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Climate change and coffee farm relocation in Ethiopia: a real-options approach

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Response to Reviewers:	We have uploaded a letter to the referee where we address all the points which have been raised.

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Keywords: Real-options, Coffee farms, Climate Adaptation, Relocation.

JEL classification: C61, Q54, Q58, R11.

1. Introduction

Climate change and emerging pests and diseases pose a serious threat to crop yields and revenues in Sub-Saharan Africa (Fischer et al., 2005; Schlenker and Lobell, 2010; Calzadilla et al., 2014; Cammarano et al., 2019). In Ethiopia, given the relevance that the agricultural sector has in the national economy, there is a growing concern about it (Deressa and Hassan 2009; Di Falco et al., 2012). As reported by Danyo et al. (2017), climate change may cause by 2050 up to a 10 percent reduction in the Ethiopian GDP. A significant part of this damage would be due to the lower production of coffee. In this respect, FAOSTAT data for the period (1993-2019) show that, even though volatile, the coffee yield per hectare has already exhibited a negative trend (see Figure 1).

Coffee is a very important commodity for Ethiopia since, alone, it represents about 30 percent of the national export earnings and supports livelihood for about 15 million Ethiopians (Moat et al., 2017b; Hirons et al., 2018). Small landholder farms produce the 95 percent of Ethiopian coffee in different environments including garden, semi forest, forest and plantation coffee (FAS, 2019). Ethiopia mainly produces Arabica coffee, which is, unlike Robusta, a very climate-sensitive variety (Davis et al., 2012; Sisay, 2018). Temperature and rainfall are crucial considering, in particular, that the production of Ethiopian coffee is entirely rain fed (see Chemura et al., 2021).

The impact of climate change on coffee yields varies across Ethiopia due to regional differences in agro-ecological conditions and climatic variations (UNDP, 2012; IPCC, 2014a, b; UNDP, 2018). Traditional coffee-producing areas in Eastern Ethiopia have experienced up to 100mm decrease in the crop-growing season’s rainfall during 1981-2016 and up to 3°C increase in the annual maximum temperature during 1979-2010 (Gebrechorkos et al., 2019). Based on the projections of multiple climate models, Moat et al. (2017b) identify vulnerable as well as climatically resilient areas. More specifically, they find that areas at higher altitude (with respect to those currently farmed) may, due to the increase in temperatures, become soon suitable for coffee production. In contrast, at low altitudes, the 39-59% percent of the current coffee-growing areas may become unsuitable by 2099. Areas such as Central Eastern Highlands, Arsi and Harar may, by now, be considered lost while the Northern Rift Valley and Bale may become unsuitable by 2040. The Rift Valley and the Eastern Rift Valley are instead highly vulnerable (Moat et al., 2017a; Moat et al., 2017b).

As new coffee-growing areas may become available, a strategy that has been suggested in order to adapt to climate change[1] is the relocation of coffee farms located in vulnerable areas[2] (Davis et al., 2012, Moat et al., 2017a, Moat et al., 2017b and Sisay, 2018). In particular, due to the favorable combination of moderate temperature and sufficient rainfall, Moat et al. (2017b) suggest the relocation to South-western Ethiopia, a move that may, up to their projections, lead to a fourfold increase in the coffee-growing area if compared with a no-migration scenario.

Farm relocation belongs to the set of transformational adaptation measures, [3] that is, as per Carter et al. (2018, p. 1), all the "*intentional responses to climate impacts that significantly shift the locations of agricultural production systems, introduce substantially new production methods or technologies at scale, or otherwise fundamentally alter key aspects of agricultural systems*". Incremental adaptation strategies,[4] such as crop diversification, the introduction of new varieties, more efficient irrigation, changing planting times, may, of course, be also helpful but they would likely allow coping only with short-term climate risks (Kate et al. 2012, Carter et al. 2018). In contrast, as climate impacts becomes increasingly severe, a more radical approach based on transformational adaptation may be needed in order to cope with climate risks in the long run (see e.g. Ovalle-Rivera et al. (2015), Läderach et al. (2017), Moat et al. (2017b) and Bunn et al. (2018).

In Ethiopia, population relocation has often been viewed as a viable strategy for addressing the mismatch between population pressure and agro-environmental conditions. Several resettlement programs have been implemented by the Ethiopian government in the past in order to mitigate the impact of demographic pressure, land fragmentation, land degradation, food insecurity and recurrent drought (Belay, 2004; Abera et al., 2020). A relatively recent example is the inter- and intra-regional resettlement of 440,000 farm households (about 2.2

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[1] See Stage (2010) for a review of the literature on the economics of climate change adaptation in developing countries.

[2] The vulnerability of coffee-growing areas at low altitudes is an issue also in other countries as reported by Läderach et al. (2017) for Nicaragua, Schroth et al. (2009) for Mexico, Rahn et al. (2018) for Uganda and Tanzania. Bunn et al. (2015) show that the altitudinal migration of coffee production may likely be a global trend.

[3] See Kates et al. (2012) for a definition of transformational adaptation and the distinction between incremental and transformational adaptation.

[4] Note that, in contrast with transformational adaptation, these strategies involve incremental "*actions where the central aim is to maintain the essence and integrity of the existing technological, institutional, governance, and value systems*" (IPCCa 2014, p. 839).

million Ethiopians) in SNNPR (Southern Nations, Nationalities, and Peoples' Region), Oromia, Sidama, Amhara and Tigray regions in the period 2003-2005 (Abera et al., 2020). Even though there is no clear evidence about the relocation of coffee farms, the most part of the resettled households came from regions in Eastern Ethiopia which are traditionally devoted to coffee production (OCHA, 2003).

In this paper, motivated by the relevance of the issue itself and by the importance of providing solid indications to policy makers, we investigate the profitability and timing of the hypothetical relocation of a coffee farm. Relocation involves high sunk establishment costs and uncertain net returns where the uncertainty is mainly due to the uncertain impact that the combination of changing temperature and rainfall may have on the coffee yields in both the current and the new growing site. In the light of these features, farmers currently engaged in the cultivation of coffee in vulnerable areas can be viewed as holding a (real) call option to relocate, an option that entitles, once exercised paying its strike price, i.e. the establishment costs, to a stochastic pay-off represented by the marginal gain in net returns from coffee production.

There are several previous studies investigating investments in climate change adaptation in the primary sector under a real-options approach.[5] Investing in an innovative irrigation technology under uncertain market and/or climate conditions has, for instance, been the focus in Seo et al. (2008), Heumesser et al. (2012), Narita and Quaas (2014), Ihli et al. (2014) and Malek et al. (2018), while Sanderson et al. (2016) and Yemshanov et al. (2015) have studied land-use change as adaptive strategy in response to climate change[6]. However, to the best of our knowledge, none has so far considered farms' relocation.

In this paper, we firstly frame the decision to relocate taking a real-options perspective. This is done assuming that establishment costs are constant while the yield differential between the two cultivation sites, i.e. the current and the new site, evolves over time following an Arithmetic Brownian motion. We determine the optimal timing of relocation and the value associated with the relocation project. We then study the impact that government subsidies may have as a stimulus for relocating earlier than privately optimal. In particular, we consider a subsidy covering a portion of the cost of establishing a new plantation. Lastly, we consider the hypothetical case of a coffee farm currently located in a coffee-growing area in Eastern or

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[5] See Dixit and Pindyck (1994) for an exhaustive treatment of the theory of real options.

[6] See Ginbo et al. (2021) for a recent review of real-options studies focusing on investment in climate change adaptation and mitigation.

South-eastern Ethiopia and apply our model to assess the profitability and timing of relocating it to South-western Ethiopia.

In the base-case, our results show that relocation is a rather attractive opportunity for farmers even in the absence of any subsidy. In fact, we find that the expected time of relocation is in about three years. Considering instead the introduction of a subsidy, inducing an immediate relocation requires a subsidy covering the 19% of the establishment cost, that is, about 17,640 ETB (696 USD)[7]. We then run a sensitivity analysis by letting both the drift and volatility characterizing the evolution of the yield differential vary. We find that the relocation time is decreasing in the trend of the yield differential. This is because the relocation project is expected to pay returns growing at a higher rate. Consistently, a 25% increase in the trend leads to an expected relocation within roughly one year and a half. This in turn implies that a lower subsidy is needed in order to induce an earlier relocation. Relocation would instead be optimal at the current period if volatility is 25% lower than in the base-case. If this is the case, no subsidies would be needed. In contrast, with a higher volatility, relocation would be further postponed in expected terms and fostering it with a subsidy may cost up to 65% of the establishment cost, that is, about 60,348 ETB (2,380 USD). Finally, we check for the impact that different degree of risk aversion may have on the decision to relocate. This is done by adding a risk premium to the risk free discount rate used in the base-case. We consider a "risk adverse" and a "strongly risk adverse" case by adding a risk premium equal to 5% and 10%, respectively. We show that the higher risk aversion, the later relocation occurs in expected terms. This is because farm relocation becomes, ceteris paribus, less attractive when the farmer requires a risk-premium for investing in it.

The remainder of the paper is organized as follows: in Section 2, we present our conceptual model for the farmer's relocation problem and discuss the impact of two possible types of subsidies; in Section 3, we introduce our case study and describe the data used for calibrating the numerical exercise. We present our findings and discuss their implications for policy design; Section 4 concludes. All proofs and additional material are available in the Appendices.

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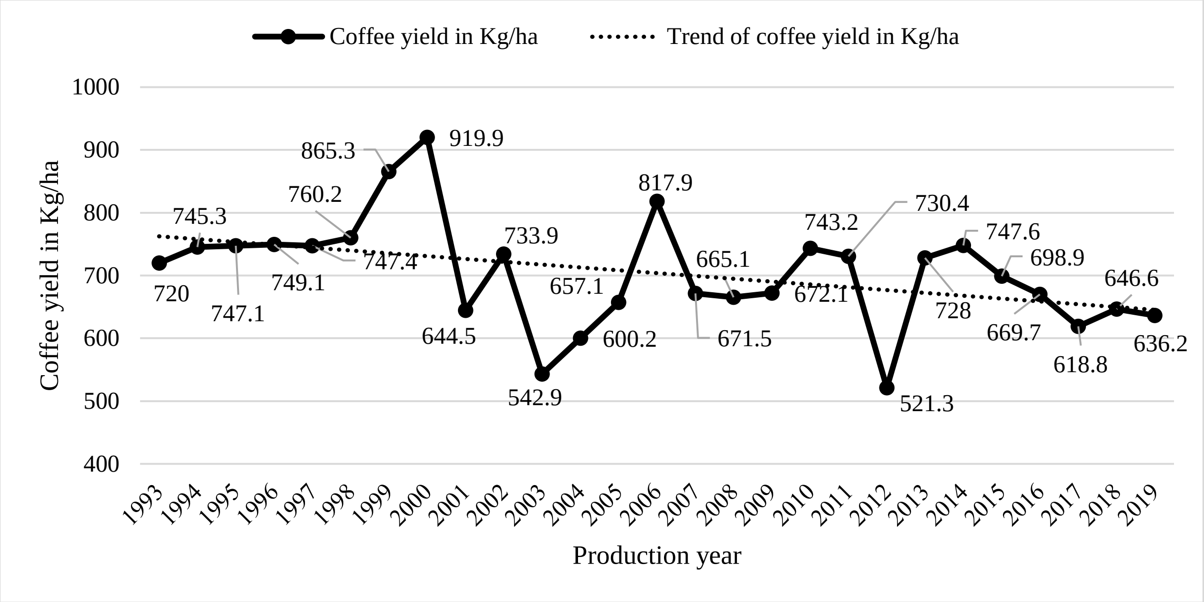
[7] We apply the currency rate 25.36 ETB = 1 USD. This currency rate results from averaging the rate reported on 30/06/2017, i.e. 23.22 ETB = 1 USD, and the rate reported on 31/12/2017, i.e. 27.50 ETB = 1 USD, both available at https://www.xe.com/en/. See Section 3 for further details.



Source: Own computations based on FAOSTAT 2019 data

Figure 1: Coffee yield and yield trend (in kg per hectare) in Ethiopia (1993 - 2019).

2. The model

In this Section, our aim is modelling the relocation of a small-holder coffee farm in Ethiopia under a real-options approach. We view the farmer as holding an option to relocate paying, upon its exercise, a stochastic pay-off represented by the marginal net gain from the relocation of coffee production. Finally, we study how the policy maker may foster the relocation process. This is done by considering a subsidy covering a portion of the relocation cost.

2.1. The model set-up

We consider a farmer contemplating the relocation of a 1-hectare coffee farm from site A (low altitude) to site B (high altitude). We assume that the yield differential,

$$Z_t = Y_{B,t} - Y_{A,t}, \tag{1}$$

where $Y_{B,t}$ and $Y_{A,t}$ are the per-hectare coffee yields at sites B and A at each time period t, respectively, evolves stochastically over time according to the following Arithmetic Brownian Motion (ABM):[8]

$$dZ_t = \alpha dt + \sigma dQ_t, \qquad with\ \ Z_0 = Z \tag{2}$$

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[8] By Eq. (1), Z_t may take also negative values over time. See Dixit and Pindyck (1994, Ch.3) for an illustration of the properties of a Brownian motion.

where the parameters α and σ represent the trend and volatility of the yield differential, respectively, and dQ_t is a standard Wiener process with $E[dQ_t] = 0$ and $E[(dQ_t)^2] = dt$.

For the sake of simplicity, we assume that i) the production costs, both fixed and variable, do not vary significantly between the two sites, ii) the variable production costs are linear in the yield and iii) the net return for 1 kg of coffee, R, is assumed constant over time.[9] Note that the first assumption implies that, when evaluating the relative economic convenience of cultivating coffee in a specific location, we can abstract away from considering some fixed costs, such as, for instance, rental payments, as they should be paid in any case, irrespective of the site where production occurs.

Further, we assume that a known and constant sunk establishment cost, K, must be paid when relocating. This includes any cost required to establish a coffee plantation in the new site, i.e. costs associated with operations such as land clearing, fencing, mulching, weeding, seedlings, etc.

Finally, we assume that the farmer discounts future cash flows using the discount rate[10] ρ and that, when considering the decision to relocate, s/he maximizes the expected net present value associated with this decision, that is,

$$W(Z_T; K) = (V(Z_T) - K) \cdot e^{-\rho T}, \tag{3}$$

with

$$V(Z_T) = E_T\left[\int_T^{\infty} R \cdot Z_t\, e^{-\rho(t-T)} dt\right] = R \cdot \left(\frac{Z_T}{\rho} + \frac{\alpha}{\rho^2}\right), \tag{4}$$

where T is the relocation time[11] and E_T is the expectation taken at this date.

In Eq. (4), we find the expected present value of the future marginal gains (in net returns from coffee production) accruing, once relocated, over an infinite time horizon.[12] As standard in the real-options literature, the farm relocation will be conditional on having an expected pay-off, $V(Z_T)$, higher than the sum of the establishment cost K plus the option value associated

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[9] See Section 4 for a discussion about the inclusion of a stochastic net return and Appendix A.4 for a more general model allowing for it.

[10] We study the relocation problem taking a dynamic programming approach. Note that in problems such as our own, contingent claims and dynamic programming approach with a constant risk adjusted discount rate are consistent with each other and lead to the same results (see e.g. Insley and Wirjanto, 2010).

[11] See Appendix A.1 for the derivation of this result.

[12] Several studies indicate a lifetime for coffee plantations from 32 up to 40 years (see e.g. Kushalappa and Eskes, 1989; Hein and Gatzweiler, 2006; Nair, 2010; Reichhuber and Requate, 2012). Hence, considering the effect of discounting, letting it tend to infinity has a negligible impact on our results.

with the decision to relocate.[13] If this condition holds, the option to relocate should be immediately exercised, otherwise, the farmer must wait until the condition is satisfied. It is worth highlighting that, by this condition, there is a range of values for Z_t where, even though $V(Z_t) \geq K$, the farmer should postpone the decision to relocate. This is to take into account the value of the option to wait which would be implicitly lost once relocated.

2.2. The value and timing of relocation

Ours is, technically speaking, a rather standard optimal stopping problem. The underlying idea is that at each generic time period t the value of immediate relocation (*stopping*) is compared with the expected value of waiting over the next dt (*continuation*), given the information available at that point in time and the knowledge of the process $\{dZ_t, t \geq 0\}$.

At the current period $t = 0$, the farmer's optimization problem is as follows:

$$F(Z) = \max_T E_0[W(Z_T)|Z_0 = Z], \tag{5}$$

where $F(Z)$ is the value of the option to relocate. Note that i) the opportunity to relocate does not provide any pay-off until time T and ii) the only return from holding the option to relocate is given by the appreciation of the option value, i.e. $E[dF(Z)]$.

As standard, the solution to problem (5) can be determined by solving the following differential equation:

$$\rho F(Z_t)dt = E[dF(Z_t)]. \tag{6}$$

Eq. (6) is a non-arbitrage condition equating the normal return, $\rho F(Z_t)dt,$ to the expected "capital gain", $E[dF(Z_t)]$ that holds in the so-called *continuation region*, that is, the region of values where exercising the option is not optimal.

By applying Ito's lemma on the RHS of Eq. (6) and rearranging, we obtain:

$$\frac{1}{2}\sigma^2 F''(Z_t) + \alpha F'(Z_t) - \rho F(Z_t) = 0. \tag{7}$$

The guessed form for the solution of Eq. (7) is:

$$F(Z_t) = Ce^{\beta Z_t}, \tag{8}$$

where C is a constant to be determined and β solves the following quadratic equation:

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[13] Note that other options may become available once relocated. These may include, for instance, the option to abandon the new plantation in order to move back to site A or to switch to an alternative economic activity (see Dixit and Pindyck, 1994 Ch.7). We abstract from these options since their incorporation would make our analytical framework more complex without having any substantial impact on the quality of our results.

$$\frac{1}{2}\sigma^2\beta^2 + \alpha\beta - \rho = 0. \tag{9}$$

Note that, as the value of the option to relocate, $F(Z_t)$, must vanish as Z_t goes to $-\infty$, we can ignore the negative root of Eq. (9) and consider only:

$$\beta_1 = -\frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{\alpha}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}} \; > 0.$$

The constant C and the optimal time threshold, Z^*, triggering farm relocation can be determined by imposing at Z^* the following boundary conditions:

$$F(Z^*) = V(Z^*) - K, \tag{10}$$

$$F'(Z^*) = V'(Z^*). \tag{11}$$

Eq. (10) is the so-called *value matching condition* by which we require that at Z^* the value of holding the option to relocate is equal to the pay-off associated with its exercise. Eq. (11) is the *smooth pasting condition* by which we require that exercising the option to relocate at $Z_t = Z^*$ is optimal. Substituting $F(Z_t) = Ce^{\beta_1 Z_t}$ into Conditions (10) and (11), we obtain:

$$Ce^{\beta_1 Z^*} = R \cdot \left(\frac{Z^*}{\rho} + \frac{\alpha}{\rho^2}\right) - K, \tag{12}$$

$$\beta_1 Ce^{\beta_1 Z^*} = \frac{R}{\rho}. \tag{13}$$

Solving the system [12-13] yields:

$$Z^* = \left(\frac{1}{\beta_1} - \frac{\alpha}{\rho}\right) + \frac{\rho K}{R}, \tag{14}$$

and

$$C = \frac{R}{\beta_1 \rho} e^{-\beta_1 Z^*}. \tag{15}$$

Hence, substituting Eq. (15) into Eq. (8), the value of the option to relocate is:

$$F(Z) = \frac{R}{\beta_1 \rho} e^{\beta_1 (Z - Z^*)}. \tag{16}$$

Rearranging Eq. (14) yields

$$R \cdot \left(\frac{Z^*}{\rho} + \frac{\alpha}{\rho^2}\right) = \frac{R}{\beta_1 \rho} + K, \tag{14.1}$$

which implies that, when relocating, the expected present value of the future flow of marginal gains from relocation, $R \cdot (\frac{Z^*}{\rho} + \frac{\alpha}{\rho^2})$, must be higher than the establishment cost K. In particular, it must cover also the option value factor, $\frac{R}{\beta_1 \rho}$, which takes into account, via β_1,[14] the presence of uncertainty. In this respect, note that letting σ go to 0 yields $\lim_{\sigma \to 0} R \cdot Z^* = \rho \cdot K$, that is, the standard *Jorgensonian* investment rule, by which one should invest (relocate in our case) when the periodic return from the investment, $R \cdot Z^*$, covers the user cost of capital, $\rho \cdot K$.[15]

The relocation time $T = \inf(t > 0 | Z_t = Z^*)$ with $Z_0 < Z^*$ is a stochastic variable with the following expected *first-hitting* value:[16]

$$E(T) = \begin{cases} \dfrac{Z^* - Z}{\alpha}, & if\ \alpha > 0, \\ \infty, & if\ \alpha \leq 0. \end{cases} \tag{17}$$

The expected *first-hitting* time has a finite value only if $\alpha > 0$, otherwise, its value is infinite. This is because, when $\alpha \leq 0$, the drift keeps the process $\{Z_t\}$ away from the barrier Z^*. The expected *first-hitting* time is instead null if $Z_0 \geq Z^*$ since, under these circumstances, the option to relocate should be exercised immediately.

Examining the effect of trend and volatility in the evolution of the yield differential, discount rate, net return and establishment cost, we find that:[17]

(i) the higher the volatility of the Z_t, the higher the threshold set for relocating since $\frac{dZ^*}{d\sigma} > 0$, which in expected terms implies that the relocation is delayed;

(ii) the higher the rate at which Z_t grows over time, the lower the threshold set for relocating since $\frac{dZ^*}{d\alpha} < 0$, which in expected terms implies that the relocation is anticipated;

(iii) the threshold set for relocating is non-monotone in the discount rate; in particular, we find that while the term $(\frac{1}{\beta_1} - \frac{\alpha}{\rho})$ is decreasing in ρ, the term $\frac{\rho K}{R}$ is increasing in ρ. This implies that the sign of $\frac{dZ^*}{d\rho}$ depends on the magnitude of the ratio $\frac{K}{R}$.

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[14] Note that β_1 denotes the elasticity of the discount factor $e^{\beta_1 (Z - Z^*)}$ with respect to Z^*. It is then a measure of the negative impact that investment delay has on the discounting of future payoffs. See Dixit et al. (1999).

[15] See Dixit and Pindyck (1994, Ch.5, pp. 144-145) .

[16] See Dixit (1993, pp. 52-57) on the probability and expected time of first hitting.

[17] See Appendix A.2 for these comparative statics.

(iv) the higher the net return R, the lower the threshold set for relocating since $\frac{\partial Z^*}{\partial R} < 0$, which in expected terms implies that the relocation is anticipated;

(v) the higher the establishment cost K, the higher the threshold set for relocating since $\frac{\partial Z^*}{\partial K} > 0$, which in expected terms implies that the relocation is delayed;

2.3. Relocation stimulus by subsidy

In the following, in the light of the initiatives taken by the Ethiopian government for supporting coffee farming at higher altitudes (Gebreselassie, 2018), we assume that the government intends controlling the relocation process and study the impact of a subsidy scheme on the timing of relocation. In particular, considering i) the dramatic impact that a lower coffee production may have on the balance of trade and the livelihood of millions of Ethiopians and ii) the reluctance that may characterize agricultural investment in rural Ethiopia,[18] we consider a subsidy scheme stimulating an immediate relocation.

Private and social optimal timing of relocation may not necessarily be the same since private and social objectives do not overlap. In fact, while farmers set their choice maximizing individual farming profits, the government must, in the interest of the whole society, address more general targets in terms of economic growth and welfare of the country. Therefore, as conditions and economic incentives at private level may fail to induce relocation at the socially optimal time, the government may intervene by introducing an incentive, i.e. a subsidy, such that the private timing equals the social one.[19]

Concerning the timing of relocation, we have shown above that the critical relocation threshold is decreasing in the establishment cost, i.e. $\frac{\partial Z^*}{\partial K} > 0$. This implies that it would suffice offering a subsidy covering part of this cost to induce an earlier relocation.

Denoting by $0 < s \leq 1$ the share of the establishment cost covered by the government subsidy, the critical relocation threshold becomes:[20]

$$Z^{*s} = Z^* - \frac{\rho K}{R} s. \tag{18}$$

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[18] See e.g. Holden et al. (1998), Yesuf and Bluffstone (2018) and Di Falco et al. (2019).

[19] See e.g. Dosi and Moretto (1997), Thorsen (1999) and Di Corato et al. (2013).

[20] Eq. (18) can be easily determined by setting the relocation cost equal to $K(1 - s)$ in the problem solved in Section 2.2.

Without loss of generality, setting the current period $t = 0$ as socially optimal for relocation, the subsidy s should be such that $Z^{*s} = Z_0$. Solving this equation yields:

$$s = \frac{R}{\rho K}(Z^{*} - Z_0) \leq 1; \tag{18.1}$$

Last, the following two remarks are in order:

1) Note that since $s \leq 1$ we may end up in a corner where $s = 1$ and $Z^{*s} > Z_0$. In this case, even though the introduction of the subsidy has, by lowering the relocation threshold, shortened the expected relocation time, it does not suffice to induce an immediate relocation.
2) The government may prefer setting a socially optimal timing different from the current period $t = 0$. In this case, it suffices setting a Z^{*s} such that the expected *first-hitting* time $E(T)$ equals the targeted timing, substituting it into Eq. (18) and solving for s.

3. Empirical Application

In the following, we consider the hypothetical case of a 1 ha coffee farm currently located in a macro area including coffee-growing areas in E and SE Ethiopia, i.e. site A, and evaluate its potential relocation in a macro area including regions coffee-growing areas in SW Ethiopia, i.e. site B. The E-SE area includes Harar, Bale, Sidama, Gedeo, Guji, Kambata, Wolayta, Dawuro and Gamo Gofa while the SW area includes Jimma, West Wollega, East Wollega, Qellem Wollega, Illubabor, Kaffa, Sheka and Bench Maji (see Figure 2).

This specific relocation plan has been chosen following studies on regional resilience to climate change such as Davis et al. (2012), Moat et al. (2017b) and Sisay (2018). These studies suggest the relocation of vulnerable coffee farms located at low altitude in E and SE Ethiopia to climatically resilient areas in SW Ethiopia where, due to the increase in temperatures, also sites at higher altitude (with respect to those currently farmed) may be or will soon become suitable for coffee production.

Before moving to the presentation of the parameters used for calibrating our numerical exercise, it is worth stressing that the scope of our analysis is merely illustrative and that, by no means, we consider it exhaustive for drawing final conclusions about the actual relocation of Ethiopian coffee farms. At the same time, we consider it useful in order to show how easily our model can be applied to the analysis of a specific case study and how informative the model can be for evaluating the effectiveness of the considered subsidy.

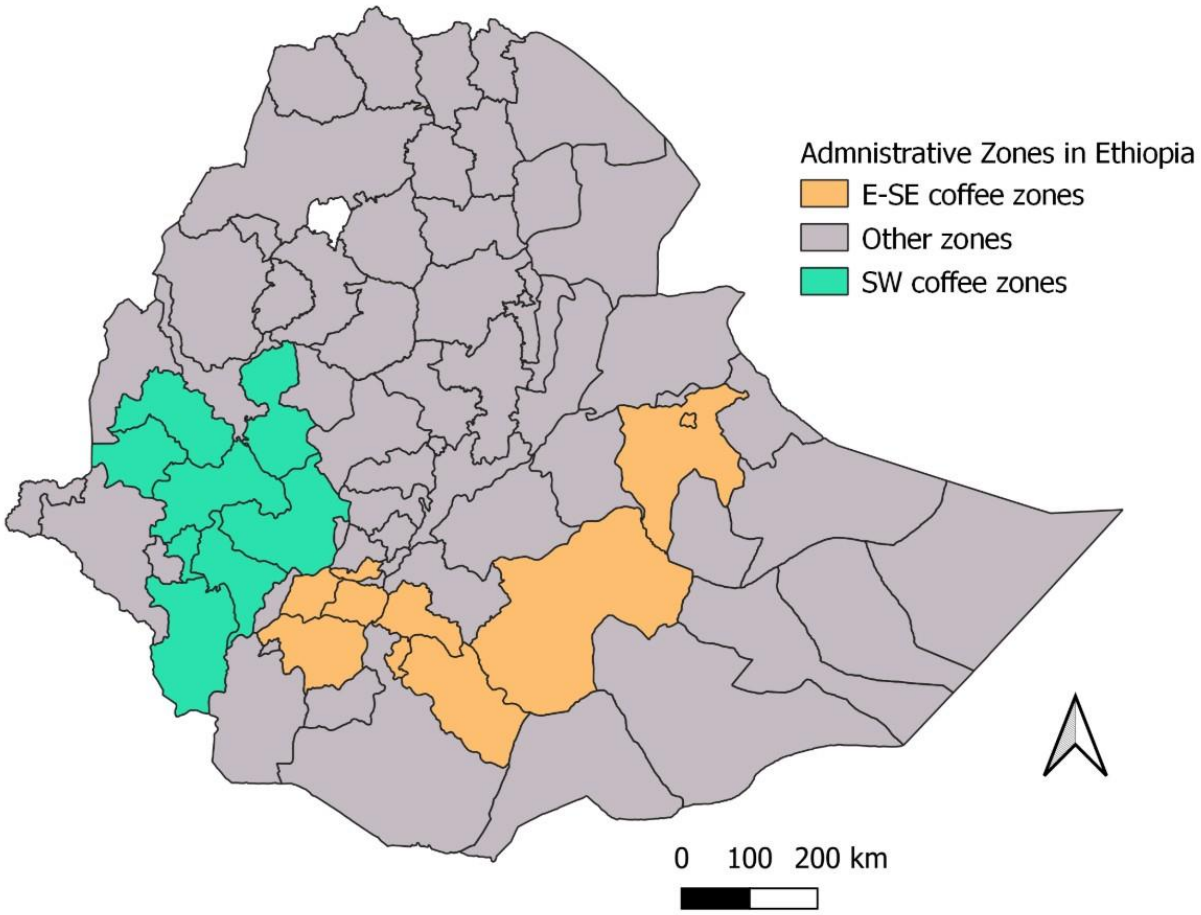

Figure 2: Map of the zones considered in the case study (own elaboration)

3.1 Parameters

In this subsection, we present and discuss our choices about the values of parameters used in the numerical analysis. These include: the current level of the yield differential, Z, its trend, α, and volatility, σ, when evolving over time, the net margin, R, the establishment cost, K, and the discount rate ρ. Table 1 summarizes all the parameter values used in our analyses.

Table 1: Parameter values

	Unit of measurement	**Base-case***	**Risk aversion****		**Sensitivity analysis****	
			Moderate	**Strong**	**-25%**	**+25%**
Discount rate (ρ)	%	5	10	15	-	-
Yield differential: trend (α)	kg/ha	9.24	-	-	6.93	11.55
Yield differential: volatility (σ)	kg/ha	76.06	-	-	57.05	95.08
Net margin (R)	ETB/kg	28.71	23.51	19.25	26.30	-
Establishment cost (K)	ETB/ha	92,842.75	-	-	-	116,053.44
Yield differential (Z_{2017})	kg/ha	296.59	-	-	-	-

Source: *Authors' computation based on the available data; **Authors' assumptions

The yield differential – We construct our time series for the yield differential between the two macro areas, i.e. $Z_t = Y_{B,t} - Y_{A,t}$, using the annual Agricultural Sample Survey (AgSS) data for the period of 2003 - 2017 provided by the Central Statistical Agency (CSA) of Ethiopia.[21]

The AgSS is a countrywide farm-level survey concerning the main crops produced in Ethiopia. The survey collects household level information about harvest area and production, land use, farm management and crop utilization. In order to construct the series Z_t, we first aggregate the responses for the variables of interest at zonal level. We then create the time series for each macro area, i.e. coffee-growing areas in E-SE Ethiopia ($Y_{A,t}$) and coffee-growing areas in SW Ethiopia ($Y_{B,t}$), grouping the areas falling within and computing the average coffee yield per hectare of land.

Plotting the two time series, $Y_{A,t}$ and $Y_{B,t}$, and the yield differential, Z_t, we notice that the coffee yield in the SW area has been higher than the yield in the E-SE area over the entire time horizon considered (see Figure 3 and Table A1 in the Appendix). For what concerns our exercise, we will use, for illustrating the current period $t = 0$, the figure relative to the yield differential in 2017, that is, $Z_{2017} =$ 296.6 kg/ha. Now, to be consistent with Assumption (2) in the model, i.e. dZ_t following an Arithmetic Brownian motion, the constructed time series Z_t must exhibit non-stationarity.[22] As standard, we test it using an Augmented Dickey Fuller (ADF) test and, as shown in Appendix A.3, we find that the null hypothesis, i.e., non-stationarity, is not rejected. Note that this means that the Arithmetic Brownian motion can be considered as a plausible assumption. We then proceed to the estimation of the parameters α and σ using an ARIMA regression and find that α = 9.24 and σ = 76.06, respectively. These estimates will be used to illustrate our base-case. However, in order to check the sensitivity of our results to these parameters, we will draw alternative scenarios by letting both parameters vary by a -25% and +25%.

Last, it is worth stressing that identifying the factors driving the trend and volatility of the yield differential over time and assessing their actual impact is not in the scope of our paper.

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[21] Note that the CSA has been collecting data through the AgSS since 1995. However, in this paper, due to the incompleteness of records concerning our variables of interest in earlier rounds, we can consider only the survey rounds starting from 2003.

[22] Note that when the available time series are too short, it is difficult to statistically distinguish between a non-stationary and a stationary process. For variables showing the tendency to revert to a mean value, one must count on many years of data in order to determine whether they are indeed mean reverting (see Dixit and Pindyck, 1994, Ch. 3).

Therefore, we do not make any claim about whether the observed dynamics is fully rather than partially explained by weather related variables such as rainfall and temperature.[23]

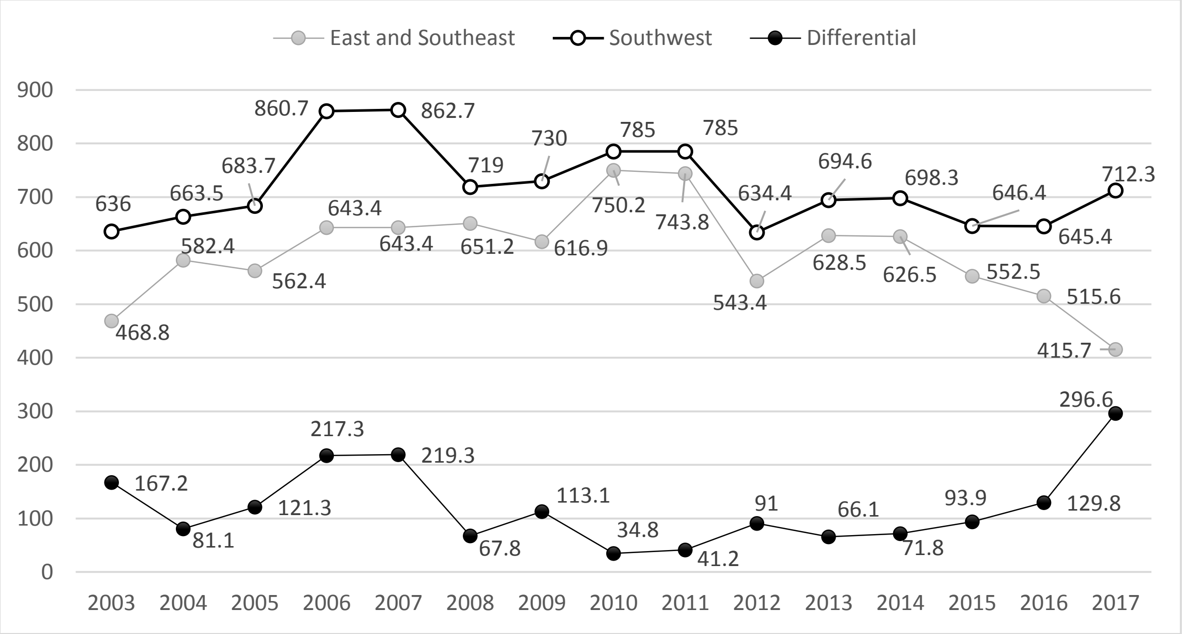

Figure 3: Coffee yield in SW and E-SE macro areas and yield differential.

Establishment cost and net returns – There are no official data when it comes to the costs of coffee production in Ethiopia. Therefore, in our analyses, we use cost parameter values resulting from the elaboration of the estimates provided by Diro et al. (2019). Their estimates are based on data collected from coffee farmers active in the Jimma zone (SW Ethiopia). They consider five growth stages for a coffee plantation with Stage I, II, III, IV and V covering the age intervals one year, two and three years, four to eight years, nine to twelve years, and above thirteen years, respectively. The establishment period, including both Stage I and Stage II, starts with site preparation and ends with the first harvest occurring when the plantation is 4 years old. Coffee is then harvested in every season falling within Stages III, IV and V with moderate variations in the average amount of the dry coffee resulting from the harvest.[24] Yield, in terms of quantity of dry coffee, and total cost borne at each stage are included in Table 2.

Concerning the calibration of our numerical exercise, we include into the establishment cost, K, any cost incurred during the period where the establishment of the plantation takes

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[23] Pests and diseases may spread more easily in the presence of a warmer and wetter weather. See Jaramillo et al. (2011) and Bebber et al. (2016) on the spread of the coffee berry borer and coffee leaf rust, respectively.

[24] See Diro et al. (2019) for further details.

place, i.e. Stages I and II. In this respect, unfortunately, Diro *et al*. (2019) do not provide any specific information about the actual timing of the expenses incurred. Thus, we assume that i) the total cost amount relative to Stage I is paid at the end of the first year, ii) 50% of the total cost amount relative to Stage II is paid at the end of the second year while the residual is paid at the end of the third year. All the amounts are discounted back accordingly assuming a risk-free interest rate equal to 5%.

The net return per kg of dry coffee is calculated subtracting from the price paid to growers the periodic production cost per kg of dry coffee paid during the harvest stages III, IV and V. For the price to growers in 2017, we use the figure provided by the International Coffee Organization[25] (ICO), that is, 1.86 US dollars per pound. The equivalent in ETB/kg, i.e. 47.18, is calculated considering the standard conversion rate kg/lbs, i.e. 0.45359 kg, and a currency rate ETB/USD equal to 25.36 ETB.[26] The periodic production cost per kg is calculated averaging the total production cost per kg relative to the harvest stages III, IV and V. The resulting cost figure is 12.11 ETB/kg[27] and subtracting it from the price to growers gives a net return equal to 35.07 ETB/kg. This amount must then be discounted back by 4 years in order to keep into account that the first harvest occurs when the plantation is 4-years-old. This yields a R = 28.71 ETB/kg when using a discount rate equal to 5%. Raising this rate to 10% and 15% gives instead R = 23.51 and R = 19.25, respectively.

Last, it is worth highlighting that in principle the difference in the plantation's age between the new and the old site may, of course, matter. For instance, a farmer whose plantation is at Stage V may find relocating more convenient than a farmer whose plantation is at Stage III. However, this seems not relevant in our numerical exercise since, as mentioned above, we observe only moderate variations in the average amount of the dry coffee resulting from harvests occurring at Stages III, IV and V.

Finally, note that in order to check the sensitivity of our results to the parameter values chosen for K and R, we will draw two alternative scenarios by letting K vary by +25% and R by a -25%. A higher K may be due to higher establishment costs or to the presence of other sunk relocation costs not considered in our analysis. A lower R may instead be due to lower

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[25] The ICO's historical data for coffee prices are available at http://www.ico.org/new_historical.asp.

[26] This currency rate results from averaging the rate reported on 30/06/2017, i.e. 23.22 ETB = 1 USD, and the rate reported on 31/12/2017, i.e. 27.50 ETB = 1 USD, both available at https://www.xe.com/en/.

[27] Note that the production cost per kg for each stage is calculated using the total cost figure (per ha) and the mean dry coffee figure (kg per ha) in Table 1.

prices paid to growers and/or to higher periodic production costs. Note that in both cases we allow for potential variations reducing the value of the relocation project and, by so doing, inducing a postponement of the relocation.

Table 2: Coffee production stages, production and costs.

Stages	**Description**	**Mean dry coffee (kg/ha)**	**Cost (ETB/ha)**
I	This stage starts with the plantation establishment and lasts until coffee age of 1 year. The main costs are associated to site preparation, seedling purchase, planting, hoeing, mulching, fertilizers application, watering, slashing, digging, fencing and guarding. There is no harvest at this stage.	0	79,920.95
II	This stage covers the coffee age 2-3 years. The main costs include watering, slashing, digging, compost and compost application, fencing and maintenance. There is no harvest at this stage.	0	19,053.14
III	This stage covers the coffee age 4-8 years. This stage is characterized by high yields and high harvesting costs.	1,734.09	22,039.29
IV	This stage covers the coffee age 9-12 years. This stage is characterized by high yields and high harvesting costs.	1,728.81	18,247.00
V	This stage covers a coffee age ≥ 13 years. As yields are expected to decline, operative costs increase in order to maintain high productivity.	1,518.14	19,843.27

Source: Data collected by the Ethiopian Institute of Agricultural Research (see Diro et al., 2019).

Discount rate and risk aversion - In our base-case, we consider a risk-neutral coffee farmer and assume a risk-free discount rate equal to 5%. This is in order to account, as opportunity cost for the capital investment required for setting up the coffee plantation, for the possibility that farmers could earn income by depositing their money into a bank account. The 5% figure is taken from Getnet et al. (2017) reporting it as saving rate paid by the Commercial Bank of Ethiopia. Then, we take into account the impact that different degree of risk aversion may have on the decision to relocate by using risk-adjusted discount rate (see e.g. Insley and Wirjanto, 2010). This is done by considering a 5% and a 10% risk premium for illustrating the cases of a risk-adverse and a strongly risk-adverse farmer (see Musshoff (2012). Adding these premia on the assumed risk-free rate leads to a 10% and 15% discount rate, respectively.

3.2 Critical relocation thresholds and expected relocation time: results

In this subsection, we investigate the optimal timing of relocation to the SW macro area for a small-holder coffee farm currently located in the E-SE macro area. We firstly determine, using Eq. (14), the threshold levels, in terms of yield differential between the two areas, triggering relocation, i.e. Z^*. This is done for the base-case that will be used as benchmark and then letting the relevant parameters vary within the intervals set in Section 3.1. Second, we identify the farmer's optimal timing strategy, i.e. relocate/wait, by comparing these threshold levels with the current level of the yield differential, that is, $Z_{2017} =$ 296.6 kg/ha. Third, we calculate, using Eq. (17), the expected time of relocation for each scenario, i.e. $E(T)$. In Tables 3, 4, 5 and 6, we present in bold the figures relative to the base-case and in italics the figures relative to scenarios where an immediate relocation is optimal.

For base-case parameters, the yield differential must exceed 326.94 kg to justify relocation. The current level of the yield differential, Z_{2017}, is below this critical threshold, then waiting is optimal for the farmer at the moment. This is because, even though the current yield differential is positive, option value considerations prevail. In other words, in the light of the establishment cost, a higher yield differential or equivalently a higher expected gain from relocation is needed to keep into account the presence of uncertainty about future returns. However, we notice that the threshold is close to the current level of the yield differential. In fact, consistently, relocation can be expected within roughly three years.

In line with findings in the real-options literature, the relocation threshold lowers as the trend of the yield differential, α, increases. This is because, ceteris paribus, relocation is expected to pay returns growing at a higher rate. Note that, consistently, relocation is, for instance, expected within 1.42 years when α is 25% higher than in the base-case. Looking at the volatility of the yield differential, σ, we notice that it has a relevant role in the decision to relocate. In fact, we find that when it lowers, an immediate relocation is optimal. Interestingly, the same conclusion holds irrespective of the trend value (see the first column of the first block in Table 3). In contrast, when the volatility increases by 25% with respect to the base-case, i.e. σ = 95.08, relocation is further postponed and is expected within roughly 9 years, that is, 3 times the amount of time in the base-case scenario. We notice that it may take even longer, roughly 5 times more, when α = 6.93, i.e. 25% lower than in the base-case, and σ = 95.08.

Table 3: Critical thresholds and expected relocation times.

$Z^* \mid E(T)$			
K = 92,842.75, R = 28.71, ρ = 0.05			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	285.62 | 0	342.68 | 6.65	400.92 | 15.05
α = 9.24	271.95 | 0	**326.94 | 3.28**	383.81 | 9.44
α = 11.55	260.37 | 0	312.99 | 1.42	368.26 | 6.20
K = 116,053.44, R = 28.71, ρ = 0.05			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	326.04 | 4.25	383.10 | 12.48	441.33 | 20.88
α = 9.24	312.37 | 1.71	367.36 | 7.66	424.23 | 13.81
α = 11.55	300.79 | 0.36	353.41 | 4.92	408.67 | 9.70
K = 92,842.75, R = 21.53, ρ = 0.05			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	339.51 | 6.19	396.57 | 14.43	454.81 | 22.83
α = 9.24	325.85 | 3.17	380.83 | 9.12	437.70 | 15.27
α = 11.55	314.27 | 1.53	366.89 | 6.09	422.15 | 10.87

Moving to the second and third blocks of Table 3, we can observe the effect of a higher establishment cost and of a lower net return per kg of coffee produced, respectively. The effect on Z^* is qualitatively similar. In fact, we notice that the threshold increases as K increases or R decreases with an expected relocation time, $E(T)$, more than two times and roughly three times longer, respectively. Letting also α and σ vary, we find that the effect on both threshold and expected time is the same under all scenarios. Further, we notice that the effect of a lower net return is stronger than the effect of higher establishment cost under all scenarios. This is because while the establishment cost is constant over time, the gain in net returns per ha associated with relocation is uncertain since it depends on the stochastic evolution of the yield differential.

Let us now focus on the effect of risk aversion. As shown in Table 4, we find that discounting at a higher rate induces, in expected terms, a further postponement of relocation with respect to the base-case. This is because relocation becomes, ceteris paribus, less attractive when the farmer requires a risk-premium for investing in it. This is, of course, not surprising considering the theoretically well-grounded result by which a higher investment reluctance is associated with a higher degree of risk aversion. Relocation is then postponed as it may be worth only when the yield differential and, consequently, actual gains from relocation reach sufficiently high levels. In terms of expected timing of relocation, we notice an important delay with respect to the base-case. In fact, the farmer should wait roughly 24 and 58 years when ρ = 0.1 and ρ = 0.15, respectively. Letting also α and σ vary, we find that the longest expected relocation time is 40.27 years when α = 6.93, σ = 95.08 and ρ = 0.1 and 83.54 years when α = 6.93, σ = 95.08 and ρ = 0.15. These results may have important implications for potential policies aiming at fostering relocation. This is because a higher budget is likely needed to compensate farmers relocating earlier than privately optimal.

Table 4: The impact of risk aversion on critical thresholds and expected relocation times.

<table>
<tr><th colspan="4">$Z^*|E(T)$</th></tr>
<tr><td colspan="4">K = 92,842.75, R = 28.71, ρ = 0.05 (risk-neutral)</td></tr>
<tr><td></td><td>σ = 57.05</td><td>σ = 76.06</td><td>σ = 95.08</td></tr>
<tr><td>α = 6.93</td><td>285.62 | 0</td><td>342.68 | 6.65</td><td>400.92 | 15.05</td></tr>
<tr><td>α = 9.24</td><td>271.95 | 0</td><td>**326.94 | 3.28**</td><td>383.81 | 9.44</td></tr>
<tr><td>α = 11.55</td><td>260.37 | 0</td><td>312.99 | 1.42</td><td>368.26 | 6.20</td></tr>
<tr><td colspan="4">K = 92,842.75, R = 23.51, ρ = 0.10 (risk-adverse)</td></tr>
<tr><td></td><td>σ = 57.05</td><td>σ = 76.06</td><td>σ = 95.08</td></tr>
<tr><td>α = 6.93</td><td>492.47 | 28.26</td><td>533.86 | 34.23</td><td>575.69 | 40.27</td></tr>
<tr><td>α = 9.24</td><td>484.41 | 20.32</td><td>524.98 | 24.72</td><td>566.30 | 29.19</td></tr>
<tr><td>α = 11.55</td><td>477.21 | 15.64</td><td>516.80 | 19.06</td><td>557.49 | 22.59</td></tr>
<tr><td colspan="4">K = 92,842.75, R = 19.25, ρ = 0.15 (strongly risk-adverse)</td></tr>
<tr><td></td><td>σ = 57.05</td><td>σ = 76.06</td><td>σ = 95.08</td></tr>
<tr><td>α = 6.93</td><td>807.15 | 73.66</td><td>841.25 | 78.58</td><td>875.59 | 83.54</td></tr>
<tr><td>α = 9.24</td><td>801.38 | 54.63</td><td>835.01 | 58.26</td><td>869.07 | 61.95</td></tr>
<tr><td>α = 11.55</td><td>796.11 | 43.24</td><td>829.18 | 46.11</td><td>862.87 | 49.02</td></tr>
</table>

3.3 Relocation stimulus by subsidy: results

In this Section, we study the effect that a subsidy covering a part of the establishment cost may have on the timing of relocation. In particular, we focus on the stimulus needed in order to make worth relocating at the current period. This is done by determining, using Eq. (18.1), the percentage s such that $Z^* = Z_{2017} = 296.6$ kg/ha. We first consider the base-case and then we let trend and volatility vary to study the effect of their variation on the stimulus needed. Further, we let also K, R and ρ vary, as specified in the previous section, to determine how the stimulus should be adjusted in order to take into account higher establishment costs, lower net returns and increasing risk aversion.

In the first block of both Table 5 and Table 6, we find the subsidy levels relative to the case of a risk-neutral farmer. In the base-case, immediate relocation may be induced by offering a subsidy covering the 19% of the establishment cost. This amount is decreasing in α since the higher the expected growth of the yield differential, the more valuable the relocation project. It becomes then, ceteris paribus, less costly inducing an earlier relocation. In fact, we find that, when $\alpha = 11.55$, it suffices offering a subsidy covering the 10% of the establishment cost. No subsidy at all is instead needed when the volatility lowers. This is because, as shown in Section 3.1, relocating at once is optimal in this case. In contrast, when volatility increases, a higher subsidy must be paid. This may require up to 54% of the establishment cost when $\sigma = 95.08$. This is because, in the presence of high volatility, option value considerations lead to higher relocation thresholds. Counterbalancing this effect is possible but requires a stronger stimulus in terms of subsidy. Last, considering all potential combinations of α and σ, we find that the costliest intervention, when adopting the first subsidy scheme, requires covering the 65% of the establishment cost when $\alpha = 6.93$ and $\sigma = 95.08$.

As shown in Table 6, we find that the percentage of establishment cost to be covered by subsidy is increasing in K and decreasing in R. This is because both variations lower, ceteris paribus, the value of the relocation project. This in turn implies that a higher subsidy should be offered in order to counterbalance the impact of this reduction on the relocation threshold. In fact, we find that the subsidy percentage raises i) to 35% when K increases by 25% with respect to the base-case and ii) to 39% when R decreases by 25% with respect to the base-case. In general, when considering all potential combinations of α and σ, we notice that the subsidy percentage ranges in the interval 2-72% when $K = 116{,}053.44$ and in the interval 8-73% when $R = 21.53$ ETB/ha.

Now, focusing on the impact of risk-aversion, we find that the higher the discount rate, the higher the percentage of establishment cost to be covered by subsidy. As mentioned before, including a risk-premium makes relocating at the current time less attractive with respect to the base-case. This translates, as shown in Section 3.1, in demanding a higher yield differential or equivalently a higher expected gain from relocation. Therefore, a higher subsidy is needed in order to counterbalance the effect of the risk-premium. This may be particularly costly with respect to the base-case. In fact, varying only the discount rate, we find that the subsidy percentage raises i) to 58% when including a 5% risk-premium and ii) to 74% when including a 10% risk-premium. Last, when considering all potential combinations of α and σ, we notice that the subsidy percentage ranges in the interval 46-71% with a 5% risk-premium and in the interval 69-80% with a 10% risk-premium.

Table 5: Subsidy levels with varying establishment cost and net returns.

s			
K = 92,842.75, R = 28.71, ρ = 0.05			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	0%	29%	65%
α = 9.24	0%	**19**%	54%
α = 11.55	0%	19%	44%
K = 116,053.44, R = 28.71, ρ = 0.05			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	15%	43%	72%
α = 9.24	8%	35%	63%
α = 11.55	2%	28%	55%
K = 92,842.75, R = 21.53, ρ = 0.05			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	20%	46%	73%
α = 9.24	14%	39%	65%
α = 11.55	8%	33%	58%

Table 6: Subsidy levels under different degree of risk aversion.

s			
K = 92,842.75, R = 28.71, ρ = 0.05 (risk-neutral)			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	0%	29%	65%
α = 9.24	0%	**19**%	54%
α = 11.55	0%	10%	44%
K = 92,842.75, R = 23.51, ρ = 0.10 (risk-adverse)			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	50%	60%	71%
α = 9.24	48%	58%	68%
α = 11.55	46%	56%	66%
K = 92,842.75, R = 19.25, ρ = 0.15 (strongly risk-adverse)			
	σ = 57.05	σ = 76.06	σ = 95.08
α = 6.93	71%	75%	80%
α = 9.24	70%	74%	79%
α = 11.55	69%	74%	78%

4. Conclusions

In this paper, we have investigated the hypothetical relocation of a small-holder coffee farm from a generic vulnerable site located in Eastern or South-eastern Ethiopia to a climatically resilient site located in South-western Ethiopia. Our results reveal that relocation, even though not optimal at the current period, is a rather attractive opportunity which may materialize within roughly three years. We find that relocation may be faster if the yield differential between the two sites would evolve over time growing at a higher rate and with lower volatility with respect to what we have been estimating using empirical data. In contrast, it will be further postponed if the cost of establishing a new plantation increases and/or net returns from coffee production decrease. Studying the effect of risk-aversion, we find that paying a risk-premium for investing in the relocation project may drastically delay relocation. Last, as increasing the climate resilience of coffee production has become an issue to be urgently addressed at policy level, we show that incentivizing farmers by offering a subsidy covering a part of the establishment cost may be an effective measure for fostering the relocation process.

However, apart from the non-trivial issue concerning the funding of measures enhancing climate resilience, there are several other issues to consider before promoting relocation (see e.g. Hirons et al., 2018). A first sensitive issue concerns the targeting of government support, that is, whether support should be given to the establishment of large-scale plantations rather than to small-holder production. Gains associated with scale, higher efficiency and capital availability should in fact be traded off with the impact that a policy favouring large-scale plantations may have on the livelihood of millions of Ethiopian small-holders. Second, migrating away may have a cost associated with the loss of the established social networks, a cost difficult to monetize but likely relevant for the decision to relocate. Third, potential conflicts between farmers previously settled in climatically resilient areas and new comers must be seriously kept into account. Similar conflicts may, of course, arise also when migrating from rural to urban areas (see e.g. Tacoli, 2009). Fourth, the conservation of natural forest may become problematic in the light of the need of clearing land for coffee production (see e.g. Girma et al., 2012). This imposes the consideration of compatible cultivation practices as, otherwise, adapting to climate change by relocating coffee farms would come at the cost of losses in terms of forests' contribution to climate mitigation and adaptation. This is to say that, apart from relocation, it may be worth considering also policy support to strategies enhancing the resilience of coffee production at the existing farm locations. These may include, as suggested by Läderach et al. (2017) and Hirons et al. (2018), the introduction of sustainable farm management practices, such as mulching, irrigation and shade-tree planting, and the development of climate resilient coffee varieties.

Last, we have a final remark for a potential future extension of our research. In this paper, due to the lack of time series data about net returns, the net return from coffee production, R, has been assumed constant over time. This is, of course, not necessarily realistic as the net return may very well evolve stochastically over time due to changing prices and production costs. Allowing for a stochastic net return does not affect qualitatively our results but it adds another argument for further postponing relocation since it increases, due to the inclusion of additional uncertainty, the option value associated with the decision to relocate. As data today missing may be available in the future or for using our frame for the analysis of similar issues, we show in the Appendix how our model can be easily generalized in order to allow for a stochastic net return.[28]

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[28] See Appendix A.4.

APPENDIX

A.1 The expected present value of the relocation benefits

The expected present value of the future pay-offs associated with relocation is:

$$V(Z_T) = E_T\left[\int_T^\infty R \cdot Z_t\, e^{-\rho(t-T)} dt\right], \qquad (A1)$$

where T is the relocation time. Note that by Fubini's Theorem,

$$E_T\left[\int_T^\infty R \cdot Z_t\, e^{-\rho(t-T)} dt\right] = R \cdot \int_T^\infty E_T[Z_t] e^{-\rho(t-T)} dt\,. \qquad (A2)$$

where, by Eq. (2),

$$E_T[Z_t] = Z_T + \alpha(t-T).$$

Rearranging Eq. (A2) as follows:

$$V(Z_T) = R \cdot e^{\rho T} \cdot (Z_T \cdot \int_T^\infty e^{-\rho t} dt + \alpha \cdot \int_T^\infty (t-T) \cdot e^{-\rho t} dt), \qquad (A3)$$

and integrating by parts the second integral in Eq. (A3) yields:

$$V(Z_T) = R \cdot e^{\rho T} \cdot (Z_T \cdot \frac{e^{-\rho T}}{\rho} + \frac{\alpha}{\rho} \cdot \int_T^\infty e^{-\rho t} dt) = R \cdot (\frac{Z_T}{\rho} + \frac{\alpha}{\rho^2}). \qquad (A4)$$

A.2 Comparative statics for the critical time threshold

It is easy to show that:

$$\frac{d\beta_1}{d\sigma} = -\frac{\sigma\beta_1^2}{\sigma^2\beta_1 + \alpha} < 0, \qquad (A5)$$

$$\frac{d\beta_1}{d\alpha} = -\frac{\beta_1}{\sigma^2\beta_1 + \alpha} < 0, \qquad (A6)$$

$$\frac{d\beta_1}{d\rho} = \frac{1}{\sigma^2\beta_1 + \alpha} > 0. \qquad (A7)$$

Hence, rearranging Z^* as follows:

$$Z^* = \frac{1}{2}\sigma^2\frac{\beta_1}{\rho} + \frac{\rho K}{R}, \qquad (A8)$$

and taking derivatives with respect to each parameter yields:

i) $\frac{dZ^*}{d\sigma} = \frac{\sigma}{\sigma^2\beta_1 + \alpha} > 0;$

ii) $\frac{dZ^*}{d\alpha} = \frac{1}{2}\frac{\sigma^2}{\rho}\frac{d\beta_1}{d\alpha} < 0;$

iii) $\frac{dZ^*}{d\rho} = \frac{1}{2}\frac{\sigma^2}{\rho}\left(\frac{d\beta_1}{d\rho} - \frac{\beta_1}{\rho}\right) + \frac{K}{R}$; Note that $\frac{d\beta_1}{d\rho} - \frac{\beta_1}{\rho} = \frac{r-(\sigma^2\beta_1^2+\alpha\beta_1)}{\sigma^2\beta_1+\alpha} < 0$. Therefore, $\frac{dZ^*}{d\rho} > 0$, if $\frac{K}{R} > -\frac{1}{2}\frac{\sigma^2}{\rho}\left(\frac{d\beta_1}{d\rho} - \frac{\beta_1}{\rho}\right)$; otherwise, $\frac{dZ^*}{d\rho} \leq 0$.

iv) $\frac{dZ^*}{dK} = \frac{\rho}{R} > 0$;

v) $\frac{dZ^*}{dR} = -\frac{\rho}{R^2}K < 0$.

A.3 Yield differential: unit root test

We construct the time series of the yield differential $Z_t = Y_{B,t} - Y_{A,t}$ using farm-level data provided by the Agricultural Sample Survey (AgSS) for the period of 2003 - 2017. This is done for the SW macro area (i.e. site A) and E and SE macro area (i.e. site B) (see Table A1).

Table A1: Coffee yield per hectare in SW (site A) and E-SE (site B) macro areas.

Year	$Y_{A,t}$	$Y_{B,t}$	Z_t	ΔZ_t
2003	468.830	636.041	167.212	-
2004	582.463	663.501	81.038	-86.173
2005	562.463	683.750	121.288	40.249
2006	643.390	860.715	217.326	96.038
2007	643.390	862.751	219.362	2.036
2008	651.236	719.002	67.767	-151.595
2009	616.899	729.983	113.083	45.317
2010	750.184	785.031	34.846	-78.237
2011	743.838	785.000	41.162	6.316
2012	543.415	634.413	90.998	49.836
2013	628.511	694.621	66.109	-24.889
2014	626.526	698.351	71.824	5.715
2015	552.536	646.383	93.848	22.023
2016	515.593	645.417	129.824	35.977
2017	415.692	712.282	296.589	166.765

In order to test whether the time series Z_t is consistent with the assumed ABM, let us first approximate dZ_t as follows:

$$\Delta Z_t = Z_t - Z_{t-1} = \alpha\Delta t + \sigma\varepsilon_t\sqrt{\Delta t} \qquad (A10)$$

where $\varepsilon_t \sim N(0,1)$. To be consistent with Eq. (2), Z_t must evolve as a random walk and be non-stationary (Gujarati, 2004).

Let us then proceed by i) rearranging (A10) as follows

$$\Delta Z_t = \theta_0 + \theta_1 Z_{t-1} + \sum_{i=2}^{n} \theta_i \, \Delta Z_{t+1-i} + \omega_t \qquad (A11)$$

where $\theta_0 = \alpha\Delta t$ and $\omega_t = \sigma\varepsilon_t\sqrt{\Delta t}$. and ii) taking an augmented Dickey-Fuller (ADF) test to check the non-stationarity of the series ΔZ_t. As standard, we use the *t*-statistic to test the null hypothesis of unit root. i.e. $H_0\colon \theta_0 = 0$. The *t*-values are higher than the critical values set for 1%, 5% and 10% significance levels (see Table A2). Hence, our null hypothesis is not rejected and that the maximum-likelihood estimates for α and σ are the mean and the standard deviation of the series ΔZ_t, that is, 9.241and 76.063, respectively.

Table A2: Unit root test for coffee yield differential and estimation of the parameters

<table>
<tr><th colspan="5">Dickey-Fuller test for unit root</th><th colspan="2">Number of obs = 14</th></tr>
<tr><th colspan="7">Interpolated Dickey- Fuller</th></tr>
<tr><td></td><td><i>Test statistic</i></td><td><i>1% Critical value</i></td><td><i>5% Critical value</i></td><td><i>10% Critical value</i></td><td colspan="2"></td></tr>
<tr><td><i>Z(t)</i></td><td><i>-1.600</i></td><td><i>-3.750</i></td><td><i>-3.000</i></td><td><i>-2.630</i></td><td colspan="2"></td></tr>
<tr><th colspan="7">MacKinnon approximate p-value for Z(t) = 0.4837</th></tr>
<tr><td>D.Yield_diff</td><td><i>Coef.</i></td><td><i>Std. Err.</i></td><td><i>t</i></td><td><i>P > |t|</i></td><td colspan="2"><i>[95% Conf. Interval]</i></td></tr>
<tr><td>Yield_diff L1.</td><td>-0.5672046</td><td>0.3545626</td><td>-1.60</td><td>0.136</td><td>-1.33973</td><td>0.2053207</td></tr>
<tr><td>_cons</td><td>70.64873</td><td>43.25371</td><td>1.63</td><td>0.128</td><td>-23.59299</td><td>164.8905</td></tr>
<tr><th colspan="2">ARIMA regression</th><th colspan="3">Log likelihood = -80.50709</th><th colspan="2">Number of obs = 14</th></tr>
<tr><td>D.Yield_diff</td><td><i>Coef.</i></td><td><i>OPG Std.</i></td><td><i>Z</i></td><td><i>P > |z|</i></td><td colspan="2"><i>[95% Conf. Interval]</i></td></tr>
<tr><td>Yield_diff_cons</td><td>9.241278</td><td>20.4556</td><td>0.45</td><td>0.651</td><td>-30.85096</td><td>49.33352</td></tr>
<tr><td>/sigma</td><td>76.06343</td><td>13.8537</td><td>5.49</td><td>0.000</td><td>48.91058</td><td>103.2163</td></tr>
</table>

A.4 A general model allowing for a stochastic net return

Let us assume that the net gain from farm relocation, that is,

$$G_t = R_t \cdot Z_t, \qquad (A12)$$

where R_t and Z_t are the net return for 1 kg of coffee and the yield differential at each time period t, respectively, evolves stochastically over time according to the following Arithmetic Brownian Motion (ABM):

$$dG_t = m dt + s dQ_t, \qquad with\ \ G_0 = G \qquad (A13)$$

where the parameters m and s represent the trend and volatility of the net gain, respectively, and dQ_t is a standard Wiener process with $E[dQ_t] = 0$ and $E[(dQ_t)^2] = dt$.

Note that, in addition to the uncertainty characterizing the yield differential, here we take into account also a second source of uncertainty, that is, the uncertainty characterizing the evolution of the net return over time (due to changing prices and production costs).

At the current period $t = 0$, the farmer's optimization problem is as follows:

$$F(G) = \max_T E_0[W(G_T)|G_0 = G], \qquad (A14)$$

where

$$W(G_T) = \left(E_T\left[\int_T^{\infty} G_t\, e^{-\rho(t-T)} dt\right] - K\right) \cdot e^{-\rho T}$$
$$= \left[\left(\frac{G_T}{\rho} + \frac{m}{\rho^2}\right) - K\right] \cdot e^{-\rho T},$$

and T is the relocation time.

Problem (A14) is, technically speaking, equivalent to Problem (5). Thus, following the steps in Section 2.2, the solution to Problem (A14) yields:

$$G^* = \left(\frac{1}{\gamma_1} - \frac{m}{\rho}\right) + \rho K, \qquad (A15)$$

that is, the critical threshold that the net gain must exceed to justify relocation and the value of the option to relocate, i.e.

$$F(G) = \frac{1}{\gamma_1 \rho} e^{\gamma_1 (G - G^*)}. \qquad (A16)$$

where

$$\gamma_1 = -\frac{m}{s^2} + \sqrt{\left(\frac{m}{s^2}\right)^2 + \frac{2\rho}{s^2}} > 0.$$

Note that as it can be immediately seen by comparing Eqs. (A15-A16) with Eq. (14) and Eq. (16), allowing for a stochastic R_t does not affect qualitatively our results in Section 2.2.

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