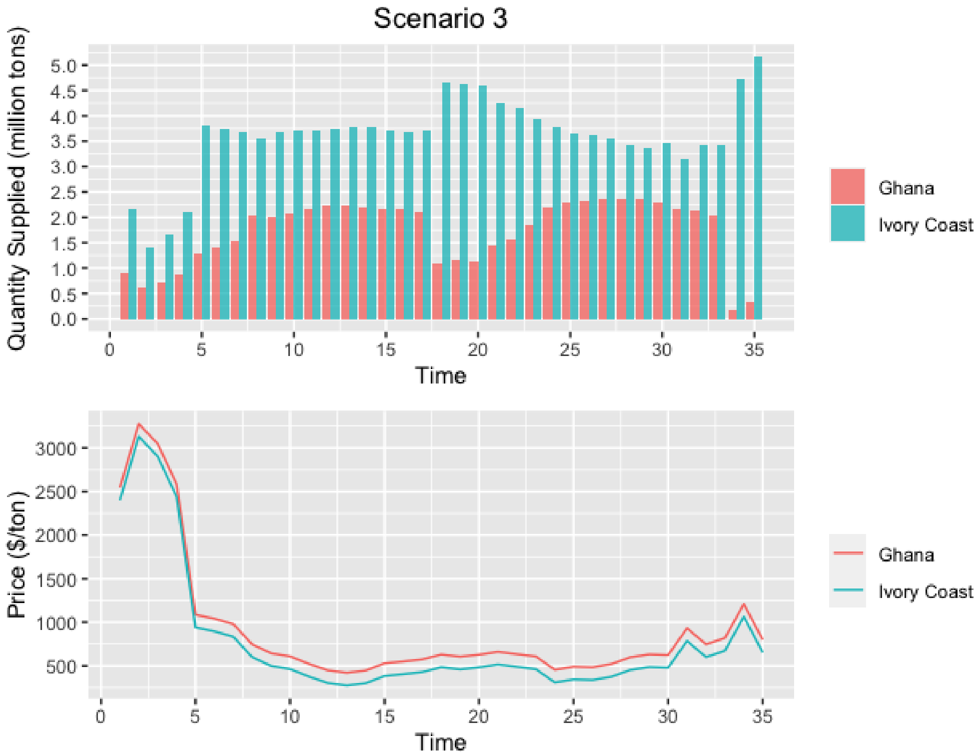


Figure 2: Quantity supplied and price for Ivory Coast and Ghana under three different scenarios.

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