# Public and Private Bargaining for the realization of adaptation investment

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March 5, 2017

**Abstract**

The impact of climate change on economic activities is becoming an increasingly important issue that must be adequately taken into account by private and public stakeholders. In this paper, we study the optimal public and/or private governance necessary to adapt natural resources owned by private agents to the new weather conditions. We compare the private case with two types of government interventions in a context of incomplete contracts. In the first case, the government set a level of subsidy contingent on the level of investment; in the second case the levels of subsidy and investment are decided through a bargaining between the public and the private sectors. We conclude that in most cases, without government intervention, the private agent underinvests. However, public intervention can be excessively costly for the society (public finance distortion). Moreover, we found that the public private bargaining is always optimal than a public subsisy in terms of final outcomes, but it is implemented only when the bargaining power is well split between the public and the private sector.

*Keywords:* climate change, adaptation, externality, PPPs
*JEL classification:* D86, D82, D62, L33, H11, C61

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# 1 Introduction

Most environmental resources such as lands, forests, pastures and fish fauna are non-excludable in consumption and are therefore defined as semi-public goods. Moreover, they are becoming increasingly scarce and are progressively shrinking due to human behaviors and natural disasters. The loss of environmental assets and species diversity is a source of great harm for the entire population both in terms of lower availability of resources and even less protection against the risks caused by ever-more frequent weather disasters (forest fires, violent storms, flooding and drought) (Guha-Sapir et al., 2004). The increase in the number of extreme events is largely explained by climate change (Tompkins and Adger, 2004; Van Aalst, 2006) that, in addition, makes natural resources less suitable and more vulnerable in their local environment. The population and especially private landowners are increasingly faced with the direct and indirect effects of climate change in terms of land degradation and monetary costs. Detailed descriptions of climate change effects on land and water resources are provided in several institutional and academic analyses (USDA et al., 2012; European-Commission, 2009; Backlund et al., 2008; European-Forest-Institute et al., 2008; Sohngen and Mendelsohn, 1998). Depending on the climate change scenario, these studies describe the direct and indirect impact factors, i.e., increase in atmospheric CO2, changes in temperature, changes in precipitation, abiotic disturbances (changes in fire occurrence, changes in wind storm frequency and intensity) and biotic disturbances (frequency and consequences of pest and disease outbreaks). All of these disturbances substantially alter the vulnerability of the ecosystem that generally affects the entire community and, in particular, private households whose main source of revenues is from land and water resources (farmers, foresters, fishermen, etc.)[1].

Some previous studies further examined several responses to actual or expected climatic variations. All of the different response mechanisms can essentially be classified into two main categories: mitigation and adaptation. These two strategies can be alternative or complementary tools to address climate change. Several authors studied the optimal mix of mitigation and adaptation investments, essentially an-

[1]For example, the higher frequency of windstorms implies negative effects on the agricultural/forest management activity as well as on the availability of final products and services for the community.

alyzing the main implications in terms of risks and flexibility (Buob and Stephan, 2011; Ingham et al., 2007; Kane and Shogren, 2000). Differences between adaptation and mitigation depend on their objective targets. Indeed, in the presence of climate change prospects, mitigation tends to reduce the likelihood of bad outcomes, while adaptation attenuates the severity of potential losses. In the past, climate policies almost exclusively focused on the mitigation of climate change. In recent decades when the impacts of climate change became increasingly observable, adaptation entered the policy agenda (Biesbroek et al., 2010). In this paper, we model an investment that aims at addressing climate change scenarios by reducing unintentional losses or by increasing unexpected revenues. Thus, even if a further generalization is possible, we focus our analysis on adaptation investments from this point forward.

According to IPCC (2007) adaptation is defined as an *adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.* From this definition we can obtain the main features of adaptation procedures.

First, adaptation implies different levels of investment intensities and management implications (Agrawala and Fankhauser, 2008). Indeed, developing infrastructure and transportation (road networks, irrigation canals or machine technology) is initially costly but facilitates adaptive management practices such as fire prevention systems, changes in species composition, silvicultural strategies, maintenance and thinning treatments, integrated pest management methods and, in general, better management planning.

Second, adaptation investment allows public and private stakeholders to face the direct and indirect consequences of climate change. In fact, the investment in adaptation aims at lowering the impact of negative weather impacts on land and water resources (Tompkins and Eakin, 2012). As a consequence, the persistence of plants and animals is made more constant over time and less vulnerable to uncertain events. Private returns are measurable essentially in terms of higher production and lower uncertainty, while final benefits for the society result from lower price fluctuations, higher availability of natural resources and a stronger ability of the environment to react to ecological disasters (storms, floods, parasites, etc.). On the one hand, if only private agents are involved, social effects are not considered in the investment decision. On the other hand, public intervention can be costly for society, notably in terms of financing costs, and final outcomes of adaptation investment are difficult to be observed and impossible to be measured. [2]

The goal of this paper is to compare private and public-private governances in terms of applying adaptation investments to address climate change. We have constructed a model based on the theory of incentives where owners are responsible for adaptation tasks, whereas the government is responsible for providing the right incentives for private stakeholders that will allow them to integrate the positive effect of adaptation on society into their decisions.

In the model we have a costly initial investment ($i$) that generates a positive externality on the management stage in which effort is required from the private agent ($e$). The greater the effort is, the lower the extent of losses (the higher the benefit) will be in the case of climate change events. For each type of governance, the decision-making process consists of two steps: the first is the choice of the level of investment, and the second is the determination of the optimal effort established by the agent. The concept of non-verifiable private effort is standard in contract theory. In our context $e$ reflects all owner activities and best management practices to improve the quality of the investment and, as a consequence, the probability to make the adaptation investment successful ex-post.

We solve the model considering two different types of intervention: a public subsidy, a Public Private Partnership (PPP). In both cases, final outcomes are not observable, thus the government can only set a transfer based on the observable level of investment. In the first case the government optimally decides a level of transfer that increases with the level of investment. In the case of PPP, the level of transfer and the level of investment are decided through a bargaining between the public regulator and the private owner. In all of the scenarios, public sector expenses are weighted with a shadow cost of public funds ($\lambda$). [3]

On the basis of our analysis, we can put forward three main results: (i) when a public-private governance is selected, both social and private returns are taken into account; nevertheless, the shadow cost of public funds distorts downward final

[2]Distortive social consequences of collecting resources from the population to finance the investment.

[3]Cost imposed on the taxpayer to finance investments.

outcomes; (ii) PPP is always optimal with respect to a public subsidy in the form of final outcomes, but it is selected only when the bargaining power is well balanced between the public and the private sector.

## 2 Literature Review

Many studies have focused on the assessment of the potential benefits of adaptation (Guo and Costello, 2013; Brunette et al., 2014; Kaminski et al., 2013). Moreover, some scholars have compared different adaptation options, obtaining interesting results in terms of policy implications and successful factors (Reed et al., 2013; Biesbroek et al., 2010; Glenk and Fischer, 2010; Adger et al., 2005; Fankhauser et al., 1999). In particular, Fankhauser et al. (1999) classify adaptation procedures and create a distinction between different generic types of adaptive responses. They first differentiate between reactive adaptation measures that automatically occur after the climate change event, and anticipatory adaptations that are preliminary decisions to be prepared when the climate change event occurs. This first classification provides reasons for a further distinction between autonomous and planned adaptation. In fact, autonomous adaptation is a spontaneous adjustment in the face of climate change, whereas a planned adaptation requires a conscious and normally anticipatory intervention. With science pushing the policy agenda on adaptation, several national plans have been developed that aim at encouraging anticipatory and planned measures within countries (Biesbroek et al., 2010).

Each type of adaptation tool consequently implies different degrees of investment requirements and management efforts to be implemented. For example, the construction of infrastructures and machinery consists of planned measures that could complement spontaneous and reactive procedures such as switching crops and management practices. The more relevant the planned strategy is, the more extensive the climate change response will be; however, if the weather deviates too much from the forecast, then the performance of the planned investment decreases and issues related to the lack of flexibility arise (Fankhauser et al., 1999). In this paper, we introduce an investment and a management stage to capture both the planned and the spontaneous aspects that characterize an adaptation strategy.

In addition to listing the different adaptation options, several scholars point out the consequences of adaptation that can favor both private and public stakeholders. Adaptation to climate change as a public policy challenge has only just emerged (Agrawala and Fankhauser, 2008). Thus, at this point, it is extremely relevant to understand whether there is a real need for government participation and what is the most appropriate method of intervention. On the one hand, public funds can enhance additional private incentives (Filatova, 2014) or remove barriers for the development of innovative procedures (Zhang and Maruyama, 2001). On the other hand, government policies may lead to unexpected results: they can undermine climate change adaptation (Urwin and Jordan, 2008) when they are not integrated with private strategies, or they can create perverse incentives when the public support is limited at the ex-post subsidization of damages from catastrophic/systematic events (Skees and Barnett, 1999). In general, to be effective, government intervention should provide private stakeholders with the right incentives to adapt and should be optimally integrated into private actions. Considering climate change as a risk factor, Agrawala and Fankhauser (2008) suggests the use of Public Private Partnerships (PPPs) in climate change adaptation to obtain an efficient and fair allocation of risks and incentives among public and private actors. PPPs have already been applied with good results in the forest sector as a way to restore forest management (Knoot and Rickenbach, 2014; Sturla, 2012), and in agriculture as a tool to develop innovative technologies and to enhance the use of sustainable agricultural practices (Spielman et al., 2010). Moreover, as a contribution to climate change adaptation, the use of PPPs has been discussed in the tourism sector (Wong et al., 2012) and in agriculture (Urwin and Jordan, 2008).

However, when speaking about PPPs, the main previous applications and research studies concern long-term infrastructure projects for providing public and private services. In such contexts, PPPs commit the government to set a long-term contract with a single consortium. Thus, the private contractor is in charge of different connected tasks such as building an infrastructure, financing the investment or managing the obtained asset for a predetermined period of time. On the one hand, thanks to this bundling mechanism, when the different stages are connected through positive externalities (the higher the quality of the infrastructure is, the lower the management costs will be), PPPs are able to create additional incentives (with respect to Traditional Public Procurement) for the private actor, reducing the problem of contract incompleteness or asymmetric information (Iossa and Martimort, 2015; Martimort and Pouyet, 2008; Hart, 2003). On the other hand, issues related to the long-term lack of flexibility may arise (Martimort and Straub, 2012; Iossa and Martimort, 2012).

Our paper proposes a general model that helps us to understand the necessary degree of government involvement in private adaptation and the optimal risk-sharing among public and private actors. To the best of our knowledge, this is the first time that public-private governances for climate change adaptation of natural assets have been modeled. Moreover, compared with the classical PPP literature, our study presents similarities and differences. Our theoretical model applies to contexts where a private agent owns a resource/an asset, while the public institution intervenes to provide incentives for adaptation to climate change events. Moreover, the adaptation investment implies two different stages (investment and management) that are connected through a positive externality. Thus, we are still dealing with multi-stage public/private investments characterized by the presence of positive links. However, we do not focus on the advantages/disadvantages of the bundling mechanism. In fact, we compare our benchmark case (private governance) with different types of public-private governances, focusing on the optimal method of public intervention in a private investment. Our results are connected to the PPP literature in that they show that the public involvement affecting the investment and, indirectly, the management stage is optimal when positive externalities within the project are sufficiently high and when the bargaining power is well split between public and private sectors.

The following sections are organized as follows. In Section 3, we present the model and study the first best case; thereafter, we consider that the private owner carries out the investment without any public help and we adopt this scenario as a benchmark. In Section 4 we introduce and compare two possible types of public intervention in a context of incomplete contracts. We then propose a comparative statics analysis to determine which governance is preferable depending on the bargaining power parameter $\alpha$. Finally, in Section 5, we conclude and discuss future developments.

# 3 The Model

In our model, in the absence of uncertainty, the private agent receives a certain level of revenue ($R_0$) from her/his own property. Moreover, the conservation of the resource implies a positive externality for the community ($S_0$). W.l.o.g. and to simplify the notation, from here onwards it is assumed that $R_0 = S_0 = 0$.

When we allow for the possibility of climate changes, the expected private revenue and social surplus may decrease. The owner can reduce negative (or increase positive) consequences of climate changes by adapting her/his own resource to the expected conditions. The level of adaptation investment is called $i$ and implies a cost equal to $c(i)$, that follows the usual properties ($c_i > 0$, $c_{ii} \geq 0$).

Hence, final outcomes of the adaptation investment can be high or low. Precisely, private revenue and social surplus are respectively equal to $R^h$ and $S^h$ with probability equal to $p(e, \epsilon)$, and $R^l$ and $S^l$ with probability equal to $1 - p(e, \epsilon)$.[4] The probability function $p$ positively depends on the effort of the private agent in executing the adaptation investment, and is further related to a parameter $\epsilon$ that is assumed to follow a random distribution with mean equal to zero and variance equal to $\sigma_\epsilon$. This latter parameter reflects a certain degree of uncertainty that is explained by the difficulty to forecast climate change scenarios and, hence, choose the best adaptation practices.

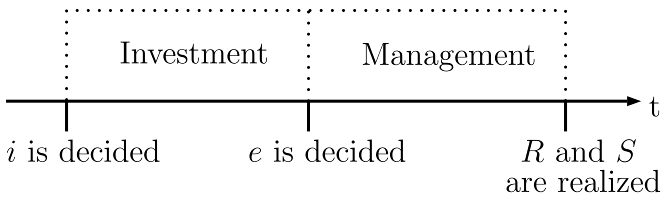
In executing the adaptation investment, the private owner exerts a level of effort $e$ that implies a disutility equals to $\psi(i, e)$. This function is increasing in and convex in $e$ ($\psi_e > 0$, $\psi_{ee} \geq 0$), and decreasing in $i$ ($\psi_i < 0$), meaning that an increase in the initial investment simplifies the owner's executing activities. In addition, we have assumed that $\psi_{ie} = \psi_{ei} \leq 0$; i.e., the marginal disutility of effort is decreasing with the level of adaptation investment.[5]

The public regulator cannot verify neither the effort, nor the final outcomes in the form of private and social benefits.

The time-line of the investment is reported in the following graph:

[4] W.l.o.g. and to simplify the notation, we assume the probabilities to attain high level of private and social returns ($R^h$ and $S^h$) to be equal.

[5] To avoid the possibility of having $i = 0$ with a positive value of $e$, we have assumed that, if $i = 0$ the disutility will be too high to provide the private owner incentives to exert effort.




The expected payoff of the private owner is equal to:

$$\pi \quad = \quad \mathbf{E}_\epsilon[p(e,\epsilon)R^h + (1 - p(e,\epsilon))R^l - c(I,e) - \psi(e)] \tag{1}$$

If $e$ and $\epsilon$ are treated as separable, w.l.o.g. we can write the probability function as $p(e,\epsilon) = e+\epsilon$. Such assumption simplifies the analysis, but it is not too restrictive. Indeed, even if we consider the probability as a function of possible interrelations between $e$ and $\epsilon$, once taken the expected value they will disappear unless we consider $e$ and $\epsilon$ as jointly dependent. [6]

Once having computed the expected value of Equation 1 using the simplified probability function, we obtain:

$$\pi \quad = \quad eR^h + (1 - e)R^l - c(i) - \psi(i,e)$$

Similarly, the payoff of the public principal can be written as:

$$w \quad = \quad \mathbf{E}_\epsilon[p(e,\epsilon)S^h + (1 - p(e,\epsilon))S^l] = eS^h + (1 - e)S^l \tag{2}$$

In the next two sections, we compute first best results and we then solve the model under the benchmark case (private governance).

*First Best Solution*. As a first best scenario we consider the case where the levels of investment and effort are derived from the maximization of the total welfare function that is given by the sum of the private and public expected payoffs. The

[6] For instance, if $p(e,\epsilon) = e + \epsilon + e\epsilon$, then $\mathbf{E}_\epsilon(e + \epsilon + e\epsilon) = e + e\mathbf{E}_\epsilon(\epsilon) + cov(e\epsilon) = e + cov(e\epsilon)$. $\epsilon$ is considered in the model as a random shock completely independent by the action of the private owner, thus we are not going too far from real situations by considering $cov(e\epsilon) = 0$.

maximization problem is solved backward.

$$\max_{e} \left[ e(R^h + S^h) + (1-e)(R^l + S^l) - c(i) - \psi(i,e) \right]$$

FOC is as follows:

$$\frac{\mathrm{d}(w+\pi)}{\mathrm{d}e} : \Delta R + \Delta S = \psi_e(i, e^{fb}) \tag{3}$$

From this FOC, by computing the total differential with respect to $i$ and $e$, we obtain:

$$\frac{de^{fb}}{di} = -\frac{\psi_{ie}(i, e^{fb})}{\psi_{ee}(i, e^{fb})} \geq 0$$

Second, we can derive the level of investment at the optimum:

$$\max_{i} \left[ e^{fb}(R^h + S^h) + (1-e^{fb})(R^l + S^l) - c(i) - \psi(i, e^{fb}) \right]$$

Using the envelope theorem:

$$\frac{\mathrm{d}(w+\pi)}{\mathrm{d}i} : c_i(i^{fb}) = -\psi_i(i^{fb}, e^{fb}) \geq 0 \tag{4}$$

Thus, from the property of the $\psi$ function, the higher $e^{fb}$, the higher $i^{fb}$.

<u>*Private Governance*</u>. Under the benchmark scenario, the private agent is responsible for financing and managing the investment, thus setting the optimal levels of effort and investment by maximizing her/his utility function. The maximization problem is still solved backward.

$$\max_{e} \left[ e(R^h) + (1-e)(R^l) - c(i) - \psi(i,e) \right]$$

FOC is as follows:

$$\frac{\mathrm{d}\pi}{\mathrm{d}e} : \Delta R = \psi_e(i, e^{pr}) \tag{5}$$

Comparing 5 with 3, we can conclude that:

**Lemma 1** *the level of effort under the private governance is lower with respect to the first best case.*

**Proof.** By comparing the two FOCs related respectively to the First Best Scenario and the Benchmark Private Governance:

$$\Delta R + \Delta S = \psi_e(i, e)$$
$$\Delta R = \psi_e(i, e)$$

we can conclude that benefits (left side) are higher under the first best scenario, while costs are the same. As a consequence, incentives to increase the level of effort are higher under the first best. The exclusion of the social surplus from the private payoff explains this difference between $e^{pr}$ and $e^{fb}$. ■

From 5, by computing the total differential with respect to $i$ and $e$, we obtain:

$$\frac{de^{pr}}{di} = -\frac{\psi_{ie}(i, e^{pr})}{\psi_{ee}(i, e^{pr})} \geq 0$$

As a result, we can say that the influence of $i$ on the level of effort at the optimum is equal between the first best and the benchmark scenario.

Second, we can derive the level of investment at the optimum:

$$\max_i \left[e^{pr} R^h + (1 - e^{pr}) R^l - c(i) - \psi(i, e^{pr})\right]$$

Using the envelope theorem:

$$\frac{\mathrm{d}\pi}{\mathrm{d}i} : c_i(i^{pr}) = -\psi_i(i^{pr}, e^{pr}) \geq 0 \tag{6}$$

By comparing 6 with 4, we can conclude that:

**Lemma 2** *the level of investment in adaptation under the private governance ($i^{pr}$) is lower with respect to the first best case ($i^{fb}$).*

**Proof.** Comparing the two FOCs:

$$c_i(i) = -\psi_i(i, e^{fb})$$
$$c_i(i) = -\psi_i(i, e^{pr})$$

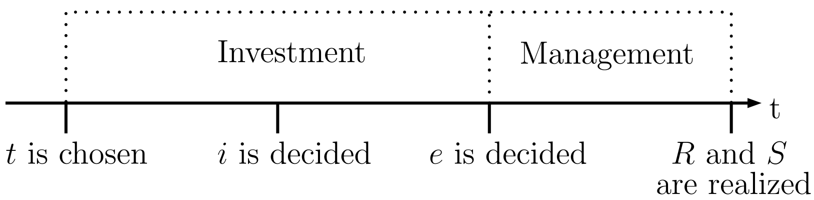
The only difference comes from the function $e$. By Lemma 1, we know that $e^{fb} \geq e^{pr}$. Moreover, from initial assumptions, we know that $c_i > 0$, $\psi_i < 0$ and $\psi_{ei} = \psi_{ie}$ is lower than zero. As a consequence, $\psi_i(i, e^{fb}) \leq \psi_i(i, e^{pr})$ that implies $-\psi_i(i, e^{fb}) \geq -\psi_i(i, e^{pr})$. ■

# 4 Public Intervention

In the following section we allow the the public regulator to intervene in the project. We consider a situation of partially incomplete contracts as the government cannot verify the level of effort neither final outcomes. However, the government can observe the investment in adaptation $i$. We then consider two cases. At first, the government can participate in the initial investment stage by providing a subsidy to the private agent. Second, we discuss the formation of a Public-Private Partnership (PPP), where the investment decision derives from a bargaining between the public and the private actor. In both cases, whenever the public regulator sustains monetary costs, the shadow cost of public funds ($\lambda$) is considered as a way to capture the distortion imposed on taxpayers to finance the investment.

## 4.1 Public subsidy

If ex-post outcomes are not verifiable, the government can only intervene through a subsidy connected with the level of investment. Indeed, before the agent invests, the public regulator can set a level of transfer $ti$ that is increasing with the level of investment.[7] The transfer choice allows the government to enhance the initial investment and to support the management stage. For a better understanding, the following graph summarizes the time-line of the project:




[7]For simplicity we assume a linear transfer, but the analysis can be generalized to any set of transfers increasing with the investment level.

The problem is solved backwards. Thus, the private agent first decides the level of effort:

$$\max_{e} \left[ e(R^h) + (1-e)(R^l) - c(i) - \psi(i,e) + ti \right]$$

FOC is as follows:

$$\frac{\mathrm{d}\pi}{\mathrm{de}} : \Delta R = \psi_e(i, e^{ps}) \tag{7}$$

From 7, by computing the total differential with respect to $i$ and $e$, we obtain:

$$\frac{de^{ps}}{di} = -\frac{\psi_{ie}(i,e)}{\psi_{ee}(i,e^{ps})} \geq 0$$

Comparing 7 with 5, we can conclude that:

**Lemma 3** *For a given level of investment, the level of effort in the case of a public subsidy is equal with respect to the private benchmark.*

Second, we obtain the level of investment at the optimum:

$$\max_{i} \left[ e^{ps}R^h + (1-e^{ps})R^l - c(i) - \psi(i,e^{ps}) + ti \right]$$

Using the envelope theorem:

$$\frac{\mathrm{d}\pi}{\mathrm{d}i} : c_i(i^{ps}) = -\psi_i(i^{ps}, e^{ps}) + t \geq 0 \tag{8}$$

From 8, by computing the total differential with respect to $i$ and $t$, we obtain:

$$\begin{aligned} \frac{di^{ps}}{dt} &= \frac{1}{c_{ii}(i) + \psi_{ii}(i,e^{ps}) + \psi_{ie}(i,e^{ps})\frac{de^{ps}}{di}} \\ \frac{di^{ps}}{dt} &= \frac{1}{c_{ii}(i) + \psi_{ii}(i,e^{ps}) - \frac{\psi_{ie}^2(i,e^{ps})}{\psi_{ee}(i,e^{ps})}} \end{aligned} \tag{9}$$

From here onwards we assume that $c_{ii}(i) + \psi_{ii}(i,e^{ps}) > \frac{\psi_{ie}^2(i,e)}{\psi_{ee}(i,e)}$. Otherwise, there are no reasons for governments to subsidy adaptation investment.

Finally, the public decides the optimal level of $t$:

$$\max_{t} \left[ e^{ps}S^h + (1-e^{ps})S^l - (1+\lambda)ti^{ps} \right]$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} : \frac{de^{ps}}{di}\frac{di^{ps}}{dt}\Delta S - (1+\lambda)i^{ps} - (1+\lambda)t\frac{di^{ps}}{dt} = 0$$

Substituting we obtain:

$$t = \frac{\frac{de^{ps}}{di}}{1+\lambda}\Delta S - \frac{i^{ps}}{\frac{di^{ps}}{dt}}$$

The level of transfer is higher than zero as long as $\frac{\frac{de^{ps}}{di}}{1+\lambda}\Delta S > \frac{i^{ps}}{\frac{di^{ps}}{dt}}$. Substituting the optimal value of $t$ in Equation 8, we obtain the equation to derive $i$ at the optimum value of $t$, that is equal to:

$$c_i(i^{ps}) = -\psi_i(i^{ps}, e^{ps}) + \frac{\frac{de^{ps}}{di}}{1+\lambda}\Delta S - \frac{i^{ps}}{\frac{di^{ps}}{dt}} \tag{10}$$

By comparing 10 with 6, we can conclude that:

**Proposition 4** *the level of investment and effort in adaptation in the case of a positive public subsidy is higher with respect to the private benchmark case.*

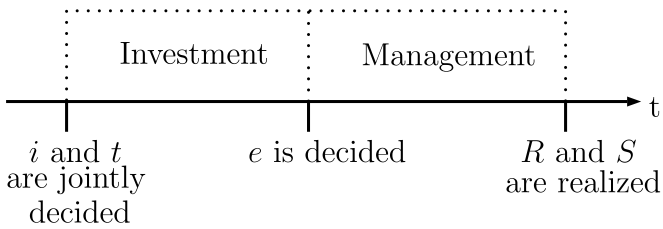
**Proof.** Comparing the two FOCs:

$$\begin{aligned} c_i(i) &= -\psi_i(i, e^{pr}) \\ c_i(i) &= -\psi_i(i, e^{ps}) + \frac{\frac{de^{ps}}{di}}{1+\lambda}\Delta S - \frac{i^{ps}}{\frac{di^{ps}}{dt}} \end{aligned}$$

As the level of effort for a given level of investment is equal between the two cases, the only difference comes from $\frac{\frac{de^{ps}}{di}}{1+\lambda}\Delta S - \frac{i^{ps}}{\frac{di^{ps}}{dt}}$ that is equal to the level of transfer at the equilibrium, thus it should be positive or at least equal to zero. As a consequence, the marginal benefit is higher in the case of a public subsidy and then also the level of investment at the equilibrium. By properties of function $\psi$ ($\psi_{ei} > 0$), we can also conclude that at the equilibrium $e^{ps} > e^{pr}$. ■

## 4.2 Public Private Partnership

The public regulator in a context of incomplete contracts, *i.e.*, final outcomes are not verifiable, has limited regulatory tools to provide private agents incentives to invest in adaptation. A possible mechanism is embodied by public subsidies contingent to the realized level of investment, we dealt with this case in the previous paragraph. A second option requires the public regulator to be more actively involved in a bargaining process with the private agent to jointly decide the level of investment in adaptation and the level of subsidy in favor of the private agent. In the paper we refer to this case as Public-Private Partnership (PPP). Differently than before, in the case of PPP the public regulator is involved in the decision making process and its role is not limited to setting a certain level of subsidy. The following graph summarizes the time-line of the project:




As usual, the problem is solved backwards, thus the private agent first set the level of effort. This level of effort is not verifiable by the public regulator, thus it cannot be a variable to be included in the bargaining between the public and the private sector.

$$\max_{e} \left[ e(R^h) + (1-e)(R^l) - c(i) - \psi(i,e) \right]$$

FOC is as follows:

$$\frac{\mathrm{d}\pi}{\mathrm{d}e} : \Delta R \quad = \quad \psi_e(i, e^{ppp}) \tag{11}$$

From 11, by computing the total differential with respect to $i$ and $e$, we obtain:

$$\frac{de^{ppp}}{di} \quad = \quad -\frac{\psi_{ie}(i,e)}{\psi_{ee}(i,e)} \geq 0$$

As a second step, the level of $i$ and $t$ are chosen from the bargaining between the public and the private agent. As in subsection 4.1, the public subsidy is assumed to be linear with respect to the level of investment. To study the bargaining we use the Nash's Approach (Osborne and Rubinstein, 2005). Precisely, according to the Nash's procedure the bargaining solution derives from the maximization of $\Pi$ that is equal to $[\pi(i, e^{ppp}) - \pi^{pr}(i^{pr}, e^{pr}) - C^p]^\alpha[w(i, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) - C^w]^{1-\alpha}$ where $\alpha$ $(1-\alpha)$ is the bargaining power of the private owner (public regulator). Moreover, we consider disagreement payoffs as equal to payoffs under the private benchmark minus the corresponding disagreement costs that are equal to either $C^p$ for the private owner or $C^w$ for the society. For simplicity, here onwards we will use the following terminology: $d\pi = \pi(i, e^{ppp}) - \pi^{pr}(i^{pr}, e^{pr}) + C^p$ and $dw = w(i, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) + C^w$.

Nash's bargaining maximization can be written as:

$$\max_{i,t} \left[d\pi(i,t)\right]^\alpha \left[dw(i,t)\right]^{1-\alpha}$$

Applying the envelope theorem, first order conditions are as follows:

$$\begin{aligned}
\frac{\mathrm{d}\Pi}{\mathrm{d}i} : \alpha[d\pi(i,t)]^{\alpha-1}[dw(i,t)]^{1-\alpha}\left[t - c_i(i) - \psi_i(i, e^{ppp})\right] + & \\
+(1-\alpha)[d\pi(i,t)]^{\alpha}[dw(i,t)]^{-\alpha}\left[\frac{de^{ppp}}{di}\Delta S - (1+\lambda)t\right] &= 0 \\
\frac{\mathrm{d}\Pi}{\mathrm{d}t} : \alpha[d\pi(i,t)]^{\alpha-1}[w(e^{ppp})]^{1-\alpha}\left[i\right] + (1-\alpha)[d\pi(i,t)]^{\alpha}[dw(i,t)]^{-\alpha}\left[-(1+\lambda)i\right] &= 0
\end{aligned}$$

Calling $A = t - c_i - \psi_i(i, e^{ppp})$ and $B = \frac{de^{ppp}}{di}\Delta S - (1+\lambda)t$, we can rewrite first order conditions as:

$$\begin{aligned}
\frac{\mathrm{d}\Pi}{\mathrm{d}i} : \frac{\alpha}{1-\alpha}\frac{dw(i,t)}{d\pi(i,t)} &= -\frac{B}{A} \\
\frac{\mathrm{d}\Pi}{\mathrm{d}t} : \frac{\alpha}{1-\alpha}\frac{dw(i,t)}{d\pi(i,t)} &= (1+\lambda)
\end{aligned}$$

Two equations leads to the following expression:

$$
\begin{aligned}
-B &= A(1+\lambda) \\
-\frac{de^{ppp}}{di}\Delta S + (1+\lambda)t &= t(1+\lambda) - c_i(1+\lambda) - \psi_i(i, e^{ppp})(1+\lambda) \\
(1+\lambda)c_{i^{ppp}} &= \frac{de^{ppp}}{di^{ppp}}\Delta S - (1+\lambda)\psi_i(i^{ppp}, e^{ppp}) \qquad (12)
\end{aligned}
$$

The next proposition summarizes a first relevant result of the paper:

**Proposition 5** *the level of investment and effort in adaptation in the case of Public Private Partnership is higher with respect to the case with a positive public subsidy. Moreover, the level of investment at the equilibrium does not depend on the level of transfer.*

**Proof.** Comparing the two FOCs:

$$
\begin{aligned}
c_i(i) &= -\psi_i(i, e^{ppp}) + \frac{\frac{de^{ppp}}{di}}{1+\lambda}\Delta S \\
c_i(i) &= -\psi_i(i, e^{ps}) + \frac{\frac{de^{ps}}{di}}{1+\lambda}\Delta S - \frac{i^{ps}}{\frac{di^{ps}}{dt}}
\end{aligned}
$$

As the level of effort for a given level of investment is equal between the two cases, the only difference comes from the marginal benefit that is higher in the case of PPP with respect to the case with a public subsidy. As a consequence, the level of investment and effort at the equilibrium ($\psi_{ei} > 0$) are higher in the case of PPP compared to the case with a public subsidy ($i_{ppp} > i_{ps}$, $e_{ppp} > e_{ps}$). ■

Finally, from the FOC we can derive the level of transfer at the equilibrium:

$$
\begin{aligned}
\alpha\left[e^{ppp}\Delta S + S^l - (1+\lambda)ti - w(i^{pr}, e^{pr}) + C^w\right] &= \\
(1+\lambda)(1-\alpha)\left[e^{ppp}\Delta R + R^l - c(i) - \psi(i,e) + ti - \pi(i^{pr}, e^{pr}) + C^p\right] & \\
-\alpha(1+\lambda)ti + \alpha\left[e^{ppp}\Delta S + S^l - w(i^{pr}, e^{pr}) + C^w\right] &= \\
+(1+\lambda)(1-\alpha)ti + (1+\lambda)(1-\alpha)\left[e^{ppp}\Delta R + R^l - c(i) - \psi(i,e) - \pi(i^{pr}, e^{pr}) + C^p\right] & \\
\alpha\left[e^{ppp}\Delta S + S^l - w(i^{pr}, e^{pr}) + C^w\right] &= \\
+(1+\lambda)ti + (1+\lambda)(1-\alpha)\left[e^{ppp}\Delta R + R^l - c(i) - \psi(i,e) - \pi(i^{pr}, e^{pr}) + C^p\right] & \\
\alpha\left[w^{pr}(i^{ppp}, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) + C^w\right] &= \\
+(1+\lambda)ti + (1+\lambda)(1-\alpha)\left[\pi^{pr}(i^{ppp}, e^{ppp}) - \pi^{pr}(i^{pr}, e^{pr}) + C^p\right] &
\end{aligned}
$$

Calling respectively, $Df(w) = w^{pr}(i^{ppp}, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) + C^w$ and $Df(\pi) = -\pi^{pr}(i^{ppp}, e^{ppp}) + \pi^{pr}(i^{pr}, e^{pr}) - C^p$, the value of $t$ can be written as:

$$
t = \frac{\alpha Df(w) + (1-\alpha)(1+\lambda)Df(\pi)}{i^{ppp}(1+\lambda)} \tag{13}
$$

Looking at equation 13 we can conclude that the level of transfer depends on the allocation of the bargaining power, on disagreement costs and on respectively differences between public and private payoffs computed at the optimal PPP outcomes minus public and private payoffs under the benchmark private scenario. The level of transfer can be either higher or equal with respect to the case with a public subsidy depending on the allocation of the bargaining power and on disagreement costs. Precisely, the higher (lower) $C^w$ ($C^p$), the higher (lower) the public transfer. In fact, when disagreement costs for the government are higher, the government is prompt to accept an higher transfer to reach an agreement. Viceversa, when disagreement costs are higher for the private owner, then the agreement can be reached with a lower level of transfer.

## 4.3 Example and Comparative Statics

To better understand when PPP is feasible for such type of investment, we will use a practical example by assigning a specific forms to cost functions we introduced. Precisely we consider: $c(i) = \frac{i^2}{2}$, $\psi(i,e) = \frac{e^2}{2i}$. Considering these cost functions we solve the problem under the four scenarios:

*First Best Solution*. For a given value of $i$, the level of effort is equal to:

$$\begin{aligned} e^{fb} &= (\Delta R + \Delta S)i \\ \frac{de^{fb}}{di} &= \Delta R + \Delta S \geq 0 \end{aligned}$$

Second, we can derive the level of investment at the optimum and, consequentially, the level of effort:

$$\begin{aligned} i^{fb} &= \frac{(\Delta R + \Delta S)^2}{2} \\ e^{fb} &= \frac{(\Delta R + \Delta S)^3}{2} \end{aligned}$$

*Private Governance*.

For a given value of $i$, the level of effort is equal to:

$$\begin{aligned} e^{pr} &= (\Delta R)i \\ \frac{de^{pr}}{di} &= \Delta R \geq 0 \end{aligned}$$

Second, we can derive the level of investment at the optimum and, consequentially, the level of effort:

$$\begin{aligned} i^{pr} &= \frac{(\Delta R)^2}{2} \\ e^{pr} &= \frac{(\Delta R)^3}{2} \end{aligned}$$

It is easy to verify that both $i^{pr}$ and $e^{pr}$ are lower than the first best.

*Public subsidy*.

For a given value of $i$, the level of effort is equal to:

$$\begin{aligned} e^{ps} &= (\Delta R)i \\ \frac{de^{ps}}{di} &= \Delta R \geq 0 \end{aligned}$$

Second, we can derive the level of investment for a given level of $t$:

$$i^{ps} = \frac{(\Delta R)^2}{2} + t$$

From the government's maximization problem we can derive the value of $t$:

$$t^{ps} = \frac{\Delta R \Delta S - (1+\lambda)\frac{\Delta R^2}{2}}{2(1+\lambda)}$$

We can easily verify that $t > 0$ if $\Delta S > (1+\lambda)\frac{\Delta R}{2}$ Substituting the optimal value of $t$, we can derive the value at the equilibrium of $i$ and $e$:

$$i^{ps} = \frac{(\Delta R)^2}{4} + \frac{\Delta R \Delta S}{2(1+\lambda)}$$
$$e^{ps} = \frac{(\Delta R)^3}{4} + \frac{(\Delta R)^2 \Delta S}{2(1+\lambda)}$$

It is easy to verify that, if $t > 0$, then $i^{fb} > i^{ps} > i^{pr}$ and $i^{fb} > i^{ps} > i^{pr}$.

*Public Private Partnership*.

For a given value of $i$, the level of effort is equal to:

$$e^{ppp} = (\Delta R) i$$
$$\frac{de^{ppp}}{di} = \Delta R \geq 0$$

Second, we can derive the level of investment and transfer at the equilibrium:

$$i^{ppp} = \frac{(\Delta R)^2}{2} + \frac{\Delta R \Delta S}{1+\lambda}$$
$$e^{ppp} = \frac{(\Delta R)^3}{2} + \frac{(\Delta R)^2 \Delta S}{1+\lambda}$$

It is easy to verify that, if $t > 0$, then $i^{fb} > i^{ppp} > i^{ps}$ and $i^{fb} > i^{ppp} > i^{ps}$. Distortions with respect to the first best derives from the role of $\lambda$ and from the fact the $e$ is not verifiable by the government and thus it cannot be part of the bargaining between the public and the private sector. Knowing that:

$$\begin{aligned}
w^{pr}(i^{ppp}, e^{ppp}) - w^{pr}(i^{pr}, e^{pr}) + C^w &= \frac{(\Delta R \Delta S)^2}{1+\lambda} + C^w \\
\pi^{pr}(i^{ppp}, e^{ppp}) - \pi^{pr}(i^{pr}, e^{pr}) + C^p &= -\frac{(\Delta R \Delta S)^2}{2(1+\lambda)} + C^p
\end{aligned}$$

the level of transfer at the equilibrium is equal to:

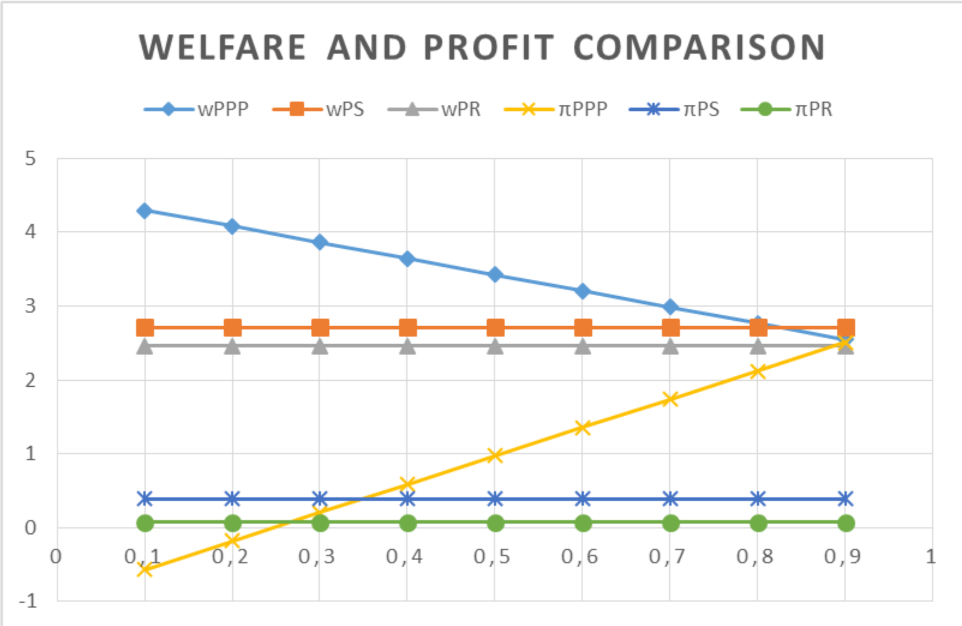
$$t^{ppp} = \frac{\alpha[\frac{(\Delta R \Delta S)^2}{1+\lambda} + C^w] + (1-\alpha)(1+\lambda)[\frac{(\Delta R \Delta S)^2}{2(1+\lambda)} - C^p]}{\Delta R \Delta S + (1+\lambda)\frac{\Delta R^2}{2}}$$

Comparing transfers under PPP and Public Subsidy, we find:

$$\begin{aligned}
t^{ppp} - t^{ps} &= \frac{\alpha[\frac{(\Delta R \Delta S)^2}{1+\lambda} + C^w] + (1-\alpha)(1+\lambda)[\frac{(\Delta R \Delta S)^2}{2(1+\lambda)} - C^p]}{\Delta R \Delta S + (1+\lambda)\frac{\Delta R^2}{2}} - \frac{\Delta R \Delta S - (1+\lambda)\frac{\Delta R^2}{2}}{2(1+\lambda)} \\
t^{ppp} - t^{ps} &= \frac{\alpha\left[\frac{(1-\lambda)(\Delta R \Delta S)^2}{2(1+\lambda)} + C^w + (1+\lambda)C^p\right] + \left[\frac{(\Delta R \Delta S)^2 \lambda}{2(1+\lambda)} - (1+\lambda)\left(C^p - \frac{\Delta R^4}{2}\right)\right]}{\Delta R \Delta S + (1+\lambda)\frac{\Delta R^2}{2}}
\end{aligned}$$

Looking at previous equation, it is straightforward to observe that the transfer under PPP is higher than the public subsidy, the higher the $\alpha$, the higher the $C^w$ and the lower the $C^p$. Moreover, if $C^p$ is equal to zero, the difference will become always positive. In the following graphs we report the difference in welfare ($w$) and profit ($\pi$) functions between the two regimes (PPP and Public Subsidy) considering a change in $\alpha$:

Figure 1: comparative statics analysis with respect to $\alpha$




From this figure we can observe that the choice of a PPP is profitable for both the public and the private sectors if $\alpha$ is between 0.3 and 0.8, meaning that the bargaining power should not be too much in favor of either the public or the private sector.[8]

# 5 Conclusion and future developments

In this paper, we focused on adaptation investments to address the consequences of natural hazard events (such as forest fires, violent storms, flooding and drought). With climate change, the probability that such disasters will occur is higher, as are the negative consequences for the population. We studied the optimal method for adapting the environment to the new weather conditions, focusing on the relation-

[8]To perform this graph, we consider the following functions and the following values for the parameters: $c(i) = \frac{i^2}{7}2$ $\psi(e) = \frac{qe^2}{2i}$, $S^h = 20$, $S^l = 2$ $R^h = 10$ $R^l = 2$ $\lambda = 0$, $C^p = 10000$, $C^w = 20000$ and $q = 100$.

ship between the public regulator and the private owners of the environmental assets (foresters, farmers, fishermen, etc.).

Our findings are related to the optimal method of government participation to support the private investment in adaptation. In this paper, the investment in adaptation involves two stages (investment and management) that are connected through an externality parameter. We found that when a contract based on contractible outcomes is not possible, PPP could represent an interesting option to obviate the presence of contract incompleteness.

In terms of policy implications, we confirm the benefit of PPPs to overcome operational constraints, enhance performances and accelerate uncertain investments (Agrawala and Fankhauser, 2008). Our results show that investments linked to climate change are not just private or public concerns. We propose different types of public-private collaborations where the governance of adaptation investments is shared between public and private stakeholders as alternative strategies to the private regime. By comparing two governances, we conclude that PPP is particularly recommended when the externality between the two stages is particularly relevant and when the bargaining power is well split between public and private sectors.

This is a first step to understanding what the optimal mix of public and private governance would be in order to carry out and manage climate change adaptation projects that involve monetary investment and management activities. Several complexities can be introduced to enrich and complete this benchmark analysis. A first step may consist in introducing the concept of optimal sharing of risks between public and private partners to help us to understand how to apply PPPs in practice. Then, as a further development, it would be interesting to consider different perceptions of climate change risks between public and private partners. This refinement could enrich the current analysis by providing further arguments in favor of government intervention in private adaptation investment.

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