On the Optimal Design of Disaster Insurance in a Federation

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Abstract: Recent experience with disasters and terrorist attacks in the US indicates that state and local governments rely on the federal sector for support after disasters occur. But these same governments invest in infrastructure designed to reduce vulnerability to natural and man-made hazards. We show that when the federal government is committed to full insurance against disasters, regions will have incentives to under-invest in ex-ante protective measures. We derive the structure of the optimal second-best insurance system when regional governments choose investment levels non-cooperatively and the central government cannot verify regional investment choices. For low probability disasters this will result in lower ex-post intergovernmental transfers (and hence less ex-post redistribution) and greater ex-ante investment. However, the second-best transfer scheme suffers from a time-inconsistency problem. Ex-post, the central government will be driven towards full insurance rather than the second-best grants, which results in a type of soft budget constraint problem. Sub-national governments will anticipate this and reduce their investment in protective infrastructure even further. The result is that the central government may be better off suffering the underinvestment that results with first-best transfers because investment is even lower under second-best transfers when the central government is unable to commit.

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I. Introduction

Chaos in New Orleans in the wake of Hurricane Katrina and the controversy that continues to swirl around the public sector response have led to a broad discussion of the appropriate roles of various levels of government in disaster management and preparedness. A central theme in press and pundit accounts of what went wrong in New Orleans was conflict between those who argued that the disaster was attributable to local officials' failure to adequately prepare for an easily predictable set of events and those who blamed a slow and inadequate response by federal officials (Walter and Kettl 2006).

While recent events have brought these questions to the forefront of public debate, many of the same issues have arisen in previous disasters, including the earthquakes, hurricanes and floods that irregularly strike particular geographic areas of the US. Clearly, a combination of preparedness and effective response are crucial to minimizing the overall welfare losses from these region-specific shocks. Yet policy design must confront a tradeoff between efficiently allocating resources ex-ante to minimize potential losses, and dealing equitably with residents of regions that experience significant losses ex-post. This tradeoff and its implications for the design of public disaster insurance are the subject of the current study.

The trade-off between efficient resource allocation ex-ante and redistributing resources ex-post is related to several strands of literature in economics. First, an important argument in the economics of the family literature is Gary Becker's (1974) "rotten kid theorem." Becker argued that children who are to receive a bequest from a benevolent parent will act to maximize family income, internalizing intra-family externalities in a fashion reminiscent of Coase (1960). This implies that the parent need do nothing more than be benevolent for selfish children to behave well. Bergstrom (1989) formalizes the analysis, finds several cases of failure for the theorem, and also finds that the theorem holds only for a particular class of utility functions – conditional transferable utility. Among the possible problems identified by Bergstrom are public goods, asymmetric information, work effort, and problems involving more than one period. Bruce and Waldman (1990) investigate the two-period problem in some detail in a world of certainty and find that this opens up two avenues for distortionary behavior; even if benevolent parents can partially solve one type of rotten kid problem they will still be faced with the Samaritan's dilemma whereby a child can induce a larger transfer by choosing actions that leave it poor in the second period. With respect to this literature, our model is closest to that of Bruce and Waldman (1990) (where our parent is the central government and our kids are state governments), but we model a world of uncertain future incomes.

A second literature emphasizes asymmetric information and the moral hazard aspects of intra-national insurance as in Persson and Tabellini (1996).[1] Persson and Tabellini study the institutions of federalism in an economy characterized by uncertainty about future income in distinct regions of a federation, a situation that well describes the natural disaster setting. Like Persson and Tabellini, we abstract from household mobility and focus on sub-central governments which are usually defined by particular geographic areas and are thus fixed in place. We thus interpret our model as shedding light on the interplay between disaster risk and the institutions of federalism, not on the relationship

[1] Other papers that study various aspects of asymmetric information and insurance in a federation include Bordignon, Manasse, and Tabellini (2001), Caplan, Cornes, and Silva (2000), Raff and Wilson (1997), and Lockwood (1999).

between a central government and individuals.[2] With respect to this literature, we adapt many features of Persson and Tabellini's (1996) model specifically to the study of natural disasters. Unlike Persson and Tabellini, we find that the Nash equilibrium regional investment associated with time-inconsistent second-best transfers is lower than the Nash equilibrium regional investment given first-best transfers. Although investment is too low under first-best transfers because of an externality from the transfer, second-best transfers that are time-inconsistent fail to improve on this because there are two reasons for underinvestment in this case: the externality from the transfer and a soft-budget constraint resulting from the ex-ante investment decision with uncertainty.

A third strand of literature relates to "second generation" models of federalism as reviewed by Oates (2005) for instance. This emerging literature is often characterized by models in which information, politics, and strategic decisions play important roles, elements that enter our model in key areas, so our paper is also a contribution to this emerging body of literature. In this literature, for instance, Goodspeed (2002) shows in a world of certainty how the central government pursuit of vote maximization can lead it to capitulate to profligate regional governments, bailing them out after bouts of excessive borrowing. The last part of our model is similar to this model but, as with the Bruce and Waldman (1990) paper, we model the case of uncertain future incomes.

Our paper complements a fourth strand of literature that examines empirically the role that federalist institutions can play in insuring residents of a federation against

[2] This focus does not imply that mobility is an unimportant feature of disasters. Indeed, location choice is a fundamental part of the process that determines vulnerability and is relevant to designing appropriate disaster response. For papers that study individuals and mobility see Kunreuther's (2006) work on public disaster insurance for individual households and firms and Wildasin's (2008b) work on federal disaster insurance with mobile households.

income loss such as a regional business cycle (von Hagen 2007 provides a useful review). When shocks to regional incomes are imperfectly correlated, an insurance contract can be derived that transfers resources from regions that realize high income to those that sustain a negative shock. In such circumstances, a policy institution that provides a transfer to regions that are experiencing a downturn can enhance both aggregate stability and equity (see, for example, Bayoumi and Masson 1995). An empirical literature has sought to quantify the actual size of such transfers, an effort which is complicated by correlations in shocks across regions, by difficulty in distinguishing temporary from permanent shocks, and by the distinction between aggregate income and aggregate output. Melitz and Zumer (2002) summarize previous results and provide a well-founded estimate that central government redistribution offsets about 10 to 20 percent of shocks to personal income in four countries.[3] Our analysis points to a somewhat different shock – natural disasters – but the similarity is clear.

To set the stage for our analysis we note that hazards policy in the United States is a complex interplay between the federal and state-local sectors. Broadly speaking, state and local officials bear primary responsibility for carrying out policies to minimize vulnerability to natural hazards through land use regulation, investment in protective infrastructure, emergency response programs and so forth. The federal government provides a number of matching grants (see Jordon, 2006, for instance), but the bulk of federal resources are devoted to providing assistance to individuals and governments *after* disasters occur. As Jordon (2006) states “Federal agencies provide a range of assistance to individual victims, state, territorial, and local governments, and

[3] France, the UK, the US and Canada

nongovernmental entities ***after*** major disasters …" (emphasis added). Between fiscal years 1974 and 2005, Presidents declared over 1,200 disasters in the United States, and the federal government appropriated over 80 billion constant FY 2005 dollars for disaster relief. As indicated in Chart 1, as the annual number of declared disasters has risen, the average cost per year has risen above $3 billion. While much of this relief was provided to individuals and businesses, a substantial portion takes the form of grants-in-aid to state and local governments.[4] Since 1998, the Federal Emergency Management Agency (FEMA) has obligated an average of over $2 billion per year to public sector disaster assistance. Roughly three quarters of these expenditures have been designated for ex-post emergency response and repair of public facilities.[5] As indicated in Chart 1, more than half of the federal funds provided for disaster relief since 1990 have been the result of ex-post supplemental appropriations. That is, Congress has elected to appropriate large amounts of additional federal compensation *after disasters occur*, raising questions about the federal government's ability to commit to any transfer scheme that limits ex-post compensation.[6]

Apart from Chart 1 and the above discussion, we do not provide empirical evidence of ex-post disaster relief, a topic that we leave for future research. However, there is some relevant literature. First, Garrett and Sobel (2003) provide evidence of political manipulation of ex-post FEMA disaster relief funds. They find that states that are politically important to the president receive more declarations of disasters and that

[4] The federal response to disasters may also include less obvious kinds of relief, like relaxation of standards for poverty relief. See (Chernick 2001).
[5] These figures exclude the response to the September 11, 2001 terrorist attack. That event alone resulted in a $7 billion Congressional appropriation.
[6] Wildasin (2007, 2008a) suggests a mandatory disaster reserve fund as one possible solution to this problem.

states that have congressional seats on FEMA oversight committees receive more funds. Healy and Malhotra (2009) find that this translates into votes; they find that the percentage of votes for the presidential incumbent rises with ex-post disaster relief spending. This is consistent with a political interpretation of the last part of our model where the central government cannot commit to ex-ante transfer design.

Our theoretical results are summarized as follows. We show that when the federal government is committed to full insurance against disasters, the transfers result in an externality and regions acting non-cooperatively will have incentives to under-invest in protective infrastructure in the Nash equilibrium. We derive the second-best transfer scheme and find that for low-probability disasters such transfers will be less than the first-best, leading to more ex-ante investment and less ex-post redistribution. However, the second-best transfer scheme suffers from a time-inconsistency problem: the central government will be unable to commit to the second-best transfer levels, and will instead opt for equalizing transfers ex-post. This behavior leads to a type of soft budget constraint and regions that anticipate the future central government action will further under-invest in protective infrastructure in the Nash equilibrium. The upshot is that the central government is better off suffering the underinvestment that results with first-best transfers because investment is even lower under second-best transfers when the central government is unable to commit.

The paper is organized as follows. Section II describes the economy we study, and lays out the basic model of federalism with uncertain incomes. In this section we also derive the optimal insurance scheme and level of investment in protective infrastructure for the federation. In section III, we derive non-cooperative regional investment levels for any transfer scheme in which regional actions do not influence transfers received. In section IV, we derive the structure of the optimal second-best insurance system when regional governments choose investment levels non-cooperatively and the central government cannot verify regional investment choices. Section V shows that the central government will be unable to commit to the second-best transfer levels, and also shows that regions that understand this will further under-invest in protective infrastructure in the Nash equilibrium. Section VI concludes with a discussion of what the model can teach us about the federal response to recent disasters and those yet to come.

II. First-Best Transfers and Regional Investment

We begin with a simple model of a federation with two regional governments that are completely symmetric. To differentiate the two regions, variables for one of the regions are denoted with asterisks. Each region has certain income in period 1 and uncertain income in period 2. The uncertainty results from i.i.d. shocks. Uncertain income can be high with probability P or low with probability (1 – P). A region can use some of its period 1 certain income ($\bar{Y} = \bar{Y}^*$) to invest in protective infrastructure, I, (e.g. levies or first responder training), leaving it with $Y = \bar{Y} - I$ (or analogously $Y^* = \bar{Y}^* - I$) period 1 income. This investment increases the probability of ending up with high income, so P is a function of I. There are thus four joint possibilities for uncertain income:

i. (Y_H, Y^*_H) with probability P(I)P(I*)

ii. (Y_H, Y^*_L) with probability P(I)(1-P(I*))

iii. (Y_L, Y^*_H) with probability (1-P(I))P(I*)

iv. (Y_L, Y^*_L) with probability (1-P(I))(1-P(I*))

While we differentiate the regions by use of the asterisk, it should be clear that our assumption of symmetry implies that each variable has the same value for the starred and unstarred region (e.g. $Y_H = Y^*_H$; P(I) = P(I*); and so forth). As mentioned above, the first derivative of P(I) is positive, P'(I) > 0. We also assume the second derivative is negative, P''(I) < 0, i.e. we assume diminishing returns in production of protection. This seems an intuitively appealing assumption. For instance, making a levee wider always reduces the probability that it will fail, but adding a foot to a two-foot wide levee adds more protection from failure than adding the same amount to one that is ten feet wide.

For most of the paper, we model a three step decision process. In stage one, the central government commits to a transfer scheme. In the second stage, regional governments choose an investment level in light of the announced transfer scheme. Once investments are in place, the state of nature is revealed (disasters, if any, occur), incomes are realized and the transfers committed to in the first stage are made. In the final part of the paper we examine the dynamic consistency of the central government's first-stage transfer commitment by adding an additional stage where the central government may choose to revisit its transfer scheme ex-post.

<u>First-best optimal transfers for given investment levels</u>

We begin by deriving the first-best transfers of the central government. Our findings are summarized in the following proposition:

PROPOSITION 1: *First-best transfers should be set to equalize the marginal utility of transfers across regions.*

We begin the discussion and proof of this proposition by stating our assumptions. Regions are assumed to be risk averse and risk sharing in the federation is accomplished through a set of self-funding transfers (i.e. the amount paid by one region is the amount received by the other). The central government wants to choose transfers for each (joint) state of nature $\{T_{HH}, T_{HL}, T_{LH}, T_{LL}\}$ where the first subscript refers to the state of nature of the unstarred region and the second subscript stands for the state of nature of the starred region. The central government's objective is to maximize the sum of expected utilities:

$$
\begin{aligned}
(1)\qquad & \underset{\{T_{HH}, T_{HL}, T_{LH}, T_{LL}\}}{\text{Max}} \; v(\bar{Y}-I) + v(\bar{Y}^* - I^*) \\
& + P(I)P(I^*)u(Y_H + T_{HH}) \\
& + P(I)(1-P(I^*)u(Y_H - T_{HL}) \\
& + (1-P(I))P(I^*)\, u(Y_L + T_{LH}) \\
& + (1-P(I))(1-P(I^*))\, u(Y_L + T_{LL}) \\
& + P(I)P(I^*)u(Y^*_H - T_{HH}) \\
& + P(I)(1-P(I^*)u(Y^*_L + T_{HL}) \\
& + (1-P(I))P(I^*)\, u(Y^*_H - T_{LH}) \\
& + (1-P(I))(1-P(I^*))\, u(Y^*_L - T_{LL})
\end{aligned}
$$

where we assume that period 1 and period 2 utility are additively separable. This yields the set of first-order conditions:

$$
(2)\qquad \frac{\partial u(Y_r + T_{rs})}{\partial T_{rs}} = \frac{\partial u^*(Y^*_s - T_{rs})}{\partial T_{rs}} \quad r, s \in (L, H)
$$

where u* henceforth denotes utility given the value of the starred region's arguments. This set of first order conditions say that transfers should be set to equalize the marginal utility of transfers, or equivalently the marginal utility of income, across the two regions.

Given declining marginal utilities, this implies that after-transfer incomes should be equalized for all states of nature. Hence, optimal transfers for a given regional investment level in the first-best results in full risk-sharing. For cases (i) and (iv) above no transfers occur since incomes are already equal. For cases (ii) and (iii), income is transferred from the region that realizes high income to the one that realizes low income. Figure 1 illustrates the optimal first-best transfer for case (ii) above - (Y_H, Y^*_L).

<u>First-best regional investment levels</u>

We next derive first-best investment levels for each region. Our findings are summarized in the following proposition:

PROPOSITION 2: *When transfers are present and there is no information problem, the marginal benefit of region i's investment depends on region j's investment, and optimal first-best investment of region i must take into account the external benefit to region j.*

The striking part about this proposition is that the introduction of the transfers introduces an externality even without spillover benefits. To see this, we now consider the level of regional investment that maximizes the sum of expected utilities. Here there is no information problem since the central government is able to choose investment levels directly. In this case, the first-best optimal investment solves:

$$
\begin{aligned}
(3) \qquad & \operatorname*{Max}_{I,I^*} v(\bar{Y} - I) + v(\bar{Y}^* - I^*) \\
& + P(I)P(I^*)u\,(Y_H + T_{HH}) \\
& + P(I)(1 - P(I^*)u(Y_H - T_{HL}) \\
& + (1 - P(I))P(I^*)\,u(Y_L + T_{LH}) \\
& + (1 - P(I))(1 - P(I^*))\,u(Y_L + T_{LL}) \\
& + P(I)P(I^*)u\,(Y^*_H - T_{HH}) \\
& + P(I)(1 - P(I^*)u(Y^*_L + T_{HL}) \\
& + (1 - P(I))P(I^*)\,u(Y^*_H - T_{LH}) \\
& + (1 - P(I))(1 - P(I^*))\,u(Y^*_L - T_{LL})
\end{aligned}
$$

The FOC with respect to I is:

$$
\begin{aligned}
(4) \qquad & \frac{\partial P}{\partial I}\left[P^*\{u(Y_H) + u(Y_H{}^*)\} - (1 - P^*)\{u(Y_L) + u(Y_L{}^*)\}\right] \\
& + \frac{\partial P}{\partial I}(1 - P^*)\left[\{u(Y_H - T_{HL})\} + \{u(Y^*_L + T_{HL})\}\right] \\
& - \frac{\partial P}{\partial I}P^*\left[\{u(Y_L + T_{LH})\} + \{u(Y^*_H - T_{LH})\}\right] = \frac{\partial v}{\partial Y}
\end{aligned}
$$

where we use the fact that $T_{HH} = T_{LL} = 0$. Analogously, the FOC with respect to I* is:

$$
\begin{aligned}
(4^*) \qquad & \frac{\partial P^*}{\partial I^*}\left[P\{u(Y_H) + u(Y_H{}^*)\} - (1 - P)\{u(Y_L) + u(Y_L{}^*)\}\right] \\
& + \frac{\partial P^*}{\partial I^*}(1 - P)\left[\{u(Y^*_H - T_{LH})\} + \{u(Y_L + T_{LH})\}\right] \\
& - \frac{\partial P^*}{\partial I^*}P\left[\{u(Y_L{}^* + T_{HL})\} + \{u(Y_H - T_{HL})\}\right] = \frac{\partial v^*}{\partial Y^*}
\end{aligned}
$$

With symmetric regions and transfers that exhibit full risk-sharing as derived above (4) reduces to:

$$
(5) \qquad 2\frac{\partial P}{\partial I}P^*\left[u(Y_H) - u(Y_L + T_{LH})\right] - 2\frac{\partial P}{\partial I}(1 - P^*)\left[u(Y_L) - u(Y_H - T_{HL})\right] = \frac{\partial v}{\partial Y}
$$

Analogously, (4*) reduces to:

$$
(5^*) \quad 2\frac{\partial P^*}{\partial I^*}P\left[u(Y_H{}^*) - u(Y_L{}^* + T_{HL})\right] - 2\frac{\partial P^*}{\partial I^*}(1 - P)\left[u(Y_L{}^*) - u(Y_H{}^* - T_{LH})\right] = \frac{\partial v^*}{\partial Y^*}
$$

Note that the implicit first-best optimal investment level for I depends on I* (through P*) and vice-versa. This is the externality: each region's investment decision affects the other region's utility. Given the assumed symmetry, the first order conditions are identical so optimal first-best investment levels I and I* must be identical. Note also that if there were no transfers the first order condition (5) would not depend on I* and would reduce to:

$$(6) \qquad 2\frac{\partial P}{\partial I}\left[u(Y_H)-u(Y_L)\right]=\frac{\partial v}{\partial Y}$$

and analogously for (5*). The presence of the transfers has inserted an externality into the problem because they make it so that one region's investment affects the utility of the other region.

III. Non-cooperative Regional Investment

Given the just noted externality in which each region's optimal investment level depends on the other region's level of investment, the natural way to model decentralized investment choices is to explore the Nash equilibrium of the two regions as they act non-cooperatively. Our results are summarized in the following proposition:

PROPOSITION 3: *When transfers are present and regions act non-cooperatively, region i ignores the benefit to region j in its investment decision. The Nash Equilibrium investment level of each region depends on the central government transfer and is less than the first-best investment level.*

From here on we will use the symmetry of regions to economize on notation. Symmetry implies that transfers paid by each region when it has high income and the other region has low income are the same ($T_{HL} = T_{LH}$) so we henceforth simplify by letting T = $T_{HL} = T_{LH}$. The unstarred region's optimal choice of protective investment will solve the following problem:

$$
(7) \qquad \begin{aligned}
&\underset{I}{\text{Max}}\; v(\bar{Y} - I) \\
&+ P(I)P(I^*)u\,(Y_H\ ) \\
&+ P(I)(1 - P(I^*)u(Y_H\ - T\ ) \\
&+ (1 - P(I))P(I^*)\,u(Y_L\ + T\ ) \\
&+ (1 - P(I))(1 - P(I^*))\,u(Y_L\ )
\end{aligned}
$$

The first order condition, which defines the reaction function for the unstarred region, is:

$$
(8) \quad P'(I)P(I^*)\left[u(Y_H\ ) - u(Y_L\ + T\ )\right] - P'(I)(1 - P(I^*))\left[u(Y_L\ ) - u(Y_H\ - T\ )\right] = v_Y
$$

The level of investment of the unstarred region depends on the transfer and the level of investment of the starred region because of P(I*); we denote the reaction function I(T, I*).

Analogously to (8) above, the first order condition for the starred region is:

$$
(8^*) \ \frac{\partial P^*}{\partial I^*}P(I)\left[u(Y^*_H\ ) - u(Y^*_L\ + T\ )\right] - \frac{\partial P^*}{\partial I^*}(1 - P(I))\left[u(Y^*_L\ ) - u(Y^*_H\ - T\ )\right] = \frac{\partial v^*}{\partial Y^*}
$$

Solving (8*) for I* would yield the reaction function of the starred region, I*(T,I). The symmetry of the problem implies that the two reaction functions are also symmetric.

We show in Appendix A1 that the reaction functions are downward sloping functions of investment and also prove the existence and stability of the Nash equilibrium; we denote this Nash equilibrium investment level as I(T)=I*(T). Figure 2 shows the Nash equilibrium graphically.

An intuitive description of (8) is as follows. The right hand side of (8) represents the direct marginal cost of greater investment which results in lower period 1 certain income and consumption. The left hand side represents the marginal expected increase in period 2 utility resulting from the fact that an increase in investment increases the probability of ending up with Y_H and decreases the probability of ending up with Y_L. Comparing to the first order conditions from the first-best problem, these are the same except that the two left hand side terms are multiplied by two in (5). This is because one region's investment decision affects the probability of ending up in each of the four joint income possibilities. The region takes into account the effect of its investment on its own utility, but does not take into account the effect on the utility of the other region. In other words, region 2 benefits from an increase in region 1's probability of ending up with Y_H (holding region 2's probabilities constant). Region 1 ignores this benefit in its investment decision and invests too little in protective infrastructure from a social point of view.

To summarize, the central government can offer full risk-sharing, which would be first-best optimal if the central government could also choose regional investment levels. However, if regions choose their own investment levels while the central government offers full risk-sharing transfers, regions acting non-cooperatively will underinvest in protective infrastructure.

IV. Second-Best Transfers

We have thus far shown that if the central government commits and offers first-best optimal transfers with full risk-sharing while regions choose their investment levels and act non-cooperatively, regions will tend to underinvest in protective infrastructure from a national perspective. Thus, first-best investment and first-best risk-sharing transfers cannot both be achieved under these circumstances. We next consider whether the central government can design a second-best transfer system that would achieve higher overall welfare. Our results are summarized in the following proposition:

PROPOSITION 4: *Let T_1 denote optimal first-best transfers and T_2 denote optimal second best transfers. When the central government recognizes that its transfer decision affects regions i's investment level and takes region i's reaction function into account,* $T_2 \stackrel{\geq}{<} T_1$ *iff* $\frac{U(Y_H)}{U(Y_L)} \stackrel{\leq}{>} \frac{(1-P)}{P}$.

The proof of this proposition follows from the central government's problem. As before we assume that the central government's problem is to choose T to maximize the sum of expected utilities. However, now the central government is assumed to know the reaction functions and Nash equilibrium investment choices I(T) = I*(T) so it recognizes that regions' investment choices will depend on the transfer they receive. In this case, the second-best transfers solve:

$$
\begin{aligned}
&\operatorname*{Max}_{T}\, v(\bar{Y} - I(T)) + v(\bar{Y}* - I*(T)) \\
&+ P(I(T))P(I*(T))u(Y_H) \\
&+ P(I(T))(1 - P(I*(T))u(Y_H - T) \\
&+ (1 - P(I(T)))P(I*(T))\, u(Y_L + T) \\
(9) \qquad &+ (1 - P(I(T)))(1 - P(I*(T)))\, u(Y_L) \\
&+ P(I(T))P(I*(T))u(Y*_H) \\
&+ P(I(T))(1 - P(I*(T))u(Y*_L + T) \\
&+ (1 - P(I(T)))P(I*(T))\, u(Y*_H - T) \\
&+ (1 - P(I(T)))(1 - P(I*(T)))\, u(Y*_L)
\end{aligned}
$$

where I(T) = I*(T) are the Nash equilibrium investment levels and the FOC for T is:

$$
(10)\quad
\begin{aligned}
&(10.0) && P(1-P^*)\frac{\partial u(Y_H-T)}{\partial T}=(1-P^*)P\,\frac{\partial u(Y^*{}_L+T)}{\partial T}\\
&(10.1) && -\left[u(Y_H-T\,)+u(Y^*{}_L+T\,)\right]\left[\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}(1-P^*)-\frac{\partial P^*}{\partial I^*}\frac{\partial I^*}{\partial T}P\right]\\
&(10.2) && -\left[u(Y^*{}_H-T\,)+u(Y_L+T\,)\right]\left[\frac{\partial P^*}{\partial I^*}\frac{\partial I^*}{\partial T^*}(1-P)-\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}P^*\right]\\
&(10.3) && +\left[u(Y_H)+u(Y^*{}_H)\right]\left[\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}P^*+\frac{\partial P^*}{\partial I^*}\frac{\partial I^*}{\partial T}P\right]\\
&(10.4) && -\left[u(Y_L)+u(Y^*{}_L)\right]\left[\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}(1-P^*)+\frac{\partial P^*}{\partial I^*}\frac{\partial I^*}{\partial T}(1-P)\right]\\
&(10.5) && +\left[\frac{\partial v}{\partial I}\frac{\partial I}{\partial T}+\frac{\partial v}{\partial I^*}\frac{\partial I^*}{\partial T}\right]
\end{aligned}
$$

We can simplify by using the envelope theorem, which in our context states that regions will always pick an investment level along their respective reaction functions so (8) and (8*) will be satisfied. Using in addition the symmetry properties, the first order condition for T simplifies to:

$$
(11)\quad
\begin{aligned}
\frac{\partial u(Y_H-T)}{\partial T}&=\frac{\partial u(Y_L+T)}{\partial T}+\left[\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}\right]\left[\left(\frac{1}{1-P}\right)2u(Y_H)-\left(\frac{1}{P}\right)2u(Y_L)\right]\\
&=\frac{\partial u(Y_L+T)}{\partial T}+\left[\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}\frac{2u(Y_L)}{P}\right]\left[\left(\frac{P}{1-P}\right)\left(\frac{u(Y_H)}{u(Y_L)}\right)-1\right]
\end{aligned}
$$

Notice that this equation is identical to the first-best first order condition for transfers except for the additional term on the right hand side, which we will denote A. In Appendix A2 we show that the additional term A term is negative iff $\dfrac{u(Y_H)}{u(Y_L)}>\dfrac{1-P}{P}$ and positive iff $\dfrac{u(Y_H)}{u(Y_L)}<\dfrac{1-P}{P}$. Proposition 4 follows from examination of the first-order conditions for second-best transfers (11) and the first-order conditions for first-best transfers (2).

A graphical depiction can be provided by reference to Figure 1. We have noted that (11) is identical to (2) except for the additional term on the right hand side denoted A. This additional term is added to the marginal utility of income for the region that suffers a low income shock. If A is positive, more weight is given to the marginal utility of the region suffering from the low-income shock than under the first-best so the marginal utility line of the starred region in figure 1 is shifted up and transfers are higher. If A is negative, less weight is given to the marginal utility of the region suffering the low-income shock than under the first-best, the marginal utility of the starred region shifts down, and transfers are lower. These possibilities are illustrated in Figure 3.

The intuition of Proposition 4 is the following. For the first-best case the central government has one goal to achieve with transfers: redistributing income to equalize marginal utilities. For the second-best case, the central government has two goals that it is trying to balance as it changes transfers: redistributing income to equalize marginal utilities and correcting for underinvestment. The trade-off is that higher transfers lead to more equal marginal utilities while lower transfers lead to higher investment. There are two cases to consider: $PU(Y_H)>(1-P)U(Y_L)$ and $PU(Y_H)<(1-P)U(Y_L)$. Consider first the $PU(Y_H)>(1-P)U(Y_L)$ case. For this case the trade-off is clear: higher investment is desirable so transfers will need to be lower in the second best to encourage investment at the cost of less redistribution. For the $PU(Y_H)<(1-P)U(Y_L)$ case, things are less clear. To understand this case, it is important to realize that the optimal transfer rule is being made from an ex-ante perspective. Consider the ranking of the (Y_L, Y^*_L) and (Y_H, Y^*_H) states of the world. Ex-post it is obvious that (Y_H, Y^*_H) is preferred to (Y_L, Y^*_L). However, ex-ante it is possible that $PU(Y_H)<(1-P)U(Y_L)$. This would happen if the difference between Y_H and Y_L is sufficiently small and (1-P) is sufficiently larger than P. In this case (Y_L, Y^*_L) is ex-ante preferred to (Y_H, Y^*_H). Higher transfers will lower investment and hence P as before, but in this case the lower P is desirable because it increases the odds of the ex-ante preferred (Y_L, Y^*_L) outcome. The redistribution motive is unaffected for the (Y_H, Y^*_L) and (Y_H, Y^*_L) outcomes, and of course is irrelevant for the (Y_L, Y^*_L) and (Y_H, Y^*_H) cases. Hence, for this case, the investment motive leads to transfers that are higher in the second-best than the first-best. To our knowledge this latter case has not been mentioned in the literature, although it bears some resemblance to the reasoning of Besfamille and Lockwood (2008).

It is perhaps the contrast between second- and first-best transfers that distinguishes the disaster case from other shocks to regional incomes. Disasters are by definition low probability, high-cost events that would typically result in very large shocks to regional income and utility. More common, lower cost shocks – perhaps like those associated with regional business cycles – are those in which second-best transfers may exceed first-best.

V. Commitment and Ex-post Central Government Grants

We now concentrate on the second-best transfer case that seems most relevant for disasters, the case where (1-P) is small and consequently second-best transfers are less than first-best from Proposition 4. Up to this point, we have assumed that the central government commits to the second-best ex-ante optimal transfers. However, second-best transfers that are smaller than first-best transfers require the central government to effectively ex-ante commit to punish regions that end up with a disaster ex-post in order to increase the incentive of regions to invest in protective infrastructure ex-ante and thereby lessen the costs of the disaster. But there is a real question concerning the credibility of the central government commitment. If the central government cannot credibly commit to this, a different and distinct reason for underinvestment in protective infrastructure will arise: the anticipation by a region that ex-post transfers from the central government can be influenced by its investment choices. Given this, the region can exploit the anticipated reaction of the central government (effectively exploiting a soft budget constraint) and further under-invest in protective infrastructure.

To model this, we consider the central government's choice of transfers from an ex-post perspective. Our results are summarized in the following proposition:

PROPOSITION 5: *Ex-post the central government will not want to implement the second-best transfers and will act as if transfers do not affect regional investment.*

The proof of this proposition follows from the first-order conditions of the central government's ex-post problem. We maintain our normative framework and assume that the central government's objective function is the sum of regions' utilities. Ex-post, the central government chooses transfers to maximize

$$\text{(12)} \qquad \underset{\{T_{rs},r,s\in(L,H),r\neq s\}}{\text{Max}} u(Y_r + T_{rs}) + u(Y*_s - T_{rs})$$

The first order conditions are:

$$\text{(13)} \qquad \frac{\partial u(Y_r + T_{rs})}{\partial T_{rs}} = \frac{\partial u*(Y*_s - T_{rs})}{\partial T_{rs}} \quad r,s \in (L,H), r \neq s$$

Ex-post, the central government will not implement second-best transfers; rather, it will want to equate the marginal utility across regions, which implies that it wants to equalize incomes ex-post. Ex-post optimal transfers are thus

$$(14) \qquad T_{LH} = \frac{Y^*_H - Y_L}{2} = T_{HL} = \frac{Y_H - Y^*_L}{2}$$

The time inconsistency of the central government's transfer decision has implications for ex-ante regional investment decisions. Ex-ante a region needs to predict its ex-post transfer. While the region could predict the ex-post form of transfers from (14) above, ex-ante the transfers are uncertain because of the uncertainty surrounding the disaster event. We assume that ex-ante a region predicts these ex-post transfers to be

$$(14') \qquad \tau_{LH} = \frac{P(I^*)Y^*_H - (1-P(I))Y_L}{2}, \tau_{HL} = \frac{P(I)Y_H - (1-P(I^*))Y^*_L}{2}$$

The regions realize that their ex-ante behavior will change the predicted ex-post transfer since greater investment is going to increase the probability of a high income outcome and decrease the probability of a low income outcome, and each region would want to take this into account in its ex-ante investment decision. This will create a soft budget constraint and an additional reason for underinvestment by the region. We characterize the ex-ante regional investment decisions below. Our results are summarized in the following proposition:

PROPOSITION 6: *Given the time inconsistency of central government transfers, regional investment will fall below the original non-cooperative Nash equilibrium.*

The intuition of the proposition is that there are now two reasons for underinvestment by a region. The first is the same as before, underinvestment due to the externality introduced by the transfers. The second is the soft budget constraint problem introduced by the time inconsistency of the central government transfer decision. The proof follows from the regional investment problems and the resulting Nash equilibrium. To explain the results, we need to derive the sign of certain derivatives of the predicted ex-post transfers, which we relegate to Appendix A3. We also show in Appendix A3 that the reaction functions are downward sloping and prove existence and stability.

Consider the ex-ante investment decision of the unstarred region when it realizes that the central government will implement the optimal ex-post transfers. The region's investment decision will solve:

$$
\begin{aligned}
&\operatorname*{Max}_{I} v(\bar{Y}-I) \\
&+P(I)P(I^*)u(Y_H) \\
&+P(I)(1-P(I^*)u(Y_H-\tau_{HL}) \\
&+(1-P(I))P(I^*)\,u(Y_L+\tau_{LH}) \\
&+(1-P(I))(1-P(I^*))\,u(Y_L)
\end{aligned}
\tag{15}
$$

The first order condition is:

$$
\begin{aligned}
&\frac{\partial P}{\partial I}P^*\left[u(Y_H)-u(Y_L+\tau_{LH})\right]-\frac{\partial P}{\partial I}(1-P^*)\left[u(Y_L)-u(Y_H-\tau_{HL})\right] \\
&+\frac{\partial u(Y_H-\tau_{HL})}{\partial \tau_{HL}}\frac{\partial \tau_{HL}}{\partial I}P(1-P^*)+\frac{\partial u(Y_L+\tau_{LH})}{\partial \tau_{LH}}\frac{\partial \tau_{LH}}{\partial I}(1-P)P^*=\frac{\partial v}{\partial I}
\end{aligned}
\tag{16}
$$

Solving (16) for I yields the reaction function of the unstarred region. We show in Appendix A3 that the reaction function is downward sloping.

The analogous first-order condition for the starred region is:

$$
\begin{aligned}
&\frac{\partial P^*}{\partial I^*}P\left[u(Y^*_H)-u(Y^*_L+\tau_{HL})\right]-\frac{\partial P^*}{\partial I^*}(1-P)\left[u(Y^*_L)-u(Y^*_H-\tau_{LH})\right] \\
&+\frac{\partial u(Y^*_H-\tau_{LH})}{\partial \tau_{LH}}\frac{\partial \tau_{LH}}{\partial I^*}P^*(1-P)+\frac{\partial u(Y^*_L+\tau_{HL})}{\partial \tau_{HL}}\frac{\partial \tau_{HL}}{\partial I^*}(1-P^*)P=\frac{\partial v^*}{\partial I^*}
\end{aligned}
\tag{16*}
$$

Solving (16*) for I* yields the reaction function of the starred region, and the symmetry of the problem implies that the two reaction functions are also symmetric. Hence, the discussion of the unstarred region's reaction function in Appendix A3 applies equally to the starred region's reaction function, which is downward sloping. The Nash Equilibrium levels of investment that simultaneously solve these two first order conditions would be identical for each region.

To prove Proposition 6, we can compare investment levels to the earlier case by reference to Figure 2. We show that the reaction functions pictured in Figure 2 are both lower. The first two terms of (16) and (16*) are the same as equations (8) and (8*) from before, so from our previous analysis we know that there will be an incentive to under-invest because of the externality. We now have two additional terms to analyze, however. The second two terms on the left-hand side of (16) and (16*) arise from the fact that the regions know that ex-post transfers will be affected by its' investment decision. We can sign these terms because we know that $\partial u/\partial \tau_{HL} < 0$ and $\partial u/\partial \tau_{LH} > 0$ in (16) and $\partial u^*/\partial \tau_{HL} > 0$ and $\partial u^*/\partial \tau_{LH} < 0$ in (16*). Using the derivative signs derived in Appendix A3, the remaining parts of the two additional terms in (16) and (16*) are positive, so the third term is negative and the fourth is positive. Furthermore, we know from Appendix A3 that the negative term is larger than the positive term so the sum of the two additional terms of (16) and (16*) is negative, and the marginal benefit of investment is lower than in (8) and (8*). The reaction functions pictured in Figure 2 are therefore both lower and thus the Nash equilibrium investment levels are also lower. This is the effect of each region's exploitation of the anticipated central government transfers (the anticipation of a type of soft budget constraint). As it undertakes its ex-ante investment decision, the region realizes that the central government will have an incentive to equalize incomes ex-post and each region consequently has less incentive to invest. In the Nash Equilibrium, as both regions anticipate the central government response, both will further under-invest in protective infrastructure relative to the initial non-cooperative Nash Equilibrium.

VI. Conclusion

This paper has studied a model of federalism which highlights the tradeoff between providing appropriate incentives for protective investment at the sub-national level and insuring actual losses after a disaster occurs. We take as given a federal structure that retains autonomy for spending at the sub-national level. Our results indicate that when regional governments undertake disaster prevention measures and act non-cooperatively, federal disaster insurance creates an externality and will result in underinvestment in pre-disaster protective investment. We assume here that unobservable or unverifiable local efforts to prevent disasters make typical externality prescriptions (such as matching grants) difficult to implement, although this would be an interesting avenue to pursue in future research.[7]

When the relative probability of a disaster is low, second-best federal transfers involve less redistributive transfers after a disaster occurs in order to increase ex-ante investment. But the effectiveness of such a regime requires credible ex-ante commitment by the federal government. This commitment may be difficult to sustain. As mentioned in

[7] The federal government does provide matching grants for preventive investments and some may question whether local efforts are verifiable. Our model is admittedly stylized to one extreme in the supposition of unverifiable local efforts. It is not without merit, though, as exemplified by Steinberg's (2000, pp 103-111) account of the problems of the National Flood Insurance Program (NFIP). The NFIP, adopted in 1968, offers insurance to residents of 100-year floodplains at heavily subsidized rates. In exchange, local officials were to increase protection by requiring that new structures be built above the 100-year flood level. Yet in the interest of economic development, officials in some locations granted numerous variances to these regulations, leading to ever-expanding claims on the flood insurance program.

the introduction and shown in Chart 1, initial Congressional appropriations to the Disaster Relief Fund have been heavily supplemented after disasters have occurred in recent years. Moreover, Garrett and Sobel (2003) provide evidence of political manipulation of ex-post FEMA disaster relief funds and Healy and Malhotra (2009) find that this translates into more votes for the presidential incumbent. This is consistent with a political interpretation of the last part of our model where the central government cannot commit to ex-ante transfer design.

When the central government cannot commit to the second-best transfers and regions anticipate ex-post equalizing transfers, the regions will further under-invest to influence anticipated future transfers, taking advantage of a type of soft budget constraint. We show that ex-ante investment in the Nash equilibrium for this case is even lower than the regional investment that would arise under first-best transfers. This is because there are two reasons for underinvestment when the central government cannot commit: underinvestment due to the externality introduced by the transfers (as with first-best transfers) and a soft budget constraint problem introduced by the time inconsistency of the central government transfer decision. The evidence mentioned above suggests that current US disaster policies may be susceptible to this problem.

While the model presented here provides preliminary insights into the nature of the problems raised by natural disasters, we see several directions in which this work could be extended. Here we describe two of these. Both of these extensions may add some richness to the findings reported here, but we believe that neither is likely to reverse our main conclusions.

We model regional government investment in protective infrastructure, but another major source of risk mitigation by state and local government consists of regulations: building codes, land use restrictions and the like. Such regulations are often seen from the state perspective as diminishing local economic growth, implying that our modeling assumption captures the basic issue. Nonetheless, explicit treatment of the choice between structural and regulatory mitigation techniques might yield more nuanced insights.

A second possible extension concerns the potential for spillovers from protective investments. In the case of flood control, for example, structures built to prevent flooding in one location can increase their probability in others. A well-known example is levees on the Mississippi River, which force flood waters to other, unprotected, locations. Generalizing the model to account for such externalities in the effects of protective investments will allow a more complete examination of the issues.

The problems raised by geographically-concentrated shocks to income, regardless of their probability and magnitude, are difficult to solve. We study a simple stylized model that captures some important features of US disaster policy. In our model, federal insurance for regions creates an externality that results in regional under-provision of investments in disaster protection. Second-best transfers that reduce redistributive transfers in the case of a disaster and increase regional investment can be devised, but these may suffer from a time-consistency problem. If regions anticipate the time-consistent transfers, their exploitation of this type of soft budget constraint will result in a further reduction in sub-national protective infrastructure investment.

The challenge for policy-makers is to provide appropriate incentives for local protective actions, whether regulatory or structural, while maintaining the benefits of insurance against large shocks. This is a difficult issue that has bedeviled disaster policy-makers for generations. The introduction of second-best transfers that reduce ex-post relief in order to increase ex-ante investment is one path to the constrained optimum. This would, however, require more post-disaster discipline on the part of Congress than it has historically demonstrated.

Appendix A1: Deriving the properties of the regional reaction functions

1. The slope

To derive the slope of the reaction function, write the reaction function defined by (8) in implicit form, $\phi(I, I^*, T) = 0$. Using the implicit function theorem, the slope of the reaction function for the unstarred region is:

$$(A1-1) \qquad \frac{dI}{dI^*} = -\frac{\phi_{I^*}}{\phi_I}$$

Assuming that $Y_H > Y_L + T$, i.e. that the transfer cannot make the region hit by a negative shock have more income than it would have received had it gotten a positive shock, the sign of ϕ_I is negative:

$$(A1-2)\ \phi_I = P''(I)P(I^*)\left[u(Y_H)-u(Y_L+T)\right]-P''(I)(1-P(I^*))\left[u(Y_L)-u(Y_H-T)\right]<0$$

Given that $Y_H > Y_L + T$, the first term in brackets is positive and since P''(I) is negative the entire first term must be negative. The second term in brackets must be negative given that $Y_H - T > Y_L$ and since P''(I) is negative (and is multiplied by -1), the entire second term must also be negative. Hence, $\phi_I < 0$. Concavity of the utility function (i.e. risk aversion) implies that ϕ_{I^*} is negative. To see this, note that ϕ_{I^*} is:

$$\begin{aligned}(A1-3) \qquad \phi_{I^*} &= P'(I)P'(I^*)\left[u(Y_H)-u(Y_L+T)\right]-P'(I)(-P'(I^*))\left[u(Y_L)-u(Y_H-T)\right]\\ &= P'(I)P'(I^*)[u(Y_H)+u(Y_L)-u(Y_L+T)-u(Y_H-T)]\end{aligned}$$

Since $T < Y_H - Y_L$, we can write T as $\alpha(Y_H - Y_L)$ where $0<\alpha<1$. Hence,

$$\begin{aligned}(A1-3') \qquad \phi_{I^*} &= P'(I)P'(I^*)[u(Y_H)+u(Y_L)-u(Y_L+\alpha(Y_H-Y_L))-u(Y_H-\alpha(Y_H-Y_L))]\\ &= P'(I)P'(I^*)[u(Y_H)+u(Y_L)-u(Y_L(1-\alpha)+\alpha Y_H)-u(Y_H(1-\alpha)+\alpha Y_L)]\end{aligned}$$

Adding and subtracting $\alpha u(Y_H)$ and $\alpha u(Y_L)$ yields:

$$(A1-3'')\quad \phi_{I*} = P'(I)P'(I*)[\alpha u(Y_H) + (1-\alpha)u(Y_H) + \alpha u(Y_L) + (1-\alpha)u(Y_L)$$
$$-u(Y_L(1-\alpha) + \alpha Y_H) - u(Y_H(1-\alpha) + \alpha Y_L)]$$

The definition of concavity states $\alpha u(Y_H) + (1-\alpha)u(Y_L) < u(\alpha Y_H + (1-\alpha)Y_L)$ and $\alpha u(Y_L) + (1-\alpha)u(Y_H) < u(\alpha Y_L + (1-\alpha)Y_H)$. Hence, $\phi_{I*} < 0$ and the slope of the reaction function is therefore negative.

2. Existence and asymptotic stability

Given the smooth concavity of the objective function, the reaction functions are continuous. To make sure that the reaction functions intersect, we impose the condition that when a region's investment is zero, the marginal benefit of investment for that region is greater than the marginal cost. As is well know, a sufficient condition for the resulting Nash equilibrium to be asymptotically stable relates to the slopes of the reaction functions, and in particular that the absolute value of the slope is less than 1. This requires $\phi_{I*} < \phi_I$ which, using the above derivatives, requires

$$(A1-4)\quad P'(I)P'(I*)[u(Y_H) + u(Y_L) - u(Y_L + T) - u(Y_H - T)]$$
$$< P''(I)P(I*)\left[u(Y_H) - u(Y_L + T)\right] - P''(I)(1-P(I*))\left[u(Y_L) - u(Y_H - T)\right]$$
$$= P''(I)P(I*)[u(Y_H) + u(Y_L)(1 - \frac{1}{P(I*)}) - u(Y_L + T) - u(Y_H - T)(1 - \frac{1}{P(I*)})]$$

Since $Y_H - T > Y_L$ and $P(I*) < 1$, the bracketed term in the third line associated with ϕ_I is greater than the bracketed term in the first line associated with ϕ_{I*}. Hence, what is needed to ensure asymptotic stability is that the absolute value of P''(I)P(I*) is not too small relative to P'(I)P'(I*). There are various ways of interpreting this, but the essential requirement is that the reaction function I(T, I*) plotted in Figure 2 needs to intersect the reaction function I*(T, I) from below. That is, the derivative of P(I) cannot diminish too rapidly. An alternative way to express this is that disaster is a low frequency, high cost event with investment having a relatively small expected payoff so that P(I*) is large,

$P'(I)$ and $P'(I^*)$ are smallish, and $P''(I)$ is small but greater in absolute value than $P'(I)P'(I^*)/P(I^*)$.

Appendix A2: Signing the additional term for second-best transfers

As noted in the text, the first order condition for second-best transfers simplifies to:

$$(A2-1) \qquad \frac{\partial u(Y_H - T)}{\partial T} = \frac{\partial u(Y_L + T)}{\partial T} + \left[\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}\right]\left[\left(\frac{1}{1-P}\right)2u(Y_H) - \left(\frac{1}{P}\right)2u(Y_L)\right]$$

$$= \frac{\partial u(Y_L + T)}{\partial T} + \left[\frac{\partial P}{\partial I}\frac{\partial I}{\partial T}\frac{2u(Y_L)}{P}\right]\left[\left(\frac{P}{1-P}\right)\left(\frac{u(Y_H)}{u(Y_L)}\right) - 1\right]$$

Notice that this equation is identical to the first-best first order condition for transfers except for the additional term on the right hand side, which we will denote A.

To sign the additional term A, we will sign each of the two bracketed terms that comprise A. Since $\partial P/\partial I>0$, the sign of the first bracketed term depends on the sign of $\partial I/\partial T$, the change in the Nash equilibrium investment level given a change in transfers. We can state the following proposition:

Proposition A2-1: *Higher transfers decrease each region's Nash Equilibrium level of investment, that is* $\partial I/\partial T<0$.

Proof: The proof proceeds by first deriving the direction of the shift in the reaction function when T changes. We show the reaction function shifts down when T increases. Given symmetry, both reaction functions shift by the same amount in the same direction, and since the reaction functions are downward sloping, such a shift results in lower investment by both regions in the new Nash Equilibrium. To derive the sign of the shift in the reaction function, we can again use the implicit function theorem as above. The change in the reaction function when T changes is:

$$(A2-2) \qquad \frac{dI}{dT} = -\frac{\phi_T}{\phi_I}$$

We have already shown that ϕ_I is negative (see above). Hence, the sign of the shift of the reaction function is the same as the sign of ϕ_T. To derive ϕ_T, differentiate (8) in the text with respect to T:

$$(A2-3) \qquad \phi_T = -\frac{\partial P}{\partial I} P(I^*) \frac{\partial u(Y_L + T)}{\partial T} + \frac{\partial P}{\partial I}(1 - P^*(I^*)) \frac{\partial u(Y_H - T)}{\partial T}$$

To sign this derivative note first that

$$\frac{\partial u(Y_L + T)}{\partial T} > 0 \text{ and } \frac{\partial u(Y_H - T)}{\partial T} < 0$$

Since $\partial P/\partial I>0$, both terms of (A2-3) are negative. Hence ϕ_T is negative and the reaction function shifts down; symmetry implies the same is true of the reaction function (8*) in the text. Since both reaction functions are downward sloping and shift down, the Nash Equilibrium level of investment of each region decreases with increases of T. QED.

Given proposition 1, the first bracketed term of A is negative. The sign of the second bracketed term of A depends on the relationship between P/(1-P) and $u(Y_H)/u(Y_L)$. The second bracketed term of A will be positive iff $\frac{u(Y_H)}{u(Y_L)} > \frac{1-P}{P}$ and negative iff $\frac{u(Y_H)}{u(Y_L)} < \frac{1-P}{P}$. For interpretation it is useful to note that the second bracketed term is negative if expected utility in the low-income state is greater than expected utility in the high-income state.

We are now in a position to evaluate the sign of A.

PropositionA2- 2*: The sign of the term A is negative iff* $\frac{u(Y_H)}{u(Y_L)} > \frac{1-P}{P}$ *and positive iff* $\frac{u(Y_H)}{u(Y_L)} < \frac{1-P}{P}$.

Proof: Since the first term of A is negative, A will be negative iff the second bracketed term is positive and A will be positive iff the second bracketed term is negative. The proposition follows immediately since the second bracketed term is positive iff $\frac{u(Y_H)}{u(Y_L)} > \frac{1-P}{P}$, and the second bracketed term is negative iff $\frac{u(Y_H)}{u(Y_L)} < \frac{1-P}{P}$. QED.

Appendix A3: Deriving the properties of the regional reaction functions when the central government cannot commit

1. Signing certain derivatives of predicted transfers

From the text, we assume a region's ex-ante prediction of ex-post transfers are

$$(A3-1) \qquad \tau_{LH} = \frac{P(I^*)Y^*_H - (1-P(I))Y_L}{2}, \tau_{HL} = \frac{P(I)Y_H - (1-P(I^*))Y^*_L}{2}$$

Differentiating the predicted ex-post transfers yields:

$$(A3-2) \qquad \frac{\partial \tau_{HL}}{\partial I} = \frac{1}{2}\frac{\partial P}{\partial I}Y_H > \frac{\partial \tau_{LH}}{\partial I} = \frac{1}{2}\frac{\partial P}{\partial I}Y_L > 0; and$$

$$(A3-2^*) \qquad \frac{\partial \tau_{LH}}{\partial I^*} = \frac{1}{2}\frac{\partial P}{\partial I^*}Y^*_H > \frac{\partial \tau_{HL}}{\partial I^*} = \frac{1}{2}\frac{\partial P}{\partial I^*}Y^*_L > 0$$

Hence, higher investment increases the predicted transfer paid in the event of a high income outcome by more than it increases the predicted transfer received in the event of a low income outcome.

2. Existence and asymptotic stability

To derive the slope of the reaction function, write the reaction function defined by (16) in the text in implicit form, $\varphi(I, I^*, \tau) = 0$. Using the implicit function theorem, the slope of the reaction function for the unstarred region is:

$$(A3-3) \qquad \frac{dI}{dI^*} = -\frac{\varphi_{I^*}}{\varphi_I}$$

We can show that φ_I is negative. To see this note that φ_I is:

$$
\begin{aligned}
&(A3-4)\ \varphi_I = P''(I)P(I^*)\left[u(Y_H)-u(Y_L+\tau)\right]-P''(I)(1-P(I^*))\left[u(Y_L)-u(Y_H-\tau)\right] \\
&-P'(I)P(I^*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I}+P'(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I} \\
&+P'(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I}+P(I)(1-P(I^*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I}\frac{\partial\,\tau}{\partial I}+P(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial^2\tau}{\partial I^2} \\
&-P'(I)P(I^*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I}+P(I^*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I}\frac{\partial\,\tau}{\partial I}+P(I^*)(1-P(I))\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial^2\tau}{\partial I^2} \\
&= P''(I)P(I^*)\left[u(Y_H)-u(Y_L+\tau)\right]-P''(I)(1-P(I^*))\left[u(Y_L)-u(Y_H-\tau)\right] \\
&-2P'(I)P(I^*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I}+2P'(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I} \\
&+P(I)(1-P(I^*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I}\frac{\partial\,\tau}{\partial I}+P(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial^2\tau}{\partial I^2} \\
&+P(I^*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I}\frac{\partial\,\tau}{\partial I}+P(I^*)(1-P(I))\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial^2\tau}{\partial I^2}
\end{aligned}
$$

Given the assumed symmetry of the regions, we can show that the sum of the sixth and eighth terms is zero. To see this, note that adding terms six and eight yields

$$(A3-5)\quad P(1-P)\frac{\partial^2\tau}{\partial I^2}\left[\frac{\partial u(Y_H-\tau)}{\partial\tau}+\frac{\partial u(Y_L+\tau)}{\partial\tau}\right]$$

But from the central government’s first order conditions, the region knows that the central government will equate marginal utilities ex-post, so (A3-5) is zero. Hence, (A3-4) reduces to

$$
\begin{aligned}
&(A3-4')\ \varphi_I = P''(I)P(I^*)\left[u(Y_H)-u(Y_L+\tau)\right]-P''(I)(1-P(I^*))\left[u(Y_L)-u(Y_H-\tau)\right] \\
&-2P'(I)P(I^*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I}+2P'(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\,\tau}{\partial I} \\
&+P(I)(1-P(I^*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I}\frac{\partial\,\tau}{\partial I}+P(I^*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I}\frac{\partial\,\tau}{\partial I}
\end{aligned}
$$

The first two terms are identical to the corresponding derivative associated with the reaction function defined by equation (8) in the text. As with that derivative, given that $Y_H > Y_L + T$ and P’’(I)<0, the first two terms are negative. The second two terms are also negative since P'(I)>0, $\partial u(Y_H - \tau)/\partial\tau < 0$, $\partial u(Y_L + \tau)/\partial\tau > 0$, and $\partial\tau/\partial I>0$. The sign of the fifth and sixth terms depend on the sign of the cross partials $\partial u^2(Y_L + \tau)/\partial\tau\partial I$ and $\partial u^2(Y_H - \tau)/\partial\tau\partial I$. These are negative since $\partial u^2(Y_L + \tau)/\partial\tau\partial I = (\partial u^2(Y_L + \tau)/\partial\tau^2)*(\partial\tau/\partial I) < 0$ and $\partial u^2(Y_H - \tau)/\partial\tau\partial I = -(\partial u^2(Y_H - \tau)/\partial\tau^2)*(\partial\tau/\partial I) < 0$. Intuitively a higher investment level increases the expected transfer which increases utility at a decreasing rate. As the other parts of the fifth and seventh terms are positive, these two terms must be negative. As all the terms are negative, $\varphi_I < 0$.

The derivative φ_{I^*} is

$$(A3-6)\quad \varphi_{I^*} = P'(I)P'(I^*)\left[u(Y_H\ )-u(Y_L\ +T\ \ )\right]+P'(I)P'(I^*)\left[u(Y_L\ )-u(Y_H\ -T\ \ )\right]$$
$$-P'(I)P(I^*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\tau}{\partial I^*}+P'(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\tau}{\partial I^*}$$
$$+P(I)(-P'(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}+P(I)(1-P(I^*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I^*}\frac{\partial\tau}{\partial I}$$
$$+(1-P(I))P'(I^*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}+P(I^*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I^*}\frac{\partial\tau}{\partial I}$$

The first two terms are identical to the corresponding derivative associated with the reaction function defined by equation (8) in the text. We have already shown that concavity of the utility function implies that the sum of these two terms is negative. Given the assumed symmetry of the regions, we can show that the sum of terms three and five is zero and the same for the sum of terms four and seven. To see this, note that adding terms three and five yields

$$(A3-7)\quad -P'P\frac{\partial\tau}{\partial I}\left[\frac{\partial u(Y_L+\tau)}{\partial\tau}+\frac{\partial u(Y_H-\tau)}{\partial\tau}\right]$$

But from the central government's first order conditions, the region knows that the central government will equate marginal utilities ex-post, so (A3-7) is zero. The same is true when we sum terms four and seven. Hence, (A3-6) reduces to

$$(A3-6') \quad \varphi_{I*} = P'(I)P'(I*)\left[u(Y_H \;)-u(Y_L \;+T \;)\right]+P'(I)P'(I*)\left[u(Y_L \;)-u(Y_H \;-T \;)\right]$$
$$+P(I)(1-P(I*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I*}\frac{\partial\tau}{\partial I}+P(I*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I*}\frac{\partial\tau}{\partial I}$$

The third and fourth terms are negative since $\partial u(Y_H - \tau)/\partial\tau < 0$, $\partial u(Y_L + \tau)/\partial\tau > 0$, and $\partial\tau/\partial I^*>0$. Hence, $\varphi_{I*} < 0$. As both φ_{I*} and φ_I are negative, the slope is negative.

To make sure that the reaction functions intersect, we impose the condition that when a region's investment is zero, the marginal benefit of investment for that region is greater than the marginal cost. A sufficient condition for the resulting Nash Equilibrium to be asymptotically stable is that the absolute value of the slope is less than 1. This requires $\varphi_{I*} < \varphi_I$ which, using the above derivatives, requires

$$(A3-8) \quad P'(I)P'(I*)[u(Y_H)+u(Y_L)-u(Y_L+T)-u(Y_H-T)]$$
$$+P(I)(1-P(I*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I*}\frac{\partial\tau}{\partial I}+P(I*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I*}\frac{\partial\tau}{\partial I}$$
$$< P''(I)P(I*)\left[u(Y_H \;)-u(Y_L \;+T \;)\right]-P''(I)(1-P(I*))\left[u(Y_L \;)-u(Y_H \;-T \;)\right]$$
$$-2P'(I)P(I*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}+2P'(I)(1-P(I*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}$$
$$+P(I)(1-P(I*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I}\frac{\partial\tau}{\partial I}+P(I*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I}\frac{\partial\tau}{\partial I}$$
$$= P''(I)P(I*)[u(Y_H)+u(Y_L)(1-\frac{1}{P(I*)})-u(Y_L+T)-u(Y_H-T)(1-\frac{1}{P(I*)})]$$
$$-2P'(I)P(I*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}+2P'(I)(1-P(I*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}$$
$$+P(I)(1-P(I*))\frac{\partial^2 u(Y_H-\tau)}{\partial\tau\partial I}\frac{\partial\tau}{\partial I}+P(I*)(1-P(I))\frac{\partial^2 u(Y_L+\tau)}{\partial\tau\partial I}\frac{\partial\tau}{\partial I}$$

Given symmetry, the last two terms on the left hand side of the inequality are equal to the last two terms on the right hand side of the inequality. Hence (A3-8) simplifies to

$$(A3-8') \quad P'(I)P'(I^*)[u(Y_H)+u(Y_L)-u(Y_L+T)-u(Y_H-T)]$$
$$< P''(I)P(I^*)[u(Y_H)+u(Y_L)(1-\frac{1}{P(I^*)})-u(Y_L+T)-u(Y_H-T)(1-\frac{1}{P(I^*)})]$$
$$-2P'(I)P(I^*)\frac{\partial u(Y_L+\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}+2P'(I)(1-P(I^*))\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}$$

The right hand side of the inequality can be further simplified because the last two terms can be written as:

$$-2P'(I)P(I^*)\frac{\partial\tau}{\partial I}\left[\frac{\partial u(Y_L+\tau)}{\partial\tau}+\frac{\partial u(Y_H-\tau)}{\partial\tau}\right]+2P'(I)\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}$$

As above, from the central government's first order conditions the region knows that the central government will equate marginal utilities ex-post, so the bracketed term is zero and (A3-8') reduces to

$$(A3-8'') \quad P'(I)P'(I^*)[u(Y_H)+u(Y_L)-u(Y_L+T)-u(Y_H-T)]$$
$$< P''(I)P(I^*)[u(Y_H)+u(Y_L)(1-\frac{1}{P(I^*)})-u(Y_L+T)-u(Y_H-T)(1-\frac{1}{P(I^*)})]+2P'(I)\frac{\partial u(Y_H-\tau)}{\partial\tau}\frac{\partial\tau}{\partial I}$$

This is identical to the condition for asymptotic stability with respect to the reaction function defined by (8) in the text except for the addition of the last term (which is negative). As we are concerned with the absolute value, the addition of this term increases the absolute value of the right hand side of the inequality. Hence the sufficient condition for asymptotic stability is somewhat eased relative to the reaction function defined by (8) in the text.

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Figure 1
Optimal First-Best Transfer for (Y_H, Y^*_L) case

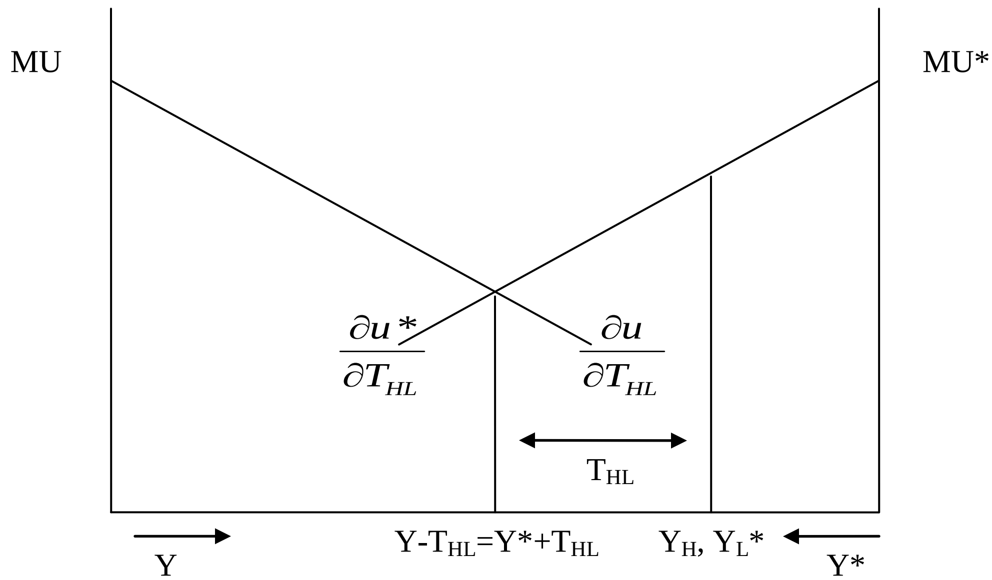


Figure 2
Nash Equilibrium Regional Investment

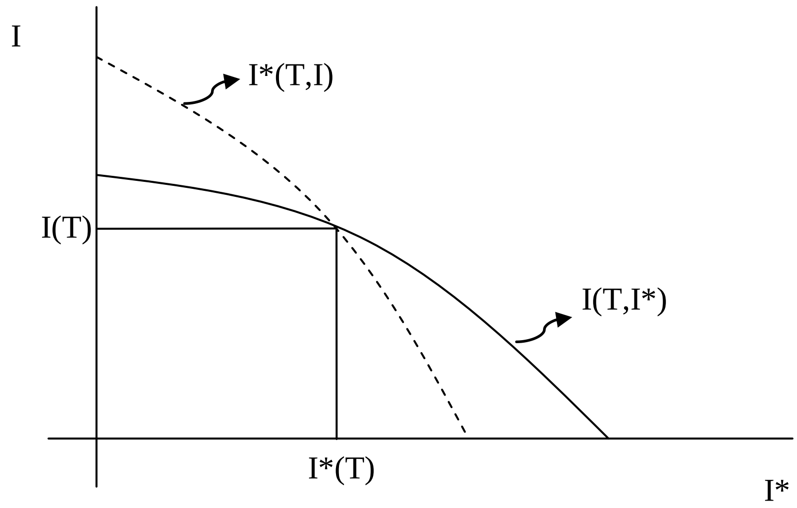


Figure 3
Second-Best Transfers can be Greater or Less than First-Best Transfers

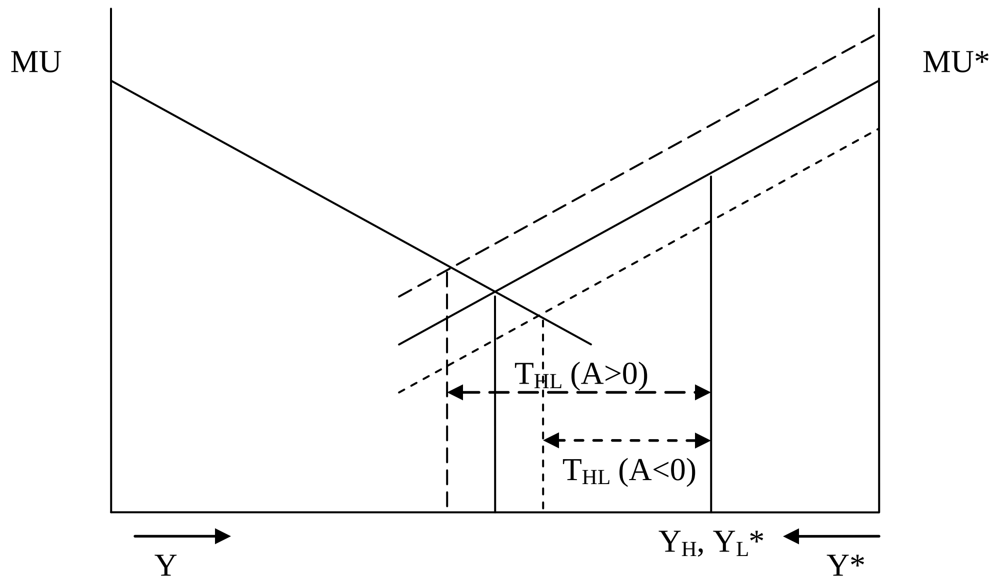
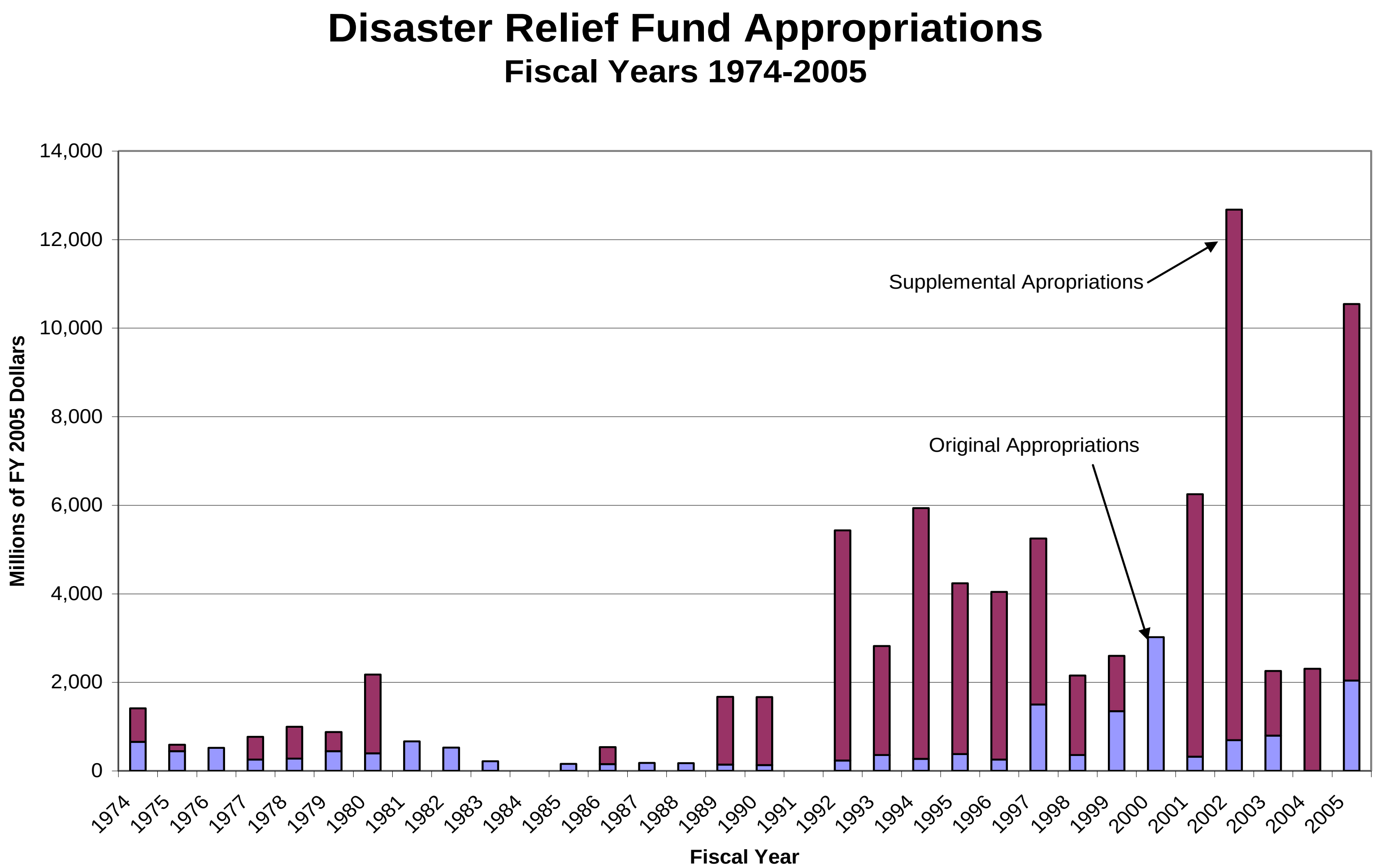


Chart 1



Source: Bea (2005). Note: Data exclude effects of Hurricane Katrina