Adaptation to Climate Change and Climate Variability: Do It Now or Wait and See?

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Abstract

As growing attention is paid to climate change adaptation as an actual policy issue, the significant meaning of climate variability in adaptation decisions is beginning to be recognized. By using a real option framework, we shed light on how climate change and climate variability affect individuals' (farmers') investment decisions with regard to adaptation. Significant effects of the option value – it delays adaptation easily for several decades with a realistic set of parameter levels – implies a critical role of risk sharing in promoting adaptation. When variability-influenced adaptation involves the use of an open-access resource (water), uncoordinated farmers may adapt too early or too late depending on the level of their risk aversion. Private adaptation should be supported or deterred accordingly if farmers are not convinced about the possibilities of collective resource management in the long run.

Keywords: Adaptation to climate change, climate variability, risk and uncertainty, real option, water, open-access resources

JEL Codes: D81, Q20, Q54

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1 Introduction

The global average surface temperature has already significantly risen over the past century (IPCC, 2007), and studies suggest that even with the best of our mitigation efforts, negative effects of global climate change on human lives will become noticeable within decades, especially in the developing world (IPCC, 2007; World Bank, 2010b). Accordingly, interests in climate change adaptation are growing in policy debates.

While adaptation to climate change is not a problem of global public good as climate change mitigation is, it still involves some important economic questions. A relatively well-explored issue is the efficient allocation of resources between mitigation and adaptation (e.g., Tol, 2005; de Bruin et al., 2009; Onuma and Arino, 2011). Also, some of the adaptation measures, such as construction of seawalls, are public or collective in nature, and this means that their implementation constitutes a classic economic problem of public good provision (Mendelsohn, 2000).

Meanwhile, there are a large number of adaptation measures that are private in nature, such as the switching of crops in farming. Simple reasoning tells us that such private adaptation just takes place spontaneously as the benefits of adaptation are brought to the individuals who take efforts – in other words, private adaptation does not generate the needs for policy intervention. In line with this logic, previous economic studies have paid relatively little attention to this aspect of climate change adaptation as a potential policy problem.

In this paper, we show that this simple reasoning does not accurately capture the entire picture of private adaptation to climate change. A key feature here is that humans do not directly perceive a gradual change of climate but the baseline change of climate is hidden behind inter-annual fluctuations of weathers. Two well-known determinants of those inter-annual weather fluctuations are El Niño and La Niña, but there are many other factors, and their combined effects make precise predictions of weather patterns difficult on a multi-year time scale (e.g., Rosenzweig and Hillel, 2008). There is an increasing recognition that adaptation to climate variability is a key element for climate change adaptation in general (e.g., Cooper et al. 2008; Urban et al. 2012). For example, Urban et al. (2012) estimate that the inter-annual variation of US maize yields increases by an average of 47% by 2030-2050 relative to 1980-2000, while the average decline of yields in the same period is a still significant but much more modest 18%. Many of the private adaptation measures to climate change are taken primarily as a response to those weather fluctuations that are influenced by climate change, not directly to the baseline change of climate. While weather fluctuations themselves do not create a market failure, we show that they add a great deal of complexity to people's adaptation decisions, and in the presence of a market failure due to some other mechanism – in this paper we examine the use of an open-access resource – they lead to remarkably nuanced policy implications. The open-access resource in the model could be seen as water. Studies show that the use of irrigation greatly reduces the negative effects of weather shocks on crop farming (e.g., Schlenker et al., 2005), not only because irrigation

resolves water deficits in dry times but also because plants tend to manage heat shocks through enhanced evapotranspiration.

We analyze this problem by employing a real option framework. The key idea is that under uncertainty, individuals have incentive to delay fixed investments for adaptation as a switch from a weather-sensitive production alternative, to a weather-resistant one. Indeed, benefits of such delaying in adaptation have already been pointed out by some non-theoretical analyses of climate change adaptation. For example, a recent World Bank report (World Bank, 2010a, p.92) states that "countries should want to *delay* adaptation decisions as much as possible...while awaiting greater certainty about climate and socioeconomic scenarios" (emphasis in the original). By delaying, farmers might be able to capture relative bumper harvests in the near future even from a crop with an overall declining yield that is better to be abandoned eventually. We show that this factor is significant, as is for a variety of cases analyzed with the real option framework (e.g., Dixit and Pindyck, 1994) – indeed, with a reasonable set of parameter levels, the model suggests that the option value can easily delay adaptation for more than 40 years. The significance of the option value in delaying adaptation implies that if some of the risk is diversifiable, risk-sharing mechanisms such as insurance schemes can greatly promote adaptation, even if those mechanisms deal with a production mode that will be eventually abandoned. Also, coupled with a market failure in the form of uncoordinated use of an open-access resource (water), this option feature of adaptation decisions becomes a significant determinant for policy actions to improve the social welfare. For example, our results show that uncoordinated farmers with a high risk aversion may adapt too late although farmers with a low risk aversion would adapt too early under the same conditions, reflecting the external costs that the farmers impose on others by using the resource and the fact that extraction of an open-access resource is generally sub-optimal. If farmers remain suspicious about viability of long-term coordination on resource use, public interventions to support or discourage adaptation could improve the social welfare.

The paper is organized as follows. In the next section, we present a brief summary of a relevant literature. Section 3 is the core part of the paper, which discusses the model for cases without and with the use of an open-access resource. Section 4 concludes.

2 Relevant Literature

The role of risk and uncertainty in adaptation decisions regarding climate change is qualitatively widely recognized (e.g., World Bank, 2010b; Howden et al., 2007), but few economic studies have shed light on its economic implications yet. As discussed in the Introduction, a number of economic studies have investigated climate change adaptation, but they mainly address different issues such as the resource allocation between climate change mitigation and adaptation.

The focus of this paper is the role of risk from persistent climate variability as a delaying factor for substantial adaptation measures in the face of a long-run climate change. Studies that examine potential adaptation methods to climate change in agriculture indicate that while some of adaptation measures are incremental measures such as shifts in planting seasons, there are also larger but potentially effective measures that involve significant initial investments, such as the adoption of irrigation, a switch on the main crop of farming (for example, from the heat-sensitive wheat farming to the heat-resistant fruit farming), and a shift from crop farming to livestock farming (which tends to be less water intensive) (e.g., Howden et al., 2007; Mendelsohn, 2000; Seo and Mendelsohn, 2008). The latter type of adaptation measures entails high monetary and non-monetary initial costs to farmers and thus is not easily reversible. The farmers would need a particular consideration for the irreversible nature of decisions under uncertainty of climatic conditions in the future.

The real option approach is an effective analytical method to study this aspect of irreversible investment. Conceptually based on similar ideas to those of the seminal studies of the quasi-option value (Arrow and Fisher, 1974; Henry, 1974), it is an established methodology and is applied to a variety of economic problems (Dixit and Pindyck, 1994). There is also a fair amount of literature employing the real option approach to investigate the policy of climate change mitigation (reviewed by Golub et al., 2011). But applications of this approach to the context of climate change adaptation are still few, at least in terms of the investigation of generic theoretical aspects (rather than project evaluations in specific contexts, such as Linquiti and Vonortas, 2012). As related groups of academic studies, a substantial number of empirical studies examine the role of weather shocks on rural households (e.g., Rosenzweig and Binswanger, 1993 and related studies), and a theoretical literature exists on agricultural commodities and price shocks (e.g., Gouel and Jean, 2012 and references therein). But they do not address the investment aspect of adaptation to climate change.

3 Model

3.1 Basic Framework

We describe the basic framework of our adaptation model. The model is based on the framework of real option analysis (e.g., Dixit and Pindyck 1994), which highlights the significance of the option value for investment decisions under uncertainty. As for the way that the model formulates the switching between two production possibilities, the model draws on Dixit and Rob (1994), who made a similar discussion of switching decisions between two economic sectors in a different context.

Here, the farmers with identical characteristics in the economy consider switching their modes of production in the face of long-run change of climate, which comes as an exogenous process to them.

By paying a fixed cost, farmers who engage in a vulnerable farming mode may permanently shift to an alternative production that can better stave off the long-run damage of climate change, such as irrigated farming, the cultivation of a crop that is relatively heat-resistant, livestock farming, and non-farm employment. The fixed cost can take various forms, such as an investment in irrigation facilities, an alteration of farmland layout and topsoil to accommodate a new crop, purchase of livestock, and training of farmers themselves.

For simplicity and tractability, we only evaluate decisions of staying in the vulnerable production mode and moving to the new production mode, and not those of moving back from the alternative production mode to the vulnerable one. Since the weather-dependent production is stochastic, the latter type of switching is technically conceivable, although it has little relevance for the actual planning of climate change adaptation. Still, it is important to recognize that the model compares the benefits of either staying in the vulnerable production mode or moving to the alternative mode, not the benefits of engaging in two production modes in a complete sense. Meanwhile, for clarity of discussion, we do not consider a simultaneous engagement in the two production modes.[1]

Farmers make their decisions of switching by weighing the fixed cost and the long-term or time-discounted expected gains from the switching. Climate variability plays a critical role in the model. Under risk of future productions, the farmers may temporarily refrain from making new investments for the alternative production mode, *even if the other production mode, which is better suited in a changed climate, brings them a net increase of expected outputs.* Note that these preferences of farmers to delay new investments are not necessarily the same as risk aversion. They can also come from the farmers' profit-maximizing behavior through waiting for a favorable timing of switching productions. This also means that a delay might be caused not only by the output variability in the alternative production mode (to which they switch) but also from the output variability in the current production mode (in which they are currently engaging).

The economy produces two goods (agricultural products), 1 and 2.[2] In this paper, we consider two cases, one without the use of an open-access resource and the other with it. The open-access resource could be interpreted as water, as the adoption of irrigation is considered a major method for climate change adaptation (e.g., Mendelsohn and Dinar,

[1]To be precise, the two production modes may be regarded as two sets of production portfolios, each of which may contain multiple crops of cultivation and any other income sources. Small-scale farmers often diversify their livelihoods to mitigate the risk of income shocks. However, there are also general observations that farmers tend to have one main source of farming income, and that their total incomes are hardly free from weather shocks. In the following discussions, we implicitly consider that the switching deals with a substantial change in farmers' main mode of farming, such as that from cereal farming to fruit farming.

[2]As explained in the previous footnote, strictly speaking, these two are production portfolios rather than goods, but they could be seen as two goods at first approximation when farmers have a main source of farming income that is or is not weather-dependent.

2003).

Without the use of an open-access resource, the output levels of two production processes for the entire economy, Y_1 and Y_2, are given by

$$Y_1 = X_1 \left(\bar{L} - L\right) \tag{1}$$

$$Y_2 = X_2 L \tag{2}$$

where L is the number of farmers engaging in production 2 and $\bar{L}$ is the total number of farmers in the economy. The output levels of two production modes are determined by the productivity parameters X_1 and X_2. Production 1 is weather- or climate-dependent, and X_1 represents exogenous shocks in productivity due to weather patterns. With normalizing the price of good 1 to one and defining the relative price of good 2 as P, the aggregate earnings of farmers producing good 1 and good 2 are Y_1 and PY_2, respectively. Throughout this paper, P is set to be constant, implying that the product can be sold externally. Note, however, that P can in principle be endogenized as well, and in so doing, this framework could also be used for a general-equilibrium modeling.[3]

The productivity parameter X_1 follows a geometric Brownian motion

$$dX_1 = \mu_1 X_1 \, dt + \sigma_1 X_1 \, dz_1 \tag{3}$$

where $\sigma_1 \geq 0$.[4]

Approximation of weather fluctuations by Brownian motion is widely practiced in the literature of weather derivatives, although the mean-reverting Brownian motion processes (Ornstein-Uhlenbeck processes) are more commonly used than the geometric Brownian motion processes are (see for example, Benth and Benth, 2013). Besides simplicity and tractability, the advantage of the use of a geometric Brownian motion

[3]The relative price can be changed by a shift in the total composition of productions in an economy, in other words, the process of adaptation itself can alter P. Incorporating this property into the model produces remarkably diverse cases, many of which entail socially sub-optimal adaptation as a result of a missing risk market (Narita and Quaas, in progress)

[4]The stochastic processes of X_1 might be determined by a combination of variables. For example, X_1 could be a linear function of a normalized stochastic temperature $\tilde{T}$, i.e.,

$$X_1 = J\tilde{T}$$

or, it could be formulated with one additional stochastic variable (such as "R" as in "rainfall"), for example,

$$X_1 = \hat{J}\tilde{T}^{\chi} R^{\omega}$$

where J, $\hat{J}$, χ, and ω are constant. Note that X_1 still follows a geometric Brownian motion if both $\tilde{T}$ and R follow geometric Brownian motions, which are indeed realistic. Empirical evidence suggests that fluctuations of both temperature and precipitation influence inter-annual variations of crop yields, while the warming, not the precipitation changes, is the main determinant of their baseline trends (Lobell et al., 2011). In a similar fashion, X_1 can also incorporate fluctuations due to economic factors, e.g., exogenous demand shocks. In the following, we simply discuss X_1 as a single variable, which might encompass all those factors.

in our context is that it can take into account the uncertainty of (the lack of information about) long-run climate change and yield responses, which is indeed prominent (Knox et al., 2012; Roudier et al., 2011; Müller et al., 2011), rather than assuming that random patterns revolve around a known baseline, which could be a reasonable characterization for short-term developments of weather patterns. However, a geometric Brownian motion would underestimate the volatility of agricultural productivity if inter-annual variations of agricultural production were determined by a small number of extreme weather events. In this sense, our formulation of variability is conservative. In fact, the actual climate variability is a composite of various planetary-scale oscillations, which differ in length of cycle and may interact with each other (e.g.,Rosenzweig and Hillel, 2008). This means that the basic dynamic rules that determine the actual variability are more complex than those of Brownian motion processes and even unknown to some extent. Our formulation of variability is conservative also in this sense, because it assumes that the basic rules of changes are known.

Production 2 is independent of climate variability but has a trend represented by $X_2 = X_2^{t=t_0}\, e^{\mu_2(t-t_0)}$. We limit our discussions to the cases where $\mu_1 < \mu_2$, i.e., production of 1 becomes comparatively unfavorable in the long run (2 is relatively favorable under a warm climate). Note that μ_1 can be both positive and negative.

Next we turn to the case where the production process 2 uses an open-access resource, while the production process of 1 remains the same as in the above. The production process 2 takes an alternative formulation to reflect resource use. We use a simple-as-possible formulation for that purpose: L farmers are using process 2 with two inputs, namely some exogenously given factor X_{21} and an amount q of the resource (water), which is used under conditions of open access. The resource does not deplete, but the marginal extraction cost increases with the total amount of flow extraction from the common pool (i.e., the extraction cost function takes a convex shape). Note that goods 1 and 2 do not have to be distinguishable, in other words, the model could be interpreted also as a description of switching from rainfed to irrigated farming of the same crop.

An individual farmer's net revenue from process 2 is then given by

$$y_2 = q^{\alpha}\, X_{21}^{1-\alpha} - c\,(q, \tilde{q}, L) \tag{4}$$

The term $q^{\alpha}\, X_{21}^{1-\alpha}$, where α satisfies $0 \leq \alpha \leq 1$, represents the gross revenue for the farmer. The cost function $c\,(q, \tilde{q}, L)$ depends on the rate of extraction by the respective farmer, q, the number of farmers using that resource L, and the extraction rate by other (identical) farmers, $\tilde{q}$.

The parameter α of the gross revenue term is particularly relevant: The larger the value of α, the more important is the resource for production 2. One can thus expect that the market failure associated with overusing the resource increases with α.

Assuming that the collective extraction costs of resource take a convex function with the exponent $\eta > 1$, and the farmers bear the costs of extraction proportional to their share of extraction, we specify the following cost function for using the common-pool resource (the generalized case of an open-access resource):

$$c\left(q,\tilde{q},L\right)=c_0\left[q+\left(L-1\right)\tilde{q}\right]^{\eta}\cdot\frac{q}{q+\left(L-1\right)\tilde{q}} \tag{5}$$

With or without the open-access resource, farmers can switch their production mode from 1 to 2 by paying a fixed cost $I>0$. They make their switching decisions according to their time-discounted stream of utility given by

$$\int_0^{\infty} U\, e^{-\rho t}\, dt$$

where ρ is the pure time preference, and U is a function of flow consumption h

$$U\left(h\right)=G\left(h\right) \tag{6}$$

where

$$G\left(h\right)=\frac{h^{1-\epsilon}}{1-\epsilon} \tag{7}$$

and ϵ is the relative risk aversion parameter ($\epsilon>0$ and $\epsilon\neq 1$) .

3.2 Adaptation without an Open-Access Resource

We first consider adaptation without the use of an open-access resource. This case does not exhibit any market failure and thus does not involve policy mechanisms by itself, but it still provides some useful insights and serves as a benchmark for later discussions with a market failure.

The farmers spend all their earnings for consumption. The instantaneous utilities for the farmers producing 1 and 2, U_1 and U_2 , are thus given by

$$U_1\left(X_1\right)=G\left(X_1\right) \tag{8}$$
$$U_2\left(X_2\right)=G\left(PX_2\right) \tag{9}$$

The instantaneous private net gain for a farmer from switching from the production of 1 to 2 is

$$\Delta U\left(X_1,X_2\right)=U_2\left(X_2\right)-U_1\left(X_1\right)=\frac{\left(PX_2\right)^{1-\epsilon}-\left(X_1\right)^{1-\epsilon}}{1-\epsilon} \tag{10}$$

The time-discounted private net gain for switching from 1 to 2 is thus given by

$$v\left(X_1,X_2\right)=E\int_0^{\infty}\Delta U\left(X_1,X_2\right)\, e^{-\rho t}\, dt \tag{11}$$

Solving the integral and taking expectation leads to

$$v\left(X_1, X_2\right) = \frac{1}{1-\epsilon}\left[\frac{\left(PX_2\right)^{1-\epsilon}}{\rho-\left(1-\epsilon\right)\mu_2} - \frac{\left(X_1\right)^{1-\epsilon}}{\rho-\left(1-\epsilon\right)\mu_1+\frac{1}{2}\epsilon\left(1-\epsilon\right)\sigma_1^2}\right] \tag{12}$$

Farmers switch production if those time-discounted gains exceed the sum of the initial fixed cost and the option value. The option value of moving to production 2, f, is a function of X_1 and X_2 and satisfies

$$\rho f\left(X_1, X_2\right) dt = E\left[df\left(X_1, X_2\right)\right]$$

By using Ito's Lemma, we obtain the following differential equation for f

$$\frac{1}{2}\sigma_1^2 X_1^2 f_{X_1X_1} + \mu_1 X_1 f_{X_1} - \rho f = 0 \tag{13}$$

Boundary conditions (the value-matching and smooth-pasting conditions) give closed-form solutions of the above. Here, we treat X_2 as given and derive a threshold X_1^* above which $f > v - I$, that is, it is favorable not to switch production.

The value matching condition is

$$f\mid_{X_1=X_1^*} = v\mid_{X_1=X_1^*} - I \tag{14}$$

The smooth pasting condition is

$$f_{X1}\mid_{X_1=X_1^*} = v_{X1}\mid_{X_1=X_1^*} \tag{15}$$

With those equation and conditions, the solution of f take the following form

$$f = A X_1^{\beta} \tag{16}$$

The two parameters A and β, and the threshold level X_1^* are the solutions of the following set of equations:

$$\frac{1}{2}\sigma_1^2\beta\left(\beta-1\right) + \mu_1\beta - \rho = 0 \tag{17}$$

$$X_1^* = \left[\frac{D_1 R_2}{\frac{1}{1-\epsilon}-\frac{1}{\beta}}\right]^{\frac{1}{1-\epsilon}} \tag{18}$$

$$A = -\frac{D_1^{\frac{-\beta}{1-\epsilon}}}{\beta}\left[\frac{R_2}{\frac{1}{1-\epsilon}-\frac{1}{\beta}}\right]^{1-\frac{\beta}{1-\epsilon}} \tag{19}$$

with

$$D_1 = \rho - \left(1-\epsilon\right)\mu_1 + \frac{1}{2}\epsilon\left(1-\epsilon\right)\sigma_1^2 \tag{20}$$

$$D_2 = \rho - \left(1-\epsilon\right)\mu_2 \tag{21}$$

$$R_2 = \frac{1}{1-\epsilon}\left[\frac{\left(PX_2\right)^{1-\epsilon}}{D_2}\right] - I \tag{22}$$

As for β, two values, one positive and the other negative, can satisfy the above conditions (obtained as solutions of a quadratic equation). However, only the negative solution of β has an economic meaning since the option value f should become negligible as X_1 becomes large: if X_1 is very large, production switching will never be necessary, and the option to switch to production 2 is valueless. If the corresponding A and X_1^* for the negative β are positive, this means that there is a range of X_1 in which $f > v - I$, in other words, it is beneficial not to exercise switching (hold the option) even if the expected net return from switching is positive. This leads to the following proposition.

Proposition 1. *If a combination of a negative β, a positive A and an X_1^* satisfying the above* (16) – (18) *exists, the farmers engaging in 1 do not switch to 2 until X_1 becomes as low as X_1^*, even if a switch to 2 brings a positive expected gain $v - I > 0$.*

The above solutions represent only the individual decisions by farmers and not the social optimum. The social optimum is found by replacing the time-discounted private gain v with the time-discounted social gain from a farmer's switching.

The time-discounted social gain is obtained as follows. First, by using U_1 and U_2, the instantaneous social welfare is expressed as:

$$B\left(L, X_1, X_2\right) = \left(\bar{L} - L\right) U_1\left(X_1\right) + L\, U_2\left(X_2\right) \tag{23}$$

The partial derivative of B with respect to L, B_L, gives the instantaneous marginal social benefit of switching by a farmer to production 2.

$$B_L = U_2\left(X_2\right) - U_1\left(X_1\right) + \left\{ L\,\frac{\partial U_2}{\partial L} + \left(\bar{L} - L\right)\frac{\partial U_1}{\partial L} \right\} \tag{24}$$

The time-discounted social gain is obtained by replacing B_L for ΔU in (11). The social optimum is calculated by the same procedure as in the case of private solutions. In other words, socially optimal switching of a farmer takes place only when $E\int_0^\infty B_L\, e^{-\rho t}\, dt - I$ is greater than or equal to the option value.[5]

In the present case, as U_1 and U_2 are independent of L, i.e., $\frac{\partial U_2}{\partial L} = \frac{\partial U_1}{\partial L} = 0$. Hence, B_L is simply given by:

$$B_L = U_2\left(X_2\right) - U_1\left(X_1\right) \tag{25}$$

Thus $B_L = \Delta U$. We thus have the following result.

[5]Note that this general form of B_L implies that the return to a switch generally depends on L, and in this sense, whether a switch today is socially optimal depends on how L evolves in the future. However, it is possible that the farmers today or the social planner today may not know how the farmers in the future decide to switch (i.e., whether they are rational or not), and this feature could add another dimension to this problem. While this issue highlights an intriguing question of strategic interactions among the farmers both at present and in the future regarding adaptation decisions, in this paper we limit our scope to the cases where the farmers or the social planner evaluate a switching decision by a farmer as if all the others remain in the same production mode throughout the entire future. See Dixit and Rob (1994) for a similar discussion of switching decisions between two economic sectors.

Proposition 2. *The solutions for private decisions represented by* (16) – (18) *are identical to the social optimum.*

As the effects of parameters are mostly ambiguous in sign, numerical examples are useful for illustrating the model solutions. In the following, we use the following parameter levels unless noted otherwise: $\rho = 0.1$, $\epsilon = 2$; $P = 1$, $\mu_1 = -0.002$, $\sigma_1 = 0.03$, $\mu_2 = 0$; $I = 5$; $X_2 = 1$. The levels of μ_1 correspond to declines of the expected yield by 10% in 50 years and by 18% in 100 years, and those of σ_1 correspond to 21% and 31% of standard deviations at the 50th and 100th years, both relative to the expected level. Our benchmark levels of expected yield losses are in agreement with the levels indicated in meta-reviews of long-run climate change impacts on major staple crops (except for rice) in Africa and South Asia (Knox et al., 2012; Roudier et al., 2011; Müller et al., 2011), two of the world regions where climate change is expected to affect agriculture most significantly (Lobell et al., 2008). Those meta-studies also report confidence intervals of their estimates generally greater than 20-30% of standard deviations that σ_1 of our model yields. Meanwhile, the levels of I and X_2 mean that the initial investment to start production 2 is worth the total net annual revenue from production 2 over 5 years.

Figure 1 illustrates the relationship between f, $v - I$ and X_1^*. Farmers gain a net positive expected return from switching when $v - I > 0$. In other words, when X_1 reaches as low as X_1^0 on the graph, a switching from 1 to 2 is already beneficial for farmers. However, the option value (the value of waiting) f is greater than $v - I$ at $X_1 = X_1^0$, and it means that a decision to switch later brings a larger expected return than a switching at X_1^0. Accordingly, it is favorable for the farmers to switch only when X_1 reaches X_1^* on the graph, whose level is determined by equation (18). In the graph, $X_1^*$and X_1^0 are located at 0.63 and 0.69, amounting to a difference of 8% – a significant level given a relatively slow progress of climate change that is assumed in this calculation.

Figure 2 shows a numerical example of the threshold productivity levels of 1 for different levels of the initial sunk investment. The solid curves represent the loci of X_1^*, which is the threshold where the farmers actually have an incentive to switch even in taking account of the option value f (the value of switching not immediately but in the future), whereas the dashed and dotted curves describe the levels of X_1 below which the net expected benefit of switching to 2 exceeds that of remaining in 1 (X_1^0: $v - I = 0$ is satisfied at $X_1 = X_1^0$). The thick solid curve and the dashed curve are for $\epsilon = 2$, and the normal solid curve and the dotted curve is for $\epsilon = 0.5$. The switching is justified in the areas below the curves, as a lower productivity of 1 gives more incentive for switching from 1. The figure exhibits general decreasing patterns of the curves with I, which conforms to intuition (high initial investment costs make a switching less attractive). Furthermore, significant differences exist between the solid curves and the dashed or dotted curves, where the latter dominates the former. This means that under fluctuations of climatic patterns, the farmers might abstain from adaptation investments even well after the time point when the production of 1 becomes unfavorable enough to bring the net expected benefit for switching from 1 to 2. This characteristic essentially origi-

nates from the fact that by delaying adaptation, the farmers might be able to capture relatively good future harvests of 1 in case that future climatic conditions (despite the general trend of unfavorable climate change) turn out to be favorable for production of 1. Put differently, farmers under uncertainty adapt later (start switching with a lower X_1) than under a deterministic climate. Another pattern observed in Figure 2 is the effect of risk aversion. Overall, risk aversion significantly alters the locations of the solid and dashed curves. For weakly risk-averse farmers, high initial investment costs for 2 strongly reduce incentive to switch, as the benefit of risk reduction from a switch to 2 is relatively small for those farmers. Significant differences between X_1^* and X_1^0, however, exist regardless of the level of risk aversion.

Figure 3 presents the mean delays of adaptation in time due to the option value (i.e., Δt obtained from $\frac{X_1^*}{X_1^0} = e^{\mu_1 \Delta t}$, or $\Delta t = \frac{1}{\mu_1} \ln\left(\frac{X_1^*}{X_1^0}\right)$,). The thick solid curve is for $\epsilon = 2$, and the normal solid curve is for $\epsilon = 0.5$. The graphs also shows the mean delays in adaptation relative to the timing of adaptation if σ_1 is fully ignored: the dashed curve is for $\epsilon = 2$, and the dotted curve is for $\epsilon = 0.5$. The solid curves dominate the dashed or dotted curves, suggesting that ignoring risk also has its own small effect of delaying adaptation. Still, for all cases, the mean delays are remarkably large. The level at $\sigma_1 = 0.03$ with $\epsilon = 2$ (the thick solid curve) corresponds to astonishing 42 years of mean delay in adaptation. Also the lengths of mean delay strongly depend on the level of stochasticity σ_1. These results suggest that risk considerably decreases incentive for investment in adaptation. Seen in a different light, however, they also hint that risk sharing among farmers, even a risk-sharing scheme aimed at the farming mode to be abandoned eventually, can significantly promote adaptation (in addition to the obvious effect of welfare enhancement). As variabilities of weather patterns are generally much reduced when averaged over a region or across the globe, risk sharing mechanisms can be beneficial even under global-scale climate change.

3.3 Adaptation with an Open-Access Resource

The above sub-section 3.2 shows that climate variability could slow down adaptation to the long-run climate change. In a perfectly competitive economy, the delay is still socially optimal. With market imperfections, however, the private decisions and the social optimum diverge, and this divergence has policy implications. In this section, we examine the important case that adaptation involves the use of an open-access resource (water). This case is consistent with the common characteristic of agriculture that the irrigated farming is better able to insulate itself from weather shocks than the rainfed farming is, partly because irrigation can smooth out water input across times but also because it allows plants to mitigate the negative effects of heat shocks by enhanced evapotranspiration (e.g., Mendelsohn and Dinar, 2003; Schlenker et al., 2005) – in other words, the adoption of irrigation, which is to use local water resources, is a possible adaptation measure to climate change. Without coordination, the use of an open-

access resource leads to socially suboptimal outcomes (overuse). That is why private adaptation and socially optimal adaptation diverge and therefore the necessity of public interventions – which would take a form of standard instruments to regulate a common resource, such as taxes or quantity restrictions – arises. Here we study the implications of open-access resource use in one production process on individually and socially optimal adaptation.

Below, we discuss sub-optimality of adaptation in focusing on the difference between the private net gain for a farmer from switching the production mode, ΔU, and the social net benefit of switching production B_L. As already discussed in sub-section 3.2, the levels of ΔU and B_L determine the value of switching immediately (v) and the option value (f), and this in turn means that if $\Delta U > B_L$, there is a range of productivity levels where adaptation (switching the production mode) proceeds even if it is not socially optimal. Inefficient adaptation may come in two forms: Individual farmers may adapt too early or too late. Too early adaptation prevails if $\Delta U > B_L$; too late adaptation if $\Delta U < B_L$.

We find that both cases (too early or too late adaptation) are possible, as the order of ΔU and B_L depends on the parameter values. This is because of two counteracting factors: On the one hand, uncoordinated use of the common-pool resource reduces the farmers' individual benefits of resource use. This factor reduces the individual benefits of adaptation, hence farmers tend to adapt too late. On the other hand, with uncoordinated use of the common-pool resource, farmers do not care about the welfare effects on other farmers when switching production mode and enter the user pool of resource. Hence, farmers tend to adapt too early with uncoordinated resource use. Evidently, if uncoordinated private decisions and the socially-optimal decisions do not match, collective actions such as policy interventions to induce socially-optimal switching may increase the social welfare and thus efficient adaptation. As the analysis in the previous subsection has shown, there is no inherent market failure associated with the switching of production itself. Hence, the first-best policy would be to coordinate resource use.

With uncoordinated, open-access extraction of the natural resource, farmers choose extraction levels q^{OA} such that they maximize their individual profits, taking extraction rates of all other farmers as given. The social optimum, by contrast, is found by choosing coordinated extraction levels q^{CE} for all farmers such as to maximize collective profits. The respective extraction rates and income levels are specified in the following lemma

Lemma 1. *Extraction rates are*

$$q^{OA} = \left[\frac{\alpha\, X_{21}^{1-\alpha}}{c_0 L^{\eta-1}}\right]^{\frac{1}{\eta-\alpha}} \qquad \textit{under open access, and} \tag{26}$$

$$q^{CE} = \eta^{-\frac{1}{\eta-\alpha}} \left[\frac{\alpha\, X_{21}^{1-\alpha}}{c_0 L^{\eta-1}}\right]^{\frac{1}{\eta-\alpha}} \qquad \textit{under coordinated extraction.} \tag{27}$$

Income levels are

$$y_2^{OA} = (1-\alpha)\left[\frac{\alpha}{c_0}\right]^{\frac{\alpha}{\eta-\alpha}} L^{-\frac{(\eta-1)\,\alpha}{\eta-\alpha}} X_2 \qquad \textit{under open access, and} \tag{28}$$

$$y_2^{CE} = (\eta-\alpha)\,\eta^{-\frac{\eta}{\eta-\alpha}}\left[\frac{\alpha}{c_0}\right]^{\frac{\alpha}{\eta-\alpha}} L^{-\frac{(\eta-1)\,\alpha}{\eta-\alpha}} X_2 \qquad \textit{under coordinated extraction,} \tag{29}$$

where we define

$$X_2 \equiv X_{21}^{\frac{\eta\,(1-\alpha)}{\eta-\alpha}} \tag{30}$$

Proof: see Appendix.

It is easy to see $\lim_{\alpha\to 0} y_2^{OA} = X_{21}$ (by using $\lim_{x\to+0} x^x = 1$). So with $\alpha \to 0$ (the open-access resource loses its significance for production of 2), the model is reduced to the case studied in the previous subsection.

Next, open-access extraction levels q^{OA} are higher than coordinated extraction levels q^{CE} by a factor $\eta^{1/(\eta-\alpha)} > 1$, which reflects the over-use of the resource under conditions of open access. Because of the over-use, incomes under open access are lower, $y_2^{OA} < y_2^{CE}$, as the first factor in (29) is larger than the corresponding factor in (28):[6]

$$(\eta-\alpha)\,\eta^{-\frac{\eta}{\eta-\alpha}} > 1-\alpha. \tag{31}$$

Note that again, if the resource plays no role for the production mode 2, $\alpha \to 0$, incomes are the same under open access and coordinated extraction.

In the following we shall analyze the question of how the problem of overusing the resource affects the farmer's decision on adaptation to climate change, i.e. the decision which production process to use.

Solutions for private decisions are obtained by following the same procedures as in the previous subsection 3.2. The private instantaneous benefit of adaptation is given by

$$\Delta U\,(L, X_1, X_2) = U_2^{OA}\,(L, X_2) - U_1\,(X_1) \tag{32}$$

Here, U_1 is the same as in the model without the open-access resource, and the utility derived from production mode 2, U_2^{OA}, is given by $G\left(y_2^{OA}\right)$.[7]

[6]This inequality is easily proven as follows: It is straightforward to verify that the left-hand side of the inequality is decreasing and convex in α, while the right-hand side is linear downward sloping in α. For $\alpha = 0$, both sides are equal to one. As for $\alpha = 0$ the slope of the left-hand side is equal to $-(1+\ln(\eta))/\eta > -1$, and as the left-hand side is convex in α, the strict inequality holds for all $0 < \alpha < 1$.

[7]Here, similar to the discussion of B_L in the previous sub-section, we rule out the possibilities that farmers act strategically to maximize their payoffs at the expense of others.

Meanwhile, the social optimum needs a slightly different formulation from that of the previous case in 3.2. Now, U_2^{CE} is dependent on L, and this means that (24) becomes:

$$B_L(L, X_1, X_2) = U_2^{CE}(L, X_2) - U_1(X_1) + L\,\frac{\partial U_2^{CE}(L, X_2)}{\partial L} \tag{33}$$

$$= U_2^{CE}(L, X_2) - U_1(X_1) - (1-\epsilon)\,\frac{(\eta-1)\,\alpha}{\eta-\alpha}\,U_2^{CE}, \tag{34}$$

where $U_2^{CE} = G(y_2^{CE}) > U_2^{OA}$ (see Lemma 1). Note that these utility levels are positive for $\epsilon < 1$ and negative for $\epsilon > 1$ (cf. equation 7).

The social net benefit of switching production B_L may be lower (or higher) than the private net gain for a farmer from switching the production mode, ΔU. It is lower, i.e. $B_L(L, X_1, X_2) < \Delta U(L, X_1, X_2)$, if and only if

$$\Omega\, U_2^{CE} < 0 \qquad \text{with} \tag{35}$$

$$\Omega \equiv 1 - \left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon} - (1-\epsilon)\,\frac{(\eta-1)\,\alpha}{\eta-\alpha} \tag{36}$$

Thus, the question whether social net benefit of switching production is lower or higher than the private net gain can be reduced to the question what is the sign of Ω. For $\epsilon < 1$, $B_L < \Delta U$ if and only if $\Omega < 0$ (as $U_2^{CE} > 0$), while for $\epsilon > 1$, $B_L < \Delta U$ if and only if $\Omega > 0$ (as $U_2^{CE} < 0$). $B_L(L, X_1, X_2) < \Delta U(L, X_1, X_2)$ means that the number of farmers who switch at the respective time point are greater than the socially optimal number, in other words, the farmers adapt too early relative to the social optimum, while $B_L(L, X_1, X_2) > \Delta U(L, X_1, X_2)$ means the number of farmers who switch at the respective time point are fewer than the socially optimal number, in other words, the farmers adapt too late relative to the social optimum.

The parameter cluster Ω captures the above-mentioned two counteracting factors. The first factor, which is that uncoordinated use of the common-pool resource reduces the farmers' individual benefits of resource use, which causes the tendency to adapt too late, is captured by the first two terms in (36). It follows from (31) that the expression in brackets in the second term is smaller than one, which reflects the result from Lemma 1 that income from production mode 2 is lower under open-access extraction of the resource. Taken together, the first two terms in (36) are positive for $\epsilon < 1$ and negative for $\epsilon > 1$: These two terms reduce the private gain from switching the production process relative to the social gain.

The second factor, which is that farmers under open access do not care about the welfare effects on the other farmers when switching the production mode and entering the the user-pool of the resource, which causes the tendency to adapt too early, is captured by the last term in (36). As $\eta > 1$, this term (including the minus sign in front of it) is negative for $\epsilon < 1$ and positive for $\epsilon > 1$. These two terms increase the private gain from switching the production process relative to the social gain. Which of these

two factors dominates depends on the three parameters α, ϵ and η. In the following analysis we will focus on the question how the difference between individual and social instantaneous benefits of switching to production 2 depends on the parameter α of the revenue function for production 2, and on the farmers degree of risk aversion ϵ.

The first important result is that for low values of α the individual benefits of changing production (under open access conditions) exceed the social benefits (under coordinated resource use), while for high values of α the social benefits are higher.

Proposition 3. *There exists a value $\bar{\alpha}$ for the output elasticity of the resource in production mode 2 such that*

- *for all $\alpha < \bar{\alpha}$ private instantaneous gains from adaptation exceed social gains, $\Delta U(L, X_1, X_2) > B_L(L, X_1, X_2)$.*
- *for all $\alpha > \bar{\alpha}$ private instantaneous gains from adaptation are lower than social gains, $\Delta U(L, X_1, X_2) < B_L(L, X_1, X_2)$.*

Proof: see Appendix.

In the proof we show that for $\alpha < \bar{\alpha}$, the parameter cluster Ω is negative if $\epsilon < 1$ and positive for $\epsilon > 1$.

Thus, if the open-access resource is not very important for generating profits from production 2 (i.e. $\alpha < \bar{\alpha}$), the individual incentives to switch to production 2 are too high, as farmers do not take into account the negative effect of adaptation on those farmers who are already producing 2. Given the discussion of 3.1, this means that farmers switch productions earlier than the social planner would prompt them to do. This conforms to the intuition that we tend to overuse a limited resource if the use of the resource is not essential for our life.[8]

If, by contrast, the open-access resource is important ($\alpha > \bar{\alpha}$), the problem of overuse associated with the resource decreases profits from production 2 so much that this reduces the individual benefit of adapting below the social benefit. If the resource is important we would thus expect the opposite pattern to the above: Farmers adapt later than the social planner would have them adapt.

The critical value of α, where the individual incentives under open access conditions switch from being inefficiently high to being inefficiently low depends on the farmers degree of risk aversion, as stated in the following proposition.

Proposition 4. *The threshold value $\bar{\alpha}$ for the output elasticity of the resource in production mode 2 below which farmers adapt too early to climate change (above which they adapt too late) decreases with risk-aversion ϵ, i.e.*

$$\frac{d\bar{\alpha}}{d\epsilon} < 0.$$

[8] Outside of the context of climate change adaptation, it is easy to find such cases, e.g., the extinction of the Passenger Pigeon in North America due to excessive hunting.

Proof: see Appendix.

Thus, the degree of risk aversion determines whether the the individual incentives are inefficiently high to being inefficiently low.

The results stated formally in Propositions 3 and 4 are illustrated by a numerical example in Figure 4. With $\eta = 2$, the threshold values, i.e. the values for α for which $\Omega = 0$, are $\bar{\alpha} = 0.94$ for $\epsilon = 0.2$, $\bar{\alpha} = 0.88$ for $\epsilon = 0.5$, and $\bar{\alpha} = 0.73$ for $\epsilon = 2$.

Considering the dynamic problem, the value of the option to switch the production process is given by (16), with the value matching and smooth pasting conditions as above.

The time-discounted private net gain for switching from 1 to 2 is thus given by

$$v^{OA}(X_1, X_2, L) = \frac{1}{1-\epsilon}\left[\left[(1-\alpha)\left[\frac{\alpha}{c_0}\right]^{\frac{\alpha}{\eta-\alpha}} L^{-\frac{(\eta-1)\alpha}{\eta-\alpha}}\right]^{1-\epsilon} \frac{X_2^{1-\epsilon}}{D_2} - \frac{X_1^{1-\epsilon}}{D_1}\right] \tag{37}$$

with D_1 and D_2 given by (20) and (22); and the time-discounted social net gain for switching from 1 to 2 is given by

$$v^{CE}(X_1, X_2, L) = \frac{1}{1-\epsilon}\left[\left[(\eta-\alpha)\,\eta^{-\frac{\eta}{\eta-\alpha}}\left[\frac{\alpha}{c_0}\right]^{\frac{\alpha}{\eta-\alpha}} L^{-\frac{(\eta-1)\alpha}{\eta-\alpha}}\right]^{1-\epsilon} \times \right.$$
$$\left. \times \left[1-(1-\epsilon)\frac{(\eta-1)\alpha}{\eta-\alpha}\right]\frac{X_2^{1-\epsilon}}{D_2} - \frac{X_1^{1-\epsilon}}{D_1}\right]. \tag{38}$$

In the following Proposition, we focus on the case where $\mu_2 = 0$, i.e. X_2 stays constant.

Proposition 5. *If $\mu_2 = 0$, the switch under open access conditions is at a lower (higher) level of X_1 than socially optimal if and only if $\alpha > \bar{\alpha}$ ($\alpha < \bar{\alpha}$).*

Proof: see Appendix.

This result is illustrated in Figures 5 and 7. In Figure 5 the threshold levels for X_1 below which it is individually and socially optimal to switch to production mode 2 are shown as functions of the number of farmers engaged in production mode 2 (top panels) and as functions of the productivity parameter X_2 of production mode 2 (bottom panels). We consider two different output elasticities of the resource in production mode 2: $\alpha = 0.5$ in the left panels and $\alpha = 0.95$ in the right panels. For all cases, $\alpha = 0.5$ is below the threshold value $\bar{\alpha}$ identified in Proposition 3, while $\alpha = 0.95$ is above this threshold. Accordingly, in the diagrams for $\alpha = 0.5$, the threshold levels for X_1 below which it is individually optimal to switch to production mode 2 are above those for which it is socially optimal to switch production, reflecting that private gains

from adaptation exceed social gains. The converse holds for the panels on the right. The curves $X_1^\star(L)$ shown in the top panels are downward sloping and convex for both levels of risk aversion and both levels of α. The curves $X_1^\star(X_2)$ shown in the bottom panels are upward sloping and convex for the lower degree of risk aversion ($\epsilon = 0.5$) and concave for the higher degree of risk aversion ($\epsilon = 0.95$).

The mean time between socially and individually optimal adaptation is shown in Figure 6 for $X_1 = 1$, $L = 0.1$, and two values of ϵ. The times are calculated as $\Delta t = \frac{1}{\mu_1} \ln\left(\frac{X_1^{\star OA}}{X_1^{\star CE}}\right)$, where $X_1^{\star OA}$ is the threshold level for the productivity of process 1 under open access and $X_1^{\star CE}$ is the socially optimal threshold level. The graph generally confirms the relationships between coordinated and uncoordinated adaptation patterns shown in Figure 5 and indicates that the time gaps of adaptation decisions are indeed large between the two, amounting to decades (too early adaptation) when α is low and to centuries (too late adaptation) when α is close to 1.

In Figure 7 we keep L and X_2 constant and vary the output elasticity of the resource in production mode 2. Again, this illustrates the result of Proposition 5. For both degrees of risk aversion, the switch under open access conditions is already at a higher level of X_1 than socially optimal for low values of α and at a lower level of X_1 for high values of α, i.e. values of α above the threshold level $\bar{\alpha}$.

Those results lead to some nuanced policy implications with regard to public support for private adaptation to climate change. In a way, the above results are not different from those of a standard model of open-access resource use in that the introduction of coordination, in the form taxes or quotas (i.e. limiting resource use to the socially optimal level given by (27)), is a sufficient condition for obtaining the social optimum – in other words, additional public interventions to either promote or discourage adaptation are unnecessary. However, the farmers make an optimal switching only when they believe that coordination is achieved not only at present *but also in the entire future*. Under suspicion of effectiveness of resource management in the future, the farmers may still adapt too early or too late even if coordination is in fact to be provided. This is hardly an unrealistic possibility particularly in some developing countries where the governance system tends to be subject to frequent breakdowns. In such a circumstance, the government should provide explicit incentives for farmers either for faster or slower adaptation in addition to coordination of resource use.[9]

Meanwhile, if the collective management of the resource is practically infeasible both at present and in the future (because of infeasibility of effective monitoring, etc.), evaluation of adaptation decisions need to be made entirely based on U_2^{OA} (i.e., without

[9]In setting up a policy scheme, the government needs to know the levels of parameters, such as those for extraction costs, farmers' utility function, and the baseline change of climate. The government, however, does not need to know exactly the developments of future climatic patterns (and also does not need to know them better than the farmers), as the option values are determined before uncertainty is revealed. Meanwhile, as a coordinator, the government knows whether it will provide coordination in the future, while the farmers may not know it.

U_2^{CE}). In that case, the economy should seek a second-best solution where benefits from uncoordinated resource use are maximized, and this means that adaptation should be always discouraged relative to the level that individual farmers are privately inclined to, e.g., by imposing an entry tax (whose level is set at $(1-\epsilon)\,\frac{(\eta-1)\,\alpha}{\eta-\alpha}\,\int_0^\infty U_2^{CE}\,e^{-\rho t}\,dt$ – recall the last term of the RHS in 34).

4 Concluding Remarks

As humans do not directly perceive a gradual change of climate but experience it primarily as shifting inter-annual fluctuations of weathers, climate variability should have a significant meaning for people's adaptation decisions to climate change. By using a real option framework, we have attempted a description of how climate variability could affect farmers' investment decisions with regard to climate change adaptation. A common characteristic across all cases of the model is that as a reflection of the option value, climate variability delays adaptation. Realistically, this factor can be extremely large: with a reasonable set of parameter levels, the model estimates that the option value can easily delay adaptation for more than 40 years. The significance of the option value in delaying adaptation implies that if some of the risk is diversifiable, risk-sharing mechanisms such as insurance schemes can greatly promote adaptation, even if those mechanisms deal with a production mode that will be eventually abandoned. Also, as a plausible example of application that involves a market failure, we have discussed a case in which adaptation involves the use of a common pool resource (water). The results show complex dynamics that would justify nuanced potential policy interventions. For example, the model indicates that there exist cases where uncoordinated farmers with a high risk aversion may adapt too late although farmers with a low risk aversion would adapt too early under the same conditions. If farmers remain suspicious about viability of long-term coordination on resource use, public interventions to explicitly support or discourage private adaptation could improve the social welfare.

Climate change adaptation has hardly been seen as it is in this study, and this study's relatively simple model already shows significant complexity of decisions on climate change adaptation combined with continuous risk. Indeed, this paper discusses still only a fraction of the cases that the model is potentially able to examine. This analysis highlights the critical role of climate variability for the designing of climate change adaptation policy, and also, a scope for further research.

5 Appendix

Proof of Lemma 1

From 5, the marginal production costs with regard to q are given by:

$$\frac{\partial c\left(q,\tilde{q},L\right)}{\partial q}=c_0\left[\left\{q+\left(L-1\right)\tilde{q}\right\}^{\eta-1}+q\left(\eta-1\right)\left\{q+\left(L-1\right)\tilde{q}\right\}^{\eta-2}\right] \tag{39}$$

Since the farmers are identical, $\tilde{q}=q$ at equilibrium. Hence

$$\frac{\partial c}{\partial q}=c_0\left(L+\eta-1\right)L^{\eta-2}q^{\eta-1} \tag{40}$$

Profit-maximizing farmers equate (40) and the marginal revenue, in other words,

$$\alpha\, q^{\alpha-1}\, X_{21}^{1-\alpha}=\ c_0\left(L+\eta-1\right)L^{\eta-2}q^{\eta-1}$$

Thus, q under uncoordinated extraction (q^{UE}) is

$$q^{UE}=\left[\frac{\alpha\, X_{21}^{1-\alpha}}{c_0\left(L+\eta-1\right)L^{\eta-2}}\right]^{\frac{1}{\eta-\alpha}} \tag{41}$$

This represents q for a common pool resource. q under open access (q^{OA}) is obtained as a special case of the above with $L\gg 1$, which is

$$q^{OA}=\left[\frac{\alpha\, X_{21}^{1-\alpha}}{c_0L^{\eta-1}}\right]^{\frac{1}{\eta-\alpha}} \tag{42}$$

Thus, under open access, each of the identical individual farmer's income becomes

$$y_2^{OA}=\left[\frac{\alpha\, X_{21}^{1-\alpha}}{c_0L^{\eta-1}}\right]^{\frac{\alpha}{\eta-\alpha}}\ X_{21}^{1-\alpha}-c_0L^{\eta-1}\left[\frac{\alpha\, X_{21}^{1-\alpha}}{c_0L^{\eta-1}}\right]^{\frac{\eta}{\eta-\alpha}} \tag{43}$$

$$=\left(1-\alpha\right)\left[\frac{\alpha}{c_0}\right]^{\frac{\alpha}{\eta-\alpha}}\ L^{-\frac{\left(\eta-1\right)\alpha}{\eta-\alpha}}\ X_{21}^{\frac{\eta\left(1-\alpha\right)}{\eta-\alpha}} \tag{44}$$

Meanwhile, the efficient level of resource extraction is found as if the social planner maximizes the collective output. The social planner would not distinguish the farmers in maximizing collective benefits, i.e., $q=\tilde{q}$. Thus, c is simply described as:

$$c=c_0L^{\eta-1}q^{\eta} \tag{45}$$

The efficient or coordinated extraction q (q^{CE}) equates the marginal revenue and cost, hence

$$\alpha \left(q^{CE}\right)^{\alpha-1} X_{21}^{1-\alpha} = \eta c_0 L^{\eta-1} \left(q^{CE}\right)^{\eta-1} \tag{46}$$

$$\Leftrightarrow q^{CE} = \left[\frac{\alpha\, X_{21}^{1-\alpha}}{\eta c_0 L^{\eta-1}}\right]^{\frac{1}{\eta-\alpha}} \tag{47}$$

Thus, if the use of resource is coordinated, each of the identical individual farmer's income is

$$y_2^{CE} = \left[\frac{\alpha\, X_{21}^{1-\alpha}}{\eta c_0 L^{\eta-1}}\right]^{\frac{\alpha}{\eta-\alpha}} X_{21}^{1-\alpha} - c_0 L^{\eta-1} \left[\frac{\alpha\, X_{21}^{1-\alpha}}{\eta c_0 L^{\eta-1}}\right]^{\frac{\eta}{\eta-\alpha}} \tag{48}$$

$$= \frac{\eta-\alpha}{\eta} \left[\frac{\alpha}{\eta c_0 L^{\eta-1}}\right]^{\frac{\alpha}{\eta-\alpha}} X_{21}^{\frac{\eta\,(1-\alpha)}{\eta-\alpha}} \tag{49}$$

Hence, we obtained the formulations for q^{OA} , y_2^{OA} , q^{CE} and y_2^{CE}. QED

Proof of Proposition 3

For $\epsilon < 1$, we have $B_L < \Delta U$ if and only if $\Omega > 0$. For $\epsilon > 1$, we have $B_L < \Delta U$ if and only if $\Omega < 0$. We consider case $\epsilon < 1$ here. The proof for $\epsilon > 1$ is similar and omitted here. For $\alpha = 1$, we then have $\Omega = \epsilon$. For $\alpha = 0$, $\Omega = 0$, but Ω is decreasing with α:

$$\begin{aligned}
&\frac{d}{d\alpha}\left(1 - \left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon} - (1-\epsilon)\,\frac{(\eta-1)\,\alpha}{\eta-\alpha}\right)\Bigg|_{\alpha=0} \\
&= -\frac{1-\epsilon}{(\eta-\alpha)^2}\left[\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon}\left[\frac{(\eta-1)\,(\eta-\alpha)}{1-\alpha} - \eta\,\ln(\eta)\right] - \eta\,(\eta-1)\right]\Bigg|_{\alpha=0} \\
&= -\frac{(1-\epsilon)\,\ln(\eta)}{\eta}
\end{aligned} \tag{50}$$

In between, Ω has a minimum at some α', which is determined by

$$\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon}\left[\frac{(\eta-1)\,(\eta-\alpha)}{1-\alpha} - \eta\,\ln(\eta)\right] = \eta\,(\eta-1) \tag{51}$$

This value α' is unique, as the LHS of this condition is monotonically increasing in α at any value of α solving (51):

$$\frac{d}{d\alpha}\left[\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon}\left[\frac{(\eta-1)\,(\eta-\alpha)}{1-\alpha}-\eta\,\ln(\eta)\right]\right]\Bigg|_{\alpha=\alpha'}$$
$$=\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon}\left[-(1-\epsilon)\left[\frac{\eta-1}{1-\alpha}-\frac{\eta\,\ln(\eta)}{\eta-\alpha}\right]^2+\left[\frac{\eta-1}{1-\alpha}\right]^2\right]>0$$

This holds because

$$\frac{\eta-1}{1-\alpha}>\frac{\eta\,\ln(\eta)}{\eta-\alpha}$$

for the value of α' solving (51).

Given these results, there must exist a threshold value $\bar{\alpha}$ such that $\Omega>0$ for all $\alpha>\bar{\alpha}$ and $\Omega<0$ for all $\alpha<\bar{\alpha}$. QED

Proof of Proposition 4

Differentiating Ω with respect to ϵ we obtain

$$\frac{\partial\Omega}{\partial\epsilon}=\ln\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon}+\frac{(\eta-1)\,\alpha}{\eta-\alpha}$$
$$\frac{\partial^2\Omega}{\partial\epsilon^2}=-\left(\ln\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)\right)^2\left(\frac{(1-\alpha)\,\eta^{\frac{\eta}{\eta-\alpha}}}{\eta-\alpha}\right)^{1-\epsilon}<0$$

which holds by condition (31).

Using the condition $\Omega=0$ for $\alpha=\bar{\alpha}$, we have

$$\frac{\partial\Omega}{\partial\epsilon}\Bigg|_{\alpha=\bar{\alpha}}=\frac{1}{1-\epsilon}\,\ln\left(1-(1-\epsilon)\,\frac{(\eta-1)\,\alpha}{\eta-\alpha}\right)\left(1-(1-\epsilon)\,\frac{(\eta-1)\,\alpha}{\eta-\alpha}\right)+\frac{(\eta-1)\,\alpha}{\eta-\alpha}$$

which is positive $\epsilon<1$ and negative for $\epsilon>1$, because $(1-x)\,\ln(1-x)>-x$.

Now differentiating the condition $\Omega=0$ for $\bar{\alpha}$ with respect to ϵ, we obtain

$$\frac{\partial\Omega}{\partial\epsilon}+\frac{\partial\Omega}{\partial\alpha}\frac{d\alpha}{d\epsilon}=0$$

As shown in the proof of the previous proposition, $\partial\Omega/\partial\alpha<0$ at $\bar{\alpha}$ for $\epsilon<1$ and $\partial\Omega/\partial\alpha>0$ for $\epsilon>1$. Taken together, we have established the proposed result.

Derivation of thresholds

We define

$$\omega^{OA}(L) = \left((1-\alpha) \left[\frac{\alpha}{c_0} \right]^{\frac{\alpha}{\eta-\alpha}} L^{-\frac{(\eta-1)\,\alpha}{\eta-\alpha}} \right)^{1-\epsilon} \tag{52}$$

for the open-access case and

$$\omega^{CE}(L) = \left((\eta-\alpha)\, \eta^{-\frac{\eta}{\eta-\alpha}} \left[\frac{\alpha}{c_0} \right]^{\frac{\alpha}{\eta-\alpha}} L^{-\frac{(\eta-1)\,\alpha}{\eta-\alpha}} \right)^{1-\epsilon} \left(1 - (1-\epsilon)\, \frac{(\eta-1)\,\alpha}{\eta-\alpha} \right) \tag{53}$$

for socially optimal extraction.

The social and individual adaptation problems differ only in whether to use ω^{OA} or ω^{CE}. We shall consider both problems at the same time, using the symbol $\omega \in \{\omega^{OA}, \omega^{CE}\}$.

$$\begin{aligned} A\, X_1^{\beta} &= \frac{1}{1-\epsilon} \left[\frac{\omega\, X_2^{1-\epsilon}}{D_2} - \frac{(X_1)^{1-\epsilon}}{D_1} \right] - I \\ \beta\, A\, X_1^{\beta} &= -\frac{X_1^{1-\epsilon}}{D_1} \end{aligned}$$

$$\begin{aligned} X_1 &= \left[\frac{D_1}{\frac{1}{1-\epsilon} - \frac{1}{\beta}} \left(\frac{\omega\, X_2^{1-\epsilon}}{(1-\epsilon)\, D_2} - I \right) \right]^{\frac{1}{1-\epsilon}} \\ A &= -\frac{D_1^{\frac{-\beta}{1-\epsilon}}}{\beta} \left[\frac{D_1}{\frac{1}{1-\epsilon} - \frac{1}{\beta}} \left(\frac{\omega\, X_2^{1-\epsilon}}{(1-\epsilon)\, D_2} - I \right) \right]^{1-\frac{\beta}{1-\epsilon}} \end{aligned}$$

Proof of Proposition 5

For $\mu_2 = 0$ and $\sigma_2 = 0$, equation (17) implies

$$\beta = \frac{1}{2} - \frac{\mu_1}{\sigma_1^2} - \sqrt{2\, \frac{\rho}{\sigma_1^2} + \left(\frac{1}{2} - \frac{\mu_1}{\sigma_1^2} \right)^2} < 0$$

Thus, β does not depend on ω.

Note that $\omega^{CE}(L) > \omega^{OA}(L)$ if and only if $\alpha > \bar{\alpha}$.

$$
\begin{aligned}
\frac{dX_1}{d\omega} &= \frac{1}{1-\epsilon}\left[\frac{D_1\,X_2^{1-\epsilon}}{\left(1-\frac{1-\epsilon}{\beta}\right)D_2}\right]^{\frac{1}{1-\epsilon}}\left(\omega-(1-\epsilon)\,\frac{D_2\,I}{X_2^{1-\epsilon}}\right)^{\frac{\epsilon}{1-\epsilon}} \\
&= X_1\,\frac{X_2^{1-\epsilon}}{(1-\epsilon)^2\,D_2}\left(\frac{\omega X_2^{1-\epsilon}}{(1-\epsilon)D_2}-I\right)^{-1}
\end{aligned}
$$

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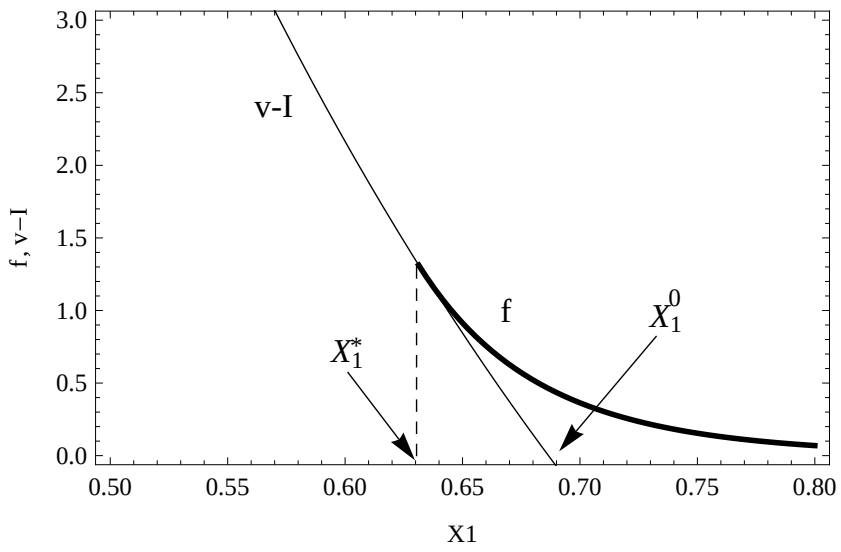

Figure 1: The relationship between f, $v-I$ and X_1^*. Parameter levels are set as follows: $\rho = 0.1$, $\epsilon = 2$; $P = 1$, $\mu_1 = -0.002$, $\sigma_1 = 0.03$, $\mu_2 = 0$; $I = 5$; $X_2 = 1$.

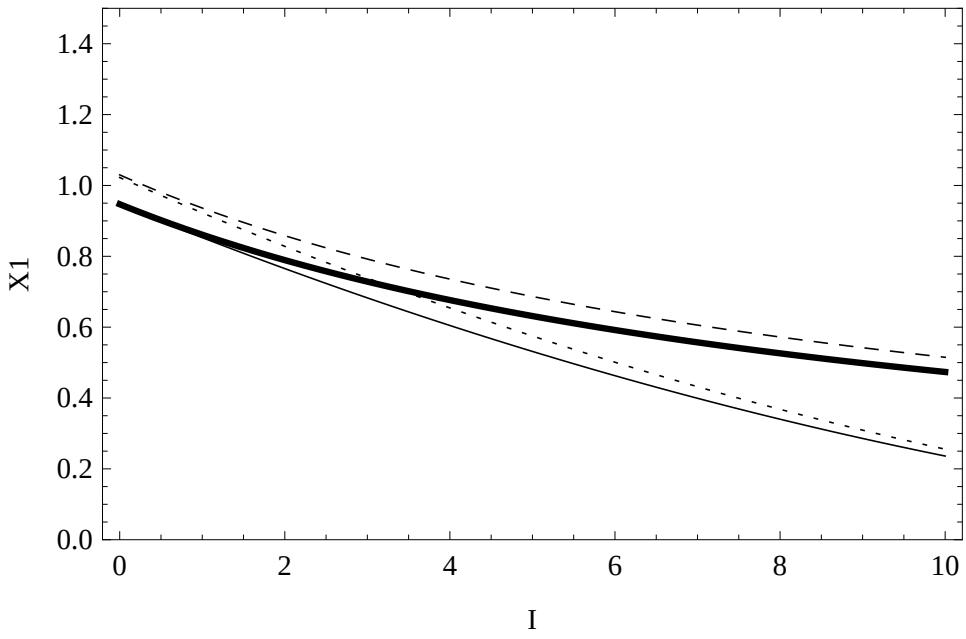

Figure 2: A numerical example of the threshold productivity levels of 1 for different levels of the initial sunk investment and for two different levels of risk aversion, $\epsilon = 0.5$ and $\epsilon = 2$. The solid curves represent the loci of X_1^*, which is the threshold where the farmers actually have an incentive to switch even in taking account of the option value f (the value of switching not immediately but in the future), whereas the dashed and dotted curves describe the levels of X_1 below which the net expected benefit of switching to 2 exceeds that of remaining in 1 (X_1^0: $v - I = 0$ is satisfied at $X_1 = X_1^0$). The thick solid curve and the dashed curve are for $\epsilon = 2$, and the normal solid curve and the dotted curve is for $\epsilon = 0.5$. The rest of the parameters are set as follows: $\rho = 0.1$; $P = 1$; $\mu_1 = -0.002$; $\sigma_1 = 0.03$;$\mu_2 = 0$; $X_2 = 1$.

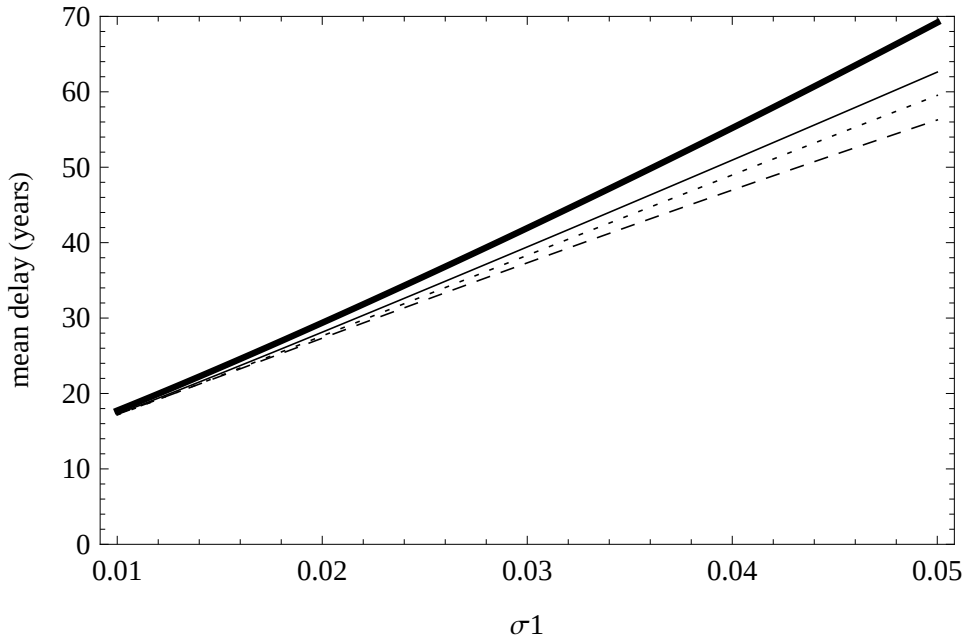

Figure 3: A numerical example of the mean delays in adaptation (Δt obtained from $\frac{X_1^*}{X_1^0} = e^{\mu_1 \Delta t}$) due to the option value. The thick solid curve is for $\epsilon = 2$, and the normal solid curve is for $\epsilon = 0.5$. The graphs also shows the mean delays in adaptation relative to the adaptation where σ_1 is ignored: the dashed curve is for $\epsilon = 2$, and the dotted curve is for $\epsilon = 0.5$. The rest of the parameters are set as follows: $\rho = 0.1$; $P = 1$; $\mu_1 = -0.002$; $\mu_2 = 0$; $I = 5$; $X_2 = 1$.

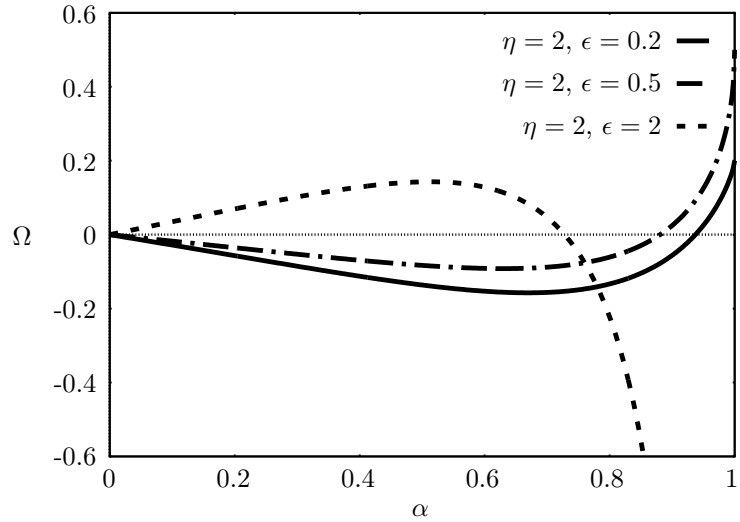

Figure 4: Numerical examples illustrating Propositions 3 and 4.

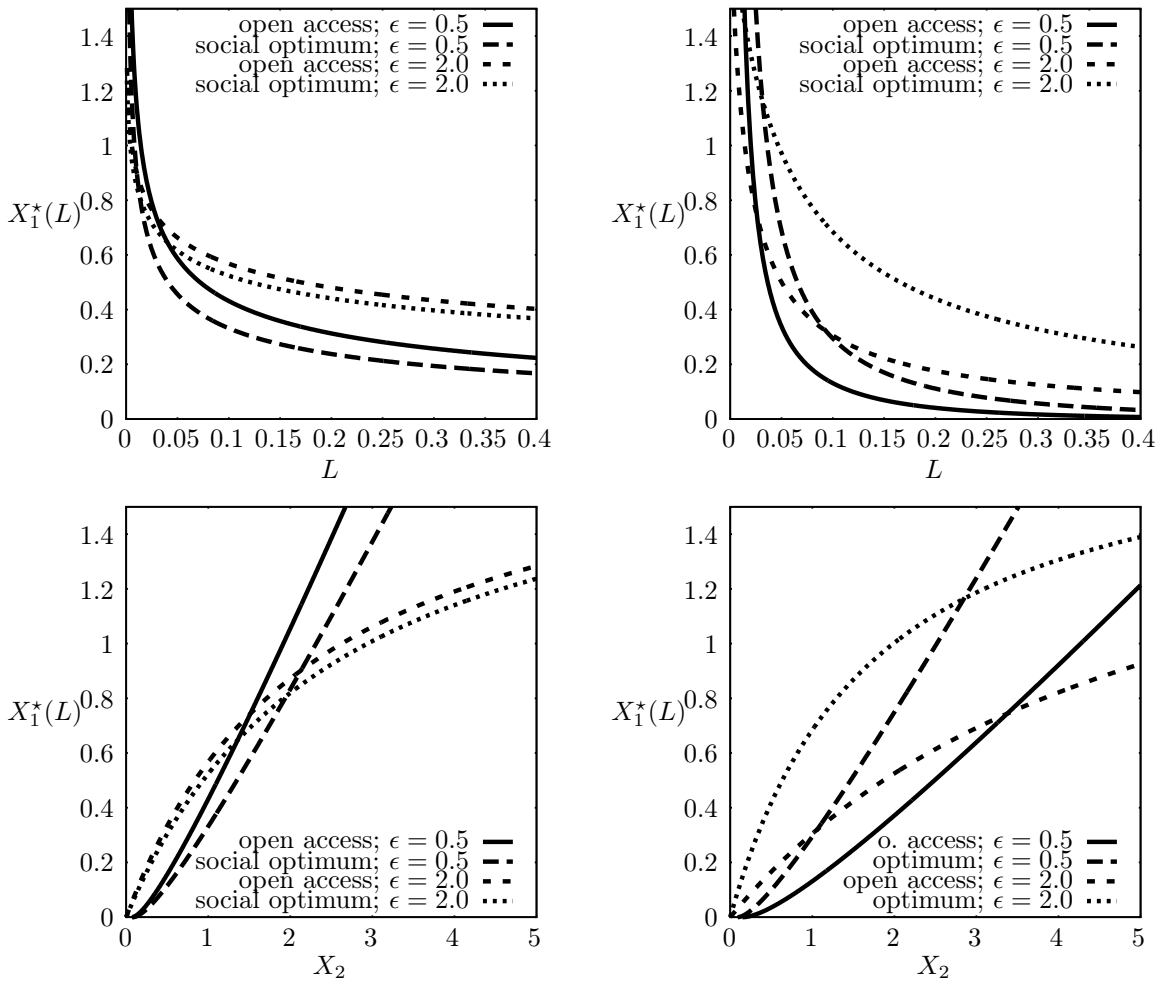

Figure 5: Numerical examples illustrating Proposition 5; using the parameter set as in Figure 1; $c_0 = 1$, $\eta = 2$; $\alpha = 0.5$ in the left panels, $\alpha = 0.95$ in the right panels. For the top panels we assume $X_2 = 1$; for the bottom panels we assume $L = 0.1$.

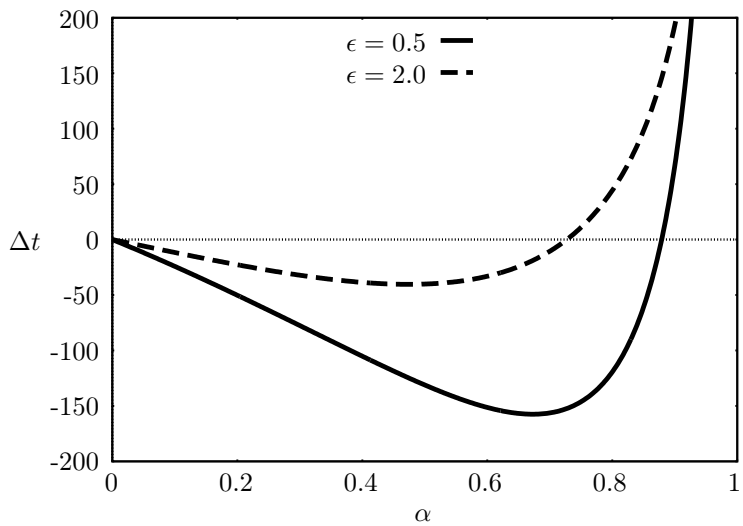

Figure 6: Numerical examples of the mean time delay between individually optimal and socially optimal adaptation, varying α while keeping fixed $X_2 = 1$ and $L = 0.1$.

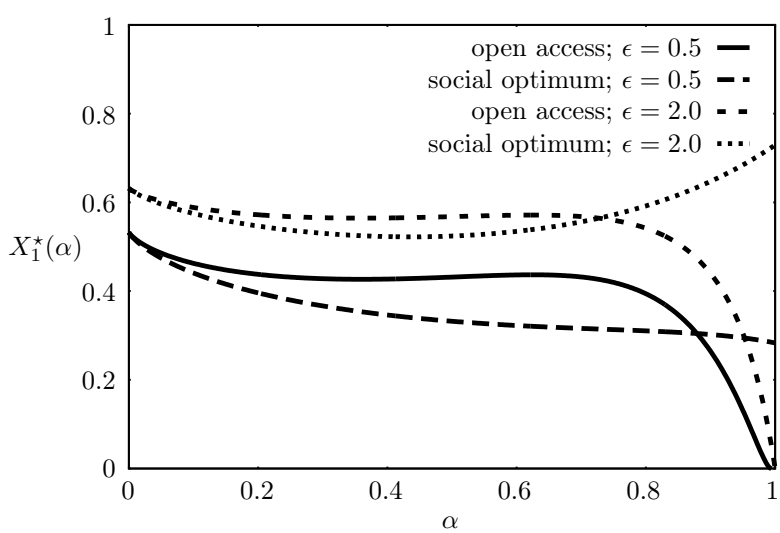

Figure 7: Numerical examples illustrating Proposition 5; using the parameter set as in Figure 1, varying α while keeping fixed $X_2 = 1$ and $L = 0.1$.