Essays on Microeconomic Theory with Applications in Political and Resource Economics

By

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Abstract

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This dissertation is an exhibition of applied microeconomic theory in political and resource economics. As three examples, I investigate three different questions, respectively: Does polarization of beliefs always intensify political gridlock in collective decision making? Will input-efficiency improvement in water use, e.g., adoption of more-efficient irrigation technologies and investment in water-conveyance systems, definitely decrease the demand for water-storage capacities, e.g., dams and reservoirs? Is collectivism, rather than individualism, generally helping society overcome the collective action problem? Using the game-theory or stochastic-control approach, I theoretically challenge conventional wisdoms about these questions, and illustrate the empirical relevance of my challenges, qualitatively or quantitatively, in different contexts, e.g., the Chinese transition from the planned economy, World War II and Operation Market–Garden, the irrigation water-inventory management of the California State Water Project, and the histories of collective action in China and Europe.

To my parents

To my grandfather, Lien-Tsao Hsieh, whom I had never met – he began his career as a student in cotton cultivation in China, switched to history during the Second World War, started writing his Ph.D. dissertation at the University of South Carolina, Columbia in 1948, worked as a research assistant in the Bancroft Library of the University of California, Berkeley and journalist in San Francisco's Chinatown from 1949 to 1950, returned to China in 1950 without finishing the dissertation, participated in the negotiation of the Korean Armistice Agreement as a member of the Chinese delegation to Panmunjom in 1952, and passed away in Beijing in 1962

To Shuang

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Chapter 1

Introduction

This dissertation is an exhibition of applied microeconomic theory in political and resource economics. In each of the following three chapters, I use economic modelling to tell a story about political and economic behaviors and discuss the empirical relevance of the story.

Chapter 2 is the 2016 working paper, *Machiavellian experimentation,* coauthored with Yinxi Xie. This paper proposes the following mechanism whereby polarization of beliefs could eliminate political gridlock instead of intensifying disagreement: the expectation of political payoffs from being proven correct by a policy failure could drive decision makers who do not believe in the new policy to agree to policy experimentation, because they are confident that the experiment will fail, thus increasing their political power. We formalize this mechanism in a collective decision making model in the presence of heterogeneous beliefs in which any decision other than the default option requires unanimity. We show that this consideration of political payoffs can eliminate the inefficiency caused by a unanimous consent requirement when beliefs are polarized, but could also create under-experimentation when two actors hold beliefs that differ only slightly from one another. We illustrate the empirical relevance of the mechanism in two examples with historical narratives: we focus on the decision making process of the Chinese leadership during the country's transition starting in the late 1970s, and we further apply the model to the disagreement within the leadership of the Allied Forces on the Western Front of World War II in the autumn of 1944.

Chapter 3 is the 2016 working paper, *Water-storage Capacities versus Water-use Efficiency: Substitutes or Complements,* coauthored with David Zilberman. This paper investigates the economic relation between two common approaches to tackling water scarcity and adapting to climate change, namely water-storage expansions and water-use efficiency improvement. We propose two theoretical challenges to the conventional wisdom that higher input efficiency in water use decreases the demand for water-storage capacities. First, when the water demand is elastic, higher water-use efficiency can increase the water demand. Second, even if the water demand is inelastic, higher water-use efficiency could still make it optimal to store more water in controlling water inventories, increasing the future probability that the water-storage capacity constraint will be binding. If any of these two impacts are sufficiently significant, higher water-use efficiency will increase the demand for water-storage capacities. We formalize these two challenges in a model for capacity choices of dams with stochastic, dynamic control of water inventories. We identify the conditions about the water demand and marginal productivity of water under which water-storage capacities and water-use efficiency could be complements, and numerically illustrate this possibility in an empirical example of the California State Water Project.

Chapter 4 is the corrected version of the published paper, Roland and Xie (2016), coauthored with Gérard Roland. In this paper, we apply the concept of self perception in comparative psychology to the analysis of collective action. We build a model of collective action with different social-psychological payoffs to participation in collective action in a collectivist and an individualist culture. The model is used to analyze different types of collective action: collective action aiming at replacing an incumbent leader by another one, and collective action aiming at changing the political institutions. The results of the model shed light on the history of collective action in China compared to Europe. Introducing social payoffs to collective action delivers new insights on collective action games in general, and in particular how social payoffs may alleviate differentially collective action in different cultures.

Chapter 2

Machiavellian Experimentation

2.1 Introduction

In real-world policymaking, policy changes that implement a new idea often require collective decision making by actors who have different beliefs about the effectiveness of the idea. In this situation, we might expect polarization of beliefs to intensify disagreement and result in political gridlock, since the decision maker who holds an extremely pessimistic view about the new idea would oppose its implementation. This paper, however, proposes a mechanism by which polarization of beliefs could do the opposite – it could motivate decision makers to agree upon policy experimentation, but by a Machiavellian consideration: the opponents of the policy are confident that they will gain political power relative to their colleagues after the experiment, because they believe that the experiment will prove them correct and their colleagues wrong.

This mechanism is primarily motivated by investigating an important question in political and development economics and economic history. The question is why China adopted a gradual, piecemeal, and experimental approach in its transition from the planned economy, starting in the late 1970s, instead of pursuing more of a full-scale, "Big Bang" approach, as the all-at-once approach is called in the literature (e.g., the surveys by Roland, 2000, 2002). Conventional wisdom assumes that the Chinese leaders were not certain about the outcome of pursuing the market reform, so they decided not to risk a more overarching reform. A more nuanced reading of the situation emerges, however, when we recognize the two prominent characteristics of Chinese politics of the time. First, from the late 1970s through the 1980s, there were opposing beliefs about market reform among the Communist Party leadership, with the conservative faction extremely conservative. Second, any radical policy change required consensus among the Party leadership. These observations transform the question into why the extremely conservative faction did not veto the experimental reform.

The key to the question is to recognize the political impact of learning through an experimental approach when heterogeneous beliefs exist. Not only can an experiment provide information about a particular reform; it can also indicate which faction was correct, and which incorrect. The correct side can expect to be rewarded in the form of stronger political power, while the incorrect side should be punished. If the two factions hold diametrically opposite beliefs, then *both* of them would be very confident in being proven correct by the experiment's result, and thus in being rewarded. Therefore, if the expected reward is sufficiently large, *both* of them would agree to the experimental approach.

We formalize this mechanism of Machiavellian experimentation by use of a model in which two players within the same organization decide together whether and how to adopt a new policy. There are three options – a Big Bang approach with full-scale adoption; a pilot approach in which adoption will begin on a small scale and then be either generalized or stopped based on the experiment's result; and a default option in which no change occurs. The model has three key assumptions, which are tailored to the context of the Chinese transition but can be generalized beyond it.

Different priors. The two players have different priors about whether the policy will be effective in achieving the desired results, this disagreement is common knowledge, and the players do not infer anything from this disagreement. We label the player who holds the more optimistic belief about the policy *the reformer*, and the other player *the conservative*. Different priors commonly exist in politics, business, and other public or private policymaking (e.g., Sabatier, 1988; Bendor and Hammond, 1992; Mutz, 2008; Minozzi, 2013; Millner et al., 2014; Hirsch, Forthcoming). This is the case because people can be endowed with different priors, just as they can be endowed with different preferences, and people can interpret public information in different ways under different psychological, cultural, or historical backgrounds. Different priors are especially prominent in intra-organizational debates if the organizations, e.g., technology-based companies, compete in a fast-changing environment

(Eisenhardt et al., 1997). As seen in a significant and growing literature in economics, management, and political science (e.g., Van den Steen, 2002, 2010a,b,c; Che and Kartik, 2009; Millner et al., 2014; Hirsch, Forthcoming), this assumption is useful in studying the implications of open belief disagreement.[1]

Consensus requirement. Any adoption of the policy requires consensus; otherwise, nothing will happen. In other words, both players can veto any adoption. It is common to see a consensus requirement in real world decision-making. For example, in the United States, the jury in a federal court must reach a unanimous verdict. In the Council of the European Union, decision-making about certain policy questions require unanimity in voting. In the German two-tier board system of corporate governance, only decisions that garner consensus within the *Vorstand* (management board) will be referred to the *Aufsichtsrat* (supervisory board) for approval (Charkham, 1994). Consensus is usually required to protect decision makers from repercussions of unpopular decisions or to demonstrate unity to those outside the decision making process (e.g., Visser and Swank, 2007). Even if a consensus requirement is not explicitly written into decision-making rules, it can also apply *de facto* when decision makers are equally powerful, as we see in the example of the Chinese transition.

Contingent, mutually exclusive payoffs. After the experiment demonstrates whether the policy achieved the desired result, the player whose side was proven correct receives some reward, while the other player is punished. We call the reward and punishment *contingent, mutually exclusive payoffs*, since the payoffs are contingent on the players' priors and the experiment's result, and they always reward one player and harm the other. Contingent, mutually exclusive payoffs are common, since people often derive profit, power, or joy simply from being proven correct, and suffer economically, politically, and psychologically from being proven incorrect. The generality and the importance of the contingent, mutually exclusive payoffs can also be shown by contradiction: if people did not care about these types of payoffs, then they would be indifferent between being proven correct and incorrect. In reality, however, people usually hope to be proven correct (and shun the notion of being

[1]Theoretical works with heterogeneous priors can be traced back to Arrow (1964). Another tradition following Harsanyi (1967, 1968a,b) and Aumann (1976) rules out "agreeing to disagree." For extensive discussions about preserving or breaking the common prior assumption, see Morris (1995), Gul (1998), Che and Kartik (2009), and Hirsch (Forthcoming).

proven incorrect) when experimentation brings new information. For example, managers know that good results of their experimental decisions would strengthen their position in the labor market, and politicians acknowledge that failed policy experiments could reveal their incompetence and drive votes away.

To show the role of the contingent, mutually exclusive payoffs in the realm of experimentation, we start with a benchmark model including only the first two key assumptions – different priors and the consensus requirement. At this point, we assume that the payoffs are not mutually exclusive, which we call *mutually inclusive payoff*. We show two simple but basic results. First, if the conservative sufficiently disbelieves in the policy prescription, then neither the Big Bang approach nor the experimental approach will be adopted, no matter how strongly the reformer believes in the proposed policy. This result comes from the conservative's veto power and corresponds to the view that polarization of beliefs could cause political stalemate. Second, it is possible for the experimental approach to be adopted *only* if the conservative has a moderate prior toward the reform. This result comes from not only the conservative's veto power but also our assumption that the players both consider the trade-off between the Big Bang approach and the experimental approach in classic terms, weighing option values and delayed costs, so it corresponds to the conventional wisdom that associates experimentation with moderate beliefs. This benchmark model can be regarded as an extension of Dewatripont and Roland (1995) from a single decision maker to two decision makers.

We then introduce the third key assumption – contingent, mutually exclusive payoffs – to the benchmark model and compare the new model to the benchmark. We show that, when players care strongly about the contingent, mutually exclusive payoffs, 1) if the players hold diametrically opposite beliefs, then the experimental approach will be adopted; 2) if at least one of the players holds a moderate belief, then no new policy will be adopted. The intuition is simple: only diametrically opposite beliefs can guarantee *both* that the conservative is confident of getting the contingent reward from the experiment and that the reformer is also confident of avoiding the contingent punishment. The two results associate experimentation with extreme beliefs, in contrast to the former association with moderate beliefs.

By comparative statics analysis, we show how the solution to the model is affected by the magnitude of the contingent, mutually exclusive payoffs and the extent to which the players care about these payoffs. We then analyze the welfare implications, asking under what conditions the organization benefits from consideration of the contingent, mutually exclusive payoffs – in other words, when do political considerations lead to good outcomes? We show that the consideration of politics is desirable when the players' priors are diametrically opposite but is undesirable when the priors are only slightly different. We further show the robustness of our main result when we extend the analysis of mutually exclusive payoffs to the Big Bang approach.

After the theoretical analysis, we will apply this model to interpret the strategy choice of the Chinese transition in more detail. We will fit the three key elements of our model with history, reject the benchmark model, show support for the empirical relevance of our mechanism of Machiavellian experimentation, and compare our explanation with alternative considerations. Our interpretation of the Chinese transition is closer to the perspective of Shirk (1993, 1994), which discusses the politics among politicians, than to the view of Acemoğlu and Robinson (2012), which evaluates the politics between politicians and the people.

Although the proposed mechanism is motivated by the Chinese transition, and we try to follow the principle of Occam's Razor in formalizing the mechanism, our model is not limited to China, and can apply to other situations, e.g., public policy debates, international affairs, and even financial transactions. In the latter part of this paper, we will further illustrate our model with another important historical example: the disagreement within the leadership of the Allied Forces on the Western Front of World War II in the autumn of 1944, namely between Dwight Eisenhower and Bernard Montgomery, and their decision to implement Operation Market–Garden, one of the most heroic but disastrous failures (from the viewpoint of the Allies) in the history of modern warfare. In this illustration, we critically analyze the memoirs of witnesses (e.g., Montgomery, 1947, 1958; Eisenhower, 1948, 1970) and works by historians (e.g., Eisenhower, 1986; Ambrose, 1990, 2012; Murray, 1996; D'Este, 2002; Brighton, 2008), and, again, establish the link between history and the assumptions, predictions, and mechanism of our model. Finally, we discuss the limitations of other potential interpretations.

We proceed in the paper as follows: The rest of this section clarifies the position of our paper in literature. Section 2.2 builds the benchmark model and Section 2.3 solves it. Section 2.4 introduces contingent, mutually exclusive payoffs to the benchmark model and shows our main result. Section 2.5 analyzes comparative statics. Section 2.6 discusses welfare implications. Section 2.7 shows the robustness of our model by extending contingent, mutually exclusive payoffs to the Big Bang approach. Section 2.8 illustrates the model with the two historical examples. Section 3.7 concludes the paper by discussing broader applications of our key logic.

Position in literature. There exist at least two papers investigating a question similar to ours: why, on many important issues, do policymakers choose policy options that are apparently contrary to their interests or beliefs?[2] One paper by Callander and Hummel (2014) models the idea that a conservative with temporary control of power would initiate an experimental, "preemptive" reform, wishing the unintended outcomes to shape the information available to the succeeding reformer in a way that favors the conservative agenda. Their story and our story are apparently similar but fundamentally different. In their story, given that the predecessor will lose power, she experiments in order to influence the information that the successor will face. In our story, however, the conservative experiments because she expects to gain power, not because she would like to change the reformer's belief.

The other paper by Hirsch (Forthcoming) formalizes the idea that a principal could allow an agent "to implement [the agent's] desired policy even when [the principal] is sure it is wrong, to persuade [the agent] through failure that [the agent] is mistaken." The underlying assumption is that implementation of any policy, even the principal's desired policy, requires the agent's effort, so the principal had better convince the agent to adopt the principal's belief.[3] Behind this idea is the literature on heterogeneous beliefs in organizations (e.g., Van den Steen, 2002, 2010a,b; Che and Kartik, 2009), which demonstrates that heterogeneity encourages players to try to convince others. Again, our idea is essentially different. In our story, each player's incentive for experimentation does not come from persuading the other player to make the right decision (which would be the case if the payoff were mutually inclusive) but comes purely from confidence in being proven correct and thereby receiving a mutually exclusive payoff. Moreover, the significance of contingent, mutually exclusive payoffs implies that people shun the notion of being proven incorrect, while the story about

[2] Callander and Hummel (2014) write: "It is striking ...that the choices of real policymakers often stand immune from rational explanation. Even on some of the most important issues of the day, policies are implemented that ostensibly work contrary to the interests of the policymakers who choose them."

[3] Roland (2000, p. 36–37) also hints to apply this idea to the Chinese transition.

convincing others suggests that significant punishment of the convinced is unnecessary and that people will comfortably admit that they have been convinced. We will use this contrast in the examples to demonstrate our empirical validity relative to alternative explanations.

Apart from these two papers, Cukierman and Tommasi (1998) investigate another similar and intriguing question: how could certain policies "are implemented by 'unlikely' political parties rather than by parties the ideologies of which favor such policies?" For example, as their paper's title reads, "when does it take a Nixon [but not some other politician with a weaker and less persistent anti-Communist record] to go to China?"[4] Their idea is that Nixon has an advantage in transmitting "to the public [his] private information about the relative desirability of" developing United States–China relations and eliciting the public's support for this policy, because "the public has less reason to suspect that [this policy] is proposed solely because of the natural ideological tendencies of [Nixon], i.e., it may be perceived as an objectively motivated policy." With a flavor similar to Cukierman and Tommasi (1998)'s question, in our paper, we show that, when the decision makers care strongly about the contingent, mutually exclusive payoffs, a conservative with an extremely pessimistic view about the new policy, rather than a decision maker with a moderate view, could be more supportive of policy experimentation. This support, however, is motivated by the hope and confidence that the experiment will fail, not by the desire to transmit some private information that the policy will be beneficial to the public.

Our paper also contributes to the literature in several other respects. First, we directly contribute to the literature on strategy choices in large-scale economic reforms, such as transition from a non-market economy (e.g., Lipton and Sachs, 1990; Fernandez and Rodrik, 1991; Murphy et al., 1992; Dewatripont and Roland, 1992a,b, 1995; Coricelli and Milesi-Ferretti, 1993; Gates et al., 1993; Zhao, 1996; Bertocchi and Spagat, 1997; Martinelli and Tommasi, 1997; Wei, 1997; Qian et al., 1999, 2006; Roland, 2002; Rausser et al., 2011, Ch. 18; the survey by Iwasaki and Suzuki, Forthcoming). Roland (2000) recognizes the interaction between politics and aggregate uncertainty about transition as the key to understanding transition and reform strategies, but few studies thoroughly model the interaction.[5]

[4]This question differs from ours in a subtle way. The question that is more similar to ours would be "when does it take Nixon to go to China [but not some other countries with which he has a more friendly record]?"

[5]For example, in Dewatripont and Roland (1995)'s discussion on strategy choices and sequencing of reforms with homogeneous agents, policymakers simply adopt the politically favorable option after the

The literature also assumes homogeneous beliefs. We recognize and emphasize the political impact of resolving aggregate uncertainty in the presence of heterogeneous beliefs, which is important in understanding the choice of strategy in the Chinese transition.

Second, the literature on strategic experimentation and policy innovation investigates whether specific decision making environments lead to over- or under-experimentation (e.g., Rose-Ackerman, 1980; Bolton and Harris, 1999; Strumpf, 2002; Keller et al., 2005; Keller and Rady, 2010; Volden et al., 2008; Strulovici, 2010; Klein, 2013; Millner et al., 2014; Callander and Harstad, 2015; Heidhues et al., 2015). Klein and Rady (2011) introduce "negatively correlated bandits," which are mutually exclusive but are not contingent on beliefs, and they focus on common priors and decentralized experimentation. Majumdar and Mukand (2004), Cai and Treisman (2009), Willems (2013), and Dewan and Hortala-Vallve (2014), assuming a single policymaker or homogeneous beliefs, recognize that policy failures could drive voters away.[6] Focusing on a consensus requirement in the presence of heterogeneous beliefs, we address the direct interaction between learning and politics, represented by contingent, mutually exclusive payoffs; show that experimentation can result from extreme disbelief in the wisdom of the experiment; and demonstrate that the heterogeneity of priors determines whether the prospect of a contingent, mutually exclusive payoff will reduce or promote under-experimentation in a consensus environment.

Third, Condorcet (1785)'s jury theorem states that having a larger number of informed decision makers produces better decisions. Numerous studies on decision making in committees investigate the boundary of the theorem (e.g., Austen-Smith and Banks, 1996; Feddersen and Pesendorfer, 1997, 1998; McLennan, 1998; Gerardi, 2000; Bhattacharya, 2013; Ahn and Oliveros, 2014; Bouton et al., 2014; Midjord et al., 2015; the surveys by Gerling et al., 2005; Li and Suen, 2009). Our extension in Appendix A.6 contributes a counterexample of the theorem to the literature: one more moderate reformer could reject experimentation, even of a policy that is indeed effective. In particular, Levy (2007a,b) discusses reputation concerns of committee members when the result of the committee's decision could show whose vote was

economic properties of the options are determined by aggregate uncertainty. In the same paper, in the investigation on sequencing of reforms with heterogeneous agents, it is not aggregate but individual uncertainty that determines the optimal sequencing. As a notable exception, Bertocchi and Spagat (1997) recognize that political instability discourages policymakers from resolving aggregate uncertainty through experimentation.

[6] Majumdar and Mukand (2004), Willems (2013), and Dewan and Hortala-Vallve (2014) focus on the feature of policy decisions to signal politicians' competence.

correct and whose was wrong, which brings a similar logic to our contingent, mutually exclusive payoffs. Those concerns, however, depend purely on the members' own voting *decisions* (and therefore their *own* priors), while our mutually exclusive payoffs are fundamentally contingent on *all* of the players' *priors*. Also, Levy (2007a,b) focuses on transparency in decision making and rules of voting, which are different foci from ours.[7]

Fourth, the logic that people acquire information when they are confident of receiving the information that will support their position is, of course, not rare in the literature on strategic information acquisition and persuasion (e.g., Brocas and Carrillo, 2007; Brocas et al., 2012; Gul and Pesendorfer, 2012; Boleslavsky and Cotton, 2013; Alonso and Câmara, 2014; Colombo et al., 2014; Egorov and Sonin, 2014; Felgenhauer and Schulte, 2014). With respect to this literature, our contingent, mutually exclusive payoffs introduce the idea that players' fundamental preferences depend on beliefs. The combination of heterogeneous beliefs and the consensus requirement is also unique.

In the most general sense, our model is linked in several subtle ways to the literature on agent diversity and organizational and economic performance. First, the literature suggests that a team with low work force diversity works well in routine implementation (e.g., Filley et al., 1976; Prat, 2002), while our model suggests that, when aggregate uncertainty exists, low diversity of priors could prevent implementation. Second, Alesina and La Ferrara (2005) identify three channels through which diversity affects economic performance: individual preferences, individual strategies, and production functions. In our model, contingent, mutually exclusive payoffs cause the diversity of priors to enter individual preferences, affect individual strategies, and become an important variable in the function for production of knowledge gained through experimentation. Last but not least, Harrison and Klein (2007) identify the typology of group diversity in the strategic management literature: separation, variety, and disparity. In our paper, variety is the diversity of priors, separation deals with players' preferences about the three options, and disparity is about the consensus requirement, which gives the conservative an advantage over the reformer.

[7] Midjord et al. (2015) consider a negative disesteem payoff in the spirit of Levy (2007a,b).

2.2 The Benchmark Model with Only Mutually Inclusive Payoff

There are two players coming to a discussion about whether and how the organization should adopt a policy. The policy can be good or bad, and the players do not know the objective probability with which the policy is good. The players have their own priors about whether the policy is good: One player believes the policy has a probability p of being good, while the other believes the probability is q. We assume $0 \leq q < p \leq 1$, and therefore we label the player with the larger prior the *reformer*, and the other the *conservative*.

There are three options for the decision: adopting the policy in a Big Bang approach, adopting it in an experimental approach, or doing nothing. The first two approaches require the agreement of both players, while each player is free to choose the do-nothing option (i.e., "do nothing" is the outcome if the players cannot agree). The solution concept that we use is the *core* of a cooperative game. The Big Bang approach will be in the core if the following two conditions are satisfied. First, both players prefer the Big Bang over doing nothing. This condition is intuitive, because, if this condition does not hold, the player who prefers doing nothing over the Big Bang will veto the Big Bang. Second, compared with the Big Bang approach, the experimental approach will not be able to generate a Pareto improvement for the players. This condition is also intuitive, because, if this condition does not hold, the two players will move away from the Big Bang approach (to the experimental approach). Similarly, the experimental approach will be in the core under the two corresponding conditions that both players prefer the experimental approach over doing nothing and that the Big Bang will not generate a Pareto improvement for both players. It is also possible that the Big Bang and the experimental approaches are both in the core. This scenario will happen if both players prefer these two approaches over doing nothing, and if one of them prefers the Big Bang approach while the other prefers experimentation.[8] When neither the Big Bang approach nor the experimental approach is in the core, the core will contain only the do-nothing option, and no reform will happen.

[8]The results derived in this setting can also be achieved by non-cooperative games with complete information, and the core including both the Big Bang and the experimental approaches will be refined into a single solution favored by the first mover. For an example of these non-cooperative games, see Appendix A.1. For robustness we use the cooperative-game setting in the main text.

We set the payoff structure as follows:

If they agree to the Big Bang approach: If the adoption succeeds, then each player gets $a_i > 0$, where for the reformer $i = r$ and for the conservative $i = c$; otherwise, each player gets $-b_i < 0$.

If they agree to the experimental approach: The policy is first implemented on a small scale ρ, where $0 < \rho < 1$. If the experiment's result shows that the policy is good, then the two players will automatically generalize the policy to the rest of the organization, and will get the payoff with a time discount. Therefore, each player will get $\rho a_i + \delta a_i$, where $0 < \delta < 1 - \rho$.[9] If the experiment's result shows the policy is bad, then they stop the adoption, and each player gets $-\rho b_i$.

If one of the players chooses doing nothing: The policy is not adopted, and both players get 0 as the default payoff.

We call this payoff structure *mutually inclusive payoff*, because, after the policy turns out to be good or bad, the two players win and get a positive payoff, or lose and get a negative payoff, always together. We shall contrast this payoff structure with contingent, mutually exclusive payoffs later. We assume the players maximize their own expected payoff, and Table 2.1 shows their expected payoffs from the three options.[10]

Table 2.1: Expected mutually inclusive payoff from the three options

Player	Big Bang approach	Experimental approach	Doing nothing
Reformer	$pa_r - (1-p)b_r$	$p(\rho a_r + \delta a_r) - (1-p)\rho b_r$	0
Conservative	$qa_c - (1-q)b_c$	$q(\rho a_c + \delta a_c) - (1-q)\rho b_c$	0

[9]We simplify the idea that $\delta = \frac{1}{1+r}(1-\rho)$, where r is the discount rate.

[10]For simplicity, we set the payoffs as a linear function in $s \in \{0, \rho, 1\}$, the scale of the adoption. More generally, we can also set the payoff structure in a nonlinear way, as follows. When the adoption follows the Big Bang approach ($s = 1$), the expected mutually inclusive payoff for the reformer is $pa_r(1) - (1-p)b_r(1)$; when the adoption follows the experimental approach ($s = \rho$), the expected payoff for the reformer is $p[a_r(\rho) + \frac{1}{1+r}a_r(1-\rho)] - (1-p)b_r(\rho)$; when there is no adoption at all ($s = 0$), the payoff for the reformer is 0. For the conservative, similar payoffs follow. Also assume that $a_r(s)$, $a_c(s)$, $b_r(s)$, and $b_c(s)$ are all increasing and are equal to 0 when $s = 0$. This generalization does not affect our results.

So far, we have introduced only different priors and the consensus requirement, the first two key assumptions of our model. We have not introduced the last key assumption, the contingent, mutually exclusive payoffs. To appreciate the role of the contingent, mutually exclusive payoffs, we shall first solve the model with only mutually inclusive payoff in the next section as a benchmark.

2.3 Analysis of the Benchmark Model

Based on the payoff structure, the trade-off between a Big Bang approach and an experimental approach is that the experimental approach enjoys the option of stopping the adoption of a possibly bad policy, but delays the adoption of a possibly good policy. For the reformer, the option value of the experimental approach (compared with the Big Bang approach) is $(1-p)(1-\rho)b_r$, which is decreasing in p, while its delay cost is $p(1-\rho-\delta)a_r$, which is increasing in p. For the conservative, a similar argument holds. Therefore, for each of the players, a higher prior makes the Big Bang approach more appealing than the experimental approach.

The prior also determines the trade-off between doing nothing, on the one hand, and agreeing to pursue either of the reform approaches, on the other. A higher prior increases the expected payoffs of both approaches, so that doing something will be more likely to beat doing nothing.

For the reformer, we define the three break-even priors A_r, B_r, and C_r by

$$A_r = \frac{(1-\rho)b_r}{(1-\rho)a_r - \delta a_r + (1-\rho)b_r}, \quad B_r = \frac{b_r}{a_r + b_r}, \quad C_r = \frac{\rho b_r}{\rho a_r + \delta a_r + \rho b_r}. \tag{2.1}$$

At these points, the reformer is indifferent among the three trade-offs: the Big Bang approach versus the experimental approach (A_r), the Big Bang approach versus doing nothing (B_r), and the experimental approach versus doing nothing (C_r).[11] It is also obvious that $A_r > B_r > C_r$. Similarly, we define the three indifference values of the conservative's prior as A_c, B_c, and C_c.

[11]If $p > A_r$, the reformer will prefer the Big Bang approach over the experimental approach. If $p > B_r$, the reformer will prefer the Big Bang approach over doing nothing. If $p > C_r$, the reformer will prefer the experimental approach over doing nothing.

With the definition of the indifference priors, we proceed with Proposition 1, the main result of this section.[12]

Proposition 1. *Assume that the only payoff from adopting the policy is mutually inclusive. Then the following two statements are true:*

i) If the conservative strongly believes that the policy is a bad idea, then neither the Big Bang approach nor the experimental approach will be adopted, no matter how strongly the reformer believes in the policy.

ii) The experimental approach will not be adopted unless the conservative neither strongly believes in the policy nor strongly believes that the policy is a bad idea.

Mathematically, if there is only mutually inclusive payoff from adopting the policy, then the following two statements are true:

i) If $0 \leq q < C_c$, then for any p such that $q < p \leq 1$, the policy will not be adopted.

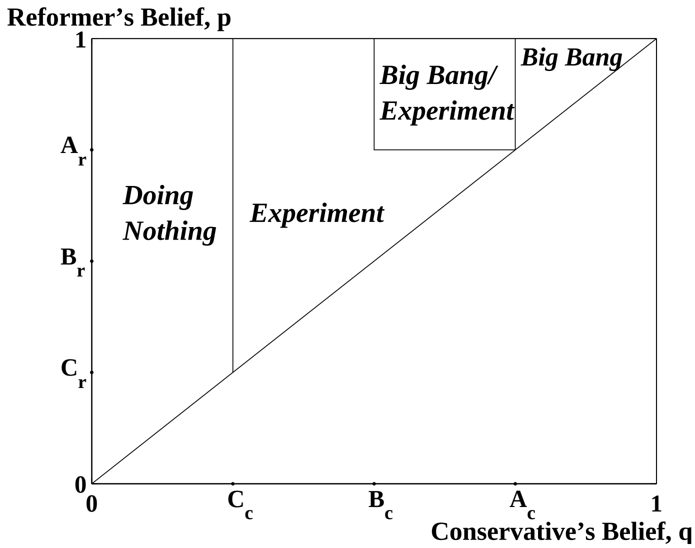
ii) The experimental approach will not be adopted unless $C_c < q < A_c$.

Appendix A.2 proves Proposition 1. The intuition of Proposition 1 is straightforward. The key is the consensus requirement for the adoption of either approach. For Result i), if the conservative sufficiently disagrees with the policy ($0 \leq q < C_c$), then she prefers doing nothing over both the Big Bang approach and the experimental approach. If so, no matter how strongly the reformer believes in the policy and no matter which option the reformer prefers, the conservative will always veto the policy adoption by withholding consensus (i.e., choosing to do nothing). For Result ii), on the one hand, the experimental approach could be adopted if the conservative does not veto it, i.e., does not exercise her choice to do nothing. In this case, the conservative does not strongly dislike the policy ($C_c < q \leq 1$). On the other hand, the experimental approach will not be adopted if both players expect higher payoffs in an agreement for a Big Bang approach, in which case even the conservative strongly believes in the policy ($A_c < q \leq 1$).

Figure 2.1 illustrates Proposition 1. Each point (p, q) represents the case in which the reformer and the conservative respectively have priors p and q. Because we assume that $0 \leq q < p \leq 1$, we consider only the upper-left triangle in the unit square. As Proposition 1 states, Figure 2.1 indicates that the two players will not agree to the adoption of any

[12]For simplicity, we consider only the cases in which p and q are not equal to any of the indifference values.

policy if the conservative is sufficiently conservative ($0 \leq q < C_c$), and that the experimental approach is possible only if the conservative has a moderate prior ($C_c < q < A_c$).[13]



$$a_r = a_c = b_r = b_c = 2,\ \rho = 0.25,\ \delta = 0.5$$
$$A_r = A_c = 0.75,\ B_r = B_c = 0.5,\ C_r = C_c = 0.25$$

Figure 2.1: An example of the model with only mutually inclusive payoff

Figure 2.1 also shows that "Doing Nothing" occupies the left-top corner of the unit square, while "Experiment" occupies the area where p is slightly higher than B_r and q is slightly lower than B_c. Here, the take-home message of this section emerges: when payoffs are mutually inclusive, diametrically opposite beliefs are associated with doing nothing, while moderate or slightly different priors are associated with the experimental approach.

2.4 Contingent, Mutually Exclusive Payoffs

Keeping the mutually inclusive payoff, we now allow the decision makers to consider a second payoff structure, where the experiment's result shows not only whether the policy is good, but also which player was on the correct side. Now, the correct side will be rewarded while the other will be punished.

[13] Another observation from Figure 2.1 is that the Big Bang approach will not be adopted unless the reformer strongly believes in the policy ($A_r < p \leq 1$) and the conservative will not veto it with doing nothing ($B_c < q \leq 1$).

If the players agree to the experimental approach: If the experiment's result shows the policy is good/bad, then the player with the higher/lower prior gets e, while the other player gets $-d$, where $d > 0$ and $e > 0$.

We call this payoff structure *contingent, mutually exclusive payoffs*, sometimes abbreviated as mutually exclusive payoffs. By "mutually exclusive," we mean that, if one player wins, the other must lose. By "contingent," we mean that the allocation of the reward and punishment depends on the relative position of the priors *and* on the result of the experiment.

We assume the players value these mutually exclusive payoffs over the mutually inclusive payoff, with a weight $\beta \in [0, \infty]$.

More realistically, the magnitude of the reward and punishment should also depend on the degree of difference between the players' priors about whether the new policy is good: when the priors are almost the same, it is difficult to distinguish who was correct and who was incorrect after the result of the experiment is observed, and therefore the magnitude of the reward and punishment are likely to be small; when the priors are significantly different, however, it is much easier to see who was correct and who was incorrect, and the corresponding reward or punishment is likely to be more substantial. We model this dependency by assuming that mutually exclusive payoffs will exist (and the players will take them into consideration) if and only if the players have some "fundamental disagreement," by which we mean that, when considering only the mutually inclusive payoff, the players disagree about whether the Big Bang is more appealing than the do-nothing option ($B_r < p \leq 1$ and $0 \leq q < B_c$). In this case, we say that the mutually exclusive payoffs are "effective," i.e., substantial enough to affect the players' considerations. In other words, the mutually exclusive payoffs are $f(p, q)e$ and $f(p, q)d$, where $f(p, q)$ is an indicator function that will be equal to one if and only if $B_r < p \leq 1$ and $0 \leq q < B_c$. This assumption, which makes the magnitude of the mutually exclusive payoffs depend on the degree of difference between the priors in a very simplistic way, does not drive our main result and will generate richer results and sharper graphs.

The expected mutually inclusive and weighted mutually exclusive payoffs for the two players from all three options are shown in Table 4.1.

Now we analyze the model with effective mutually exclusive payoffs, i.e., when the conservative would prefer doing nothing over the Big Bang approach while the reformer

Table 2.2: Expected mutually inclusive and weighted mutually exclusive payoffs from the three options

Player	Big Bang approach	Experimental approach	Doing nothing
Reformer	$pa_r - (1-p)b_r$	$p[\rho a_r + \delta a_r + \beta f(p,q)e] - (1-p)\,[\rho b_r + \beta f(p,q)d]$	0
Conservative	$qa_c - (1-q)b_c$	$q[\rho a_c + \delta a_c - \beta f(p,q)d] - (1-q)\,[\rho b_c - \beta f(p,q)e]$	0

$f(p,q) = 1$ if $p \in \left(\frac{b_r}{a_r+b_r}, 1\right]$ and $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$; otherwise $f(p,q) = 0$.

would prefer the Big Bang approach to doing nothing if the players considered only the mutually inclusive payoff. First, observe that mutually exclusive payoffs are possible only with the experimental approach, and therefore they only affect the experimental versus Big Bang trade-off and the experimental versus doing nothing trade-off, but not the Big Bang versus doing nothing trade-off, so the conservative still always prefers doing nothing over the Big Bang approach, just as in the model with only mutually inclusive payoffs. Therefore, the Big Bang approach will still not be adopted. As a result, we care only about the effect of the mutually exclusive payoffs on the trade-off between the experimental approach and doing nothing. For the conservative and the reformer, we respectively define the break-even priors D and E, with which they would be indifferent between an experimental approach and doing nothing when the mutually exclusive payoffs are effective, as follows:

$$D = \frac{\rho b_c - \beta e}{\rho a_c + \delta a_c + \rho b_c - \beta(e+d)}, \quad E = \frac{\rho b_r + \beta d}{\rho a_r + \delta a_r + \rho b_r + \beta(e+d)}. \tag{2.2}$$

With the two newly-introduced indifference priors, we proceed with Proposition 2, the main result of this section and this paper.[14]

Proposition 2. *Assume the two players have different preferences between the Big Bang approach and doing nothing when considering only the mutually inclusive payoff. Then contingent, mutually exclusive payoffs are effective. Further assume the players care strongly about these contingent, mutually exclusive payoffs. Then the following two statements are true:*

i) If the conservative holds a sufficiently strong disbelief in the policy, while the reformer sufficiently believes in the policy, then the experimental approach will be adopted.

ii) Otherwise, the policy will not be adopted.

[14]For simplicity, we only consider the cases in which p and q are not equal to any of the indifference priors.

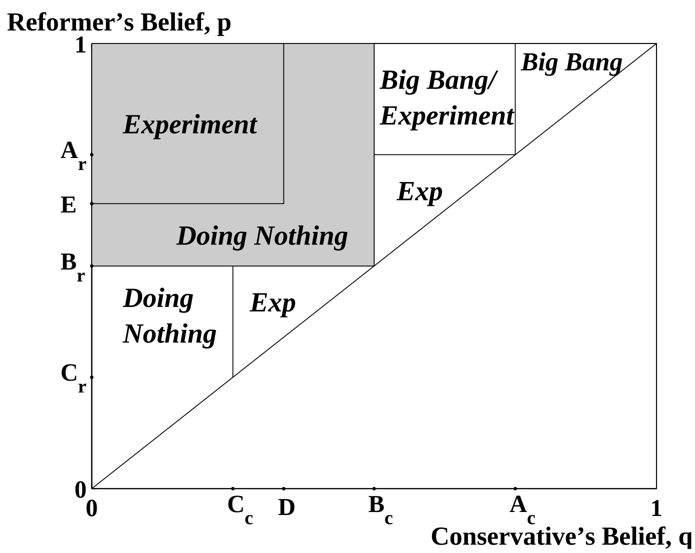
Mathematically and more precisely, assume $B_r < p \leq 1$ *and* $0 \leq q < B_c$. *Then* $f(p,q) = 1$. *Further assume* $\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{e+d}, \frac{\rho b_c}{e}\right\}$. *Then the following two statements are true:*

i) If $0 \leq q < \min\{D, B_c\}$ *and* $\max\{B_r, E\} < p \leq 1$, *then the experimental approach will be adopted.*

ii) If $D < q < B_c$ *or* $B_r < p < E$, *then the policy will not be adopted.*

Appendix A.3 proves Proposition 2. The intuition of Proposition 2 is straightforward. The key is still the requirement of consensus for adopting either approach. When the mutually exclusive payoffs are effective, the conservative always prefers doing nothing over a Big Bang approach, so the Big Bang approach will not be adopted. If the conservative sufficiently cares about the mutually exclusive payoffs ($\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{e+d}, \frac{\rho b_c}{e}\right\}$), then the mutually exclusive-payoff consideration will dominate her mutually inclusive-payoff consideration about the experimental approach. More specifically, she will prefer a failed experiment to *both* of a successful experiment ($-\rho b_c + \beta e > \rho a_c + \delta a_c - \beta d$) and doing nothing ($-\rho b_c + \beta e > 0$). In this case, on the one hand, if the conservative holds a sufficiently strong disbelief in the policy ($0 \leq q < \min\{D, B_c\}$), then she will be confident enough of seeing a failed experiment if the experimental approach is adopted, and thus being proven correct. With this consideration in mind, she will prefer the experimental approach over doing nothing. On the other hand, the experimental approach will still not be adopted if the reformer does not sufficiently believe in the policy ($B_r < p < E$), since she will be afraid of losing too much in the "political gamble" in the form of policy experimentation, and the expected loss will induce her to prefer doing nothing over the experimental approach. Therefore, the experimental approach will be adopted *only* if the players have diametrically opposite priors; otherwise, the policy will not be adopted.

Figure 2.2 illustrates Proposition 2. The mutually exclusive payoffs are effective only in the shaded area. In this area, as Proposition 2.2 states, the experimental approach will be adopted if the players hold diametrically opposite beliefs ($0 \leq q < \min\{D, B_c\}$ and $\max\{B_r, E\} < p \leq 1$); the policy will not be adopted if one of the player's prior is not sufficiently extreme ($D < q < B_c$ or $B_r < p < E$). In other words, "Experiment" occupies the left-top corner of both the shaded area and the unit square, while "Doing Nothing" occupies the right-bottom corner of the shaded area, which is the area where p is slightly higher than B_r and q is slightly lower than B_c. In contrast to Figure 2.1, Figure 2.2 shows that introducing contingent, mutually exclusive payoffs reverses the relationship between priors and the experimental approach: extreme, diametrically opposite beliefs are associated with the experimental approach, while moderate, slightly different priors are associated with doing nothing if the mutually exclusive payoffs are effective and if the players care strongly about these payoffs.



$a_r = a_c = b_r = b_c = 2$, $e = 1$, $d = 2$, $\rho = 0.25$, $\delta = 0.50$, $\beta = 10$
$A_r = A_c = 0.75$, $B_r = B_c = 0.5$, $C_r = C_c = 0.25$, $D = 0.34$, $E = 0.64$

Figure 2.2: The typical case with large β

An interesting way to appreciate Proposition 2 is to observe the relationship between the conservative's prior, q, and the model solution, given an optimistic reformer ($E < p \leq 1$). In Figure 2.1, as q increases from 0 to 1, the model solution evolves from doing nothing, to the experimental approach, and ends up with the Big Bang approach. This conventional monotonicity is broken up in Figure 2.2: the model solution starts from the experimental approach, then turns into doing nothing, and later goes back to the experimental approach or the Big Bang approach. A similar nonmonotonic relation also exists between the reformer's prior, p, and the model solution, given a moderate conservative ($C_c < q < D$), as p increases from (C_r, B_r) to 1.

A little discussion is deserved about the role of unanimity in Proposition 2. Because of the unanimity requirement, the veto power of the reformer can protect her from being forced to implement reforms about which she is not extremely confident. A decision rule that only grants the conservative the veto power, e.g., a majority rule with the conservative being the majority, will not provide this protection for the reformer, but the logic about need for the conservative's approval for any policy change, including an experimental implementation of the new policy, will remain.

Extending the model from two to N players would demonstrate a more significant role of the contingent, mutually exclusive payoffs. A newly introduced, moderate reformer could veto a formerly agreed experimentation, because she would be afraid of being proven incorrect and therefore being punished. As the extension adds little intuition, we leave it to Appendix A.4.

To conclude this section, we emphasize that in our model, given *a sufficiently small* q ($0 \leq q < \min\{D, C_c\}$) and *a sufficiently large* β ($\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{e+d}, \frac{\rho b_c}{e}\right\}$), the adoption of an experimental approach comes from the interaction between different priors and the contingent, mutually exclusive payoffs:

Similar priors with only mutually inclusive payoff If $0 \leq p < C_r$ and $0 \leq q < \min\{D, C_c\}$, then as shown in Figure 2.1, both players prefer doing nothing, and there is no policy adoption.

Different priors with only mutually inclusive payoff If $C_r < p < 1$ and $0 \leq q < \min\{D, C_c\}$, then as shown in Figure 2.1, the conservative vetoes the experimental approach (and the Big Bang approach), and there is no policy adoption.

Similar priors with contingent, mutually exclusive payoffs As shown in Figure 2.2, there are two cases: 1) if $0 \leq p < B_r$ and $0 \leq q < \min\{D, C_c\}$, then the mutually exclusive payoffs are ineffective; 2) if $B_r < p < E$ and $0 \leq q < \min\{D, C_c\}$, then the mutually exclusive payoffs are effective, and the conservative prefers the experimental approach over doing nothing, but the reformer is afraid of losing too much politically during the experimental approach. In both cases, there is still no policy adoption.

Different priors with contingent, mutually exclusive payoffs As shown in Figure 2.2, the experimental approach will be adopted only if the priors are diametrically opposite

($\max\{B_r, E\} < p \leq 1$ and $0 \leq q < \min\{D, C_c\}$) and contingent, mutually exclusive payoffs exist. In this case, the adoption of the experimental approach results from *both* players' confidence in being proven correct by the experiment's result and thus being rewarded.

2.5 Comparative Statics

To demonstrate the mechanism of our main result we now analyze the comparative statics of the model when contingent, mutually exclusive payoffs are effective ($B_r < p \leq 1$ and $0 \leq q < B_c$). By comparative statics, we mean how the magnitude of the mutually exclusive payoffs, d and e, affects the size of the area occupied by "Experiment" within the shaded area in Figure 2.2, and how the weight of the mutually exclusive payoffs, β, changes the solution pattern of the shaded area.[15]

The Impact of the Magnitude of the Mutually Exclusive Payoffs

Assume $\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{e+d}, \frac{\rho b_c}{e}\right\}$. By Equation (2.2), we can derive that D, the break-even prior between the experimental approach and doing nothing for the conservative is weakly increasing in the contingent reward e, while the corresponding break-even prior E for the reformer is weakly decreasing in e.[16] Note that in Figure 2.2, the size of the area of interest is increasing in D and decreasing in E, and thus it is weakly increasing in e. The intuition is simple: with a larger contingent reward e, the players will have more incentive to agree to an experimental approach.

The analysis around the contingent punishment d follows the same logic: With a larger contingent punishment d, the players will have less incentive to agree to an experimental approach, so the size of the area of interest is weakly decreasing in d.

To see how the relative scale of d and e affects the size of the area of interest, we consider the extreme case in which β approaches infinity, i.e., the players care almost entirely about the effective mutually exclusive payoffs but hardly about the mutually inclusive payoff. In

[15] The comparative statics around the experimental scale, ρ, is less straightforward, so we do not detail it here. The main point is, that the monotonicity of D with respect to ρ is ambiguous, although E is monotonically increasing in ρ, which means the monotonicity of the size of the area of interest in ρ is ambiguous.

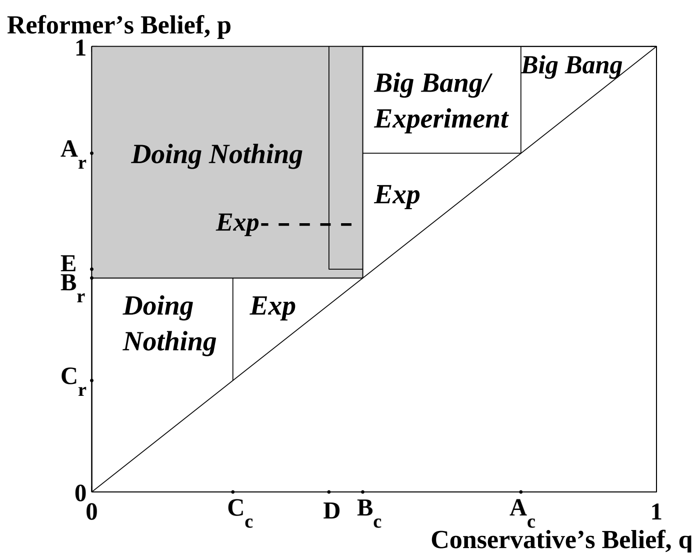
[16] If $D > B_r$ and $E < B_r$, then the entire shadowed area in Figure 2.2 is occupied by the experimental approach.

this extreme case, Equation (2.2) tells that D approaches $\frac{e}{e+d}$ and E approaches $\frac{d}{e+d}$. For any given prior pair (p, q), if $\frac{e}{d}$ decreases, then the relative gain in an experimental approach shrinks, and the experimental approach becomes less preferable for both of the players. If $\frac{e}{d}$ approaches zero, there will be no experimental approach adopted at all. To conclude, the size of the area of interest is increasing in $\frac{e}{d}$ when β approaches infinity.

The Impact of the Weight of the Mutually Exclusive Payoffs

We now focus on the solutions to the model if the players do not care enough about the mutually exclusive payoffs ($\beta < \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{e+d}, \frac{\rho b_c}{e}\right\}$). Appendix A.3 details the solutions to the model with different β.

If the players care little about the mutually exclusive payoffs ($\beta < \min\left\{\frac{\rho(a_c+b_c)+\delta a_c}{e+d}, \frac{\rho b_c}{e}\right\}$), then the model solution, as illustrated in Figure 2.3, should be similar to the case with only mutually inclusive payoff, as illustrated in Figure 2.1. The two figures are similar in that "Experiment" always occupies the upper right part of the shaded area, and in that the experimental approach is adopted only when the conservative hold moderate priors.

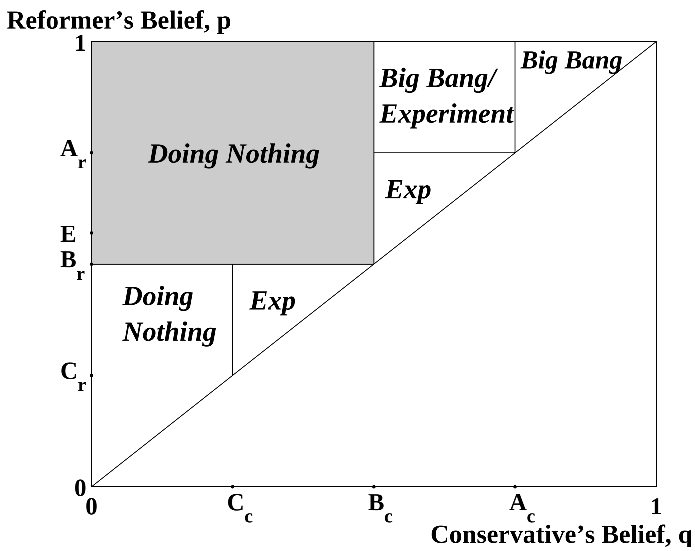


$a_r = a_c = 1.1$, $b_r = b_c = 1$, $e = 2.4$, $d = 8$, $\rho = 0.29$, $\delta = 0.50$, $\beta = 0.1$
$A_r = A_c = 0.76$, $B_r = B_c = 0.48$, $C_r = C_c = 0.25$, $D = 0.42$, $E = 0.50$

Figure 2.3: The typical case with small β

If the players care moderately about the mutually exclusive payoffs, we have two cases:

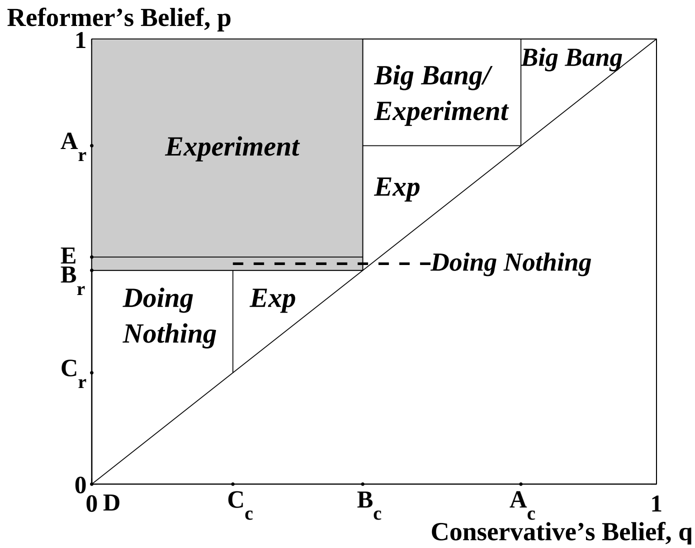
$\frac{\rho(a_c+b_c)+\delta a_c}{e+d} < \beta < \frac{\rho b_c}{e}$ and $\frac{\rho b_c}{e} < \beta < \frac{\rho(a_c+b_c)+\delta a_c}{e+d}$. In the first case, we have $-\rho b_c + \beta e > \rho a_c + \delta a_c - \beta d$ but $-\rho b_c + \beta e < 0$. The two inequalities indicate, that in the presence of the mutually exclusive payoffs, the conservative prefers a failed experiment to a successful one, but a failed experiment is still worse than doing nothing. The conservative then always vetoes the experimental approach, and the policy will not be adopted, no matter how large the reformer's prior is. Figure 2.4 illustrates the case, in which "Doing Nothing" occupies the entire shaded area.



$a_r = a_c = b_r = b_c = 2$, $e = 1$, $d = 5$, $\rho = 0.25$, $\delta = 0.50$, $\beta = 0.4$
$A_r = A_c = 0.75$, $B_r = B_c = 0.5$, $C_r = C_c = 0.25$, $D = -0.25$, $E = 0.57$

Figure 2.4: One typical case with moderate β

In the second case, we have $-\rho b_c + \beta e < \rho a_c + \delta a_c - \beta d$ and $-\rho b_c + \beta e > 0$. The inequalities imply that the conservative prefers a successful experiment to a failed one, and even a failed experiment is better than doing nothing. She will then always prefer the experimental approach to doing nothing, even when her prior q approaches zero. Now whether to adopt the experimental approach depends on the reformer decision. One typical situation with $E > B_r$ is illustrated by Figure 2.5, where "Experiment" covers only the upper part of the shaded area, since the reformer is afraid of losing too much politically during the experimental approach when $B_r < p < E$.



$a_r = a_c = 1.1$, $b_r = b_c = 1$, $e = 1$, $d = 2.6$, $\rho = 0.33$, $\delta = 0.50$, $\beta = 0.34$
$A_r = A_c = 0.78$, $B_r = B_c = 0.48$, $C_r = C_c = 0.27$, $D = -0.53$, $E = 0.51$

Figure 2.5: Another typical case with moderate β

2.6 A Perspective of Organizational Welfare

As shown in our main result, serious consideration of the political implications of experimental learning will induce experimentation when the priors are diametrically opposite and will shut down any reform when the priors are slightly different. Are these outcomes desirable from the perspective of the organization, and how should an "organizational planner" make use of the political consideration? To answer these questions, in this section, we compare 1) the collective decision in the benchmark model, 2) the collective decision in the model with mutually exclusive payoffs, and 3) the decision that maximizes organizational welfare, which is defined as the total value of the mutually inclusive payoff.

For simplicity, we assume that the mutually inclusive payoff is symmetric across the players, which means $a_r = a_c \equiv a$ and $b_r = b_c \equiv b$. Given this symmetry, there is an equivalence between the organizational planner who maximizes the *sum of the players' expectations* of the mutually inclusive payoff given the players' priors, p and q, and the organizational planner who maximizes *her expectation of the sum* of the players' mutually inclusive payoff and believes that the probability that the policy is good is $\pi \equiv \frac{p+q}{2}$. In other words, given any p and q, the two organizational planners will always make the same choice among the

Big Bang approach, the experimental approach, and doing nothing. We therefore consider these two organizational planners together as just one planner.

We can then identify that this organizational planner will prefer the Big Bang approach to the experimental approach if and only if

$$\pi \equiv \frac{p+q}{2} > A \equiv \frac{(1-\rho)b}{(1-\rho)a - \delta a + (1-\rho)b}. \tag{2.3}$$

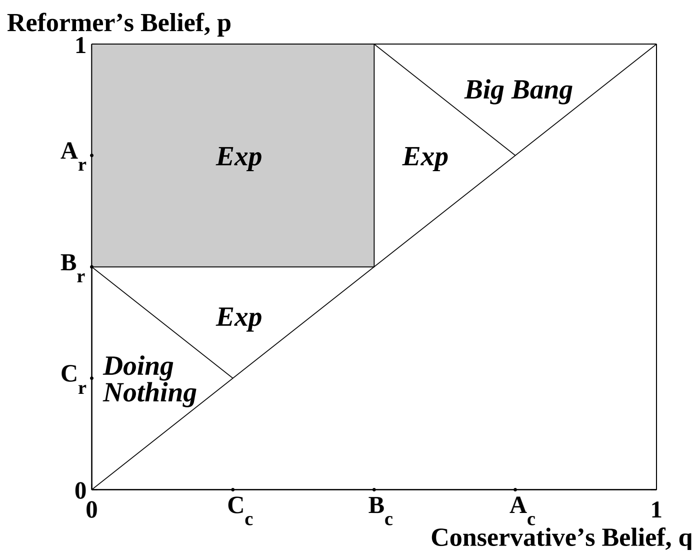
She will prefer the Big Bang approach to doing nothing if and only if

$$\pi \equiv \frac{p+q}{2} > B \equiv \frac{b}{a+b}. \tag{2.4}$$

She will prefer the experimental approach to doing nothing if and only if

$$\pi \equiv \frac{p+q}{2} > C \equiv \frac{\rho b}{\rho a + \delta a + \rho b}. \tag{2.5}$$

Also note $C < B < A$, so she will adopt the Big Bang approach if $\pi > A$ and the experimental approach if $C < \pi < A$ and do nothing if $\pi < C$.[17]



$a_r = a_c \equiv a = b_r = b_c \equiv b = 2,\ \rho = 0.25,\ \delta = 0.50$
$A_r = A_c \equiv A = 0.75,\ B_r = B_c \equiv B = 0.5,\ C_r = C_c \equiv C = 0.25$

Figure 2.6: An example of the decision of the organizational planner

Figure 2.6 shows the decision of the organizational planner using the same parameters as in Figures 2.1 and 2.2, and the shaded area corresponds to the shaded area in Figure 2.2

[17] We still ignore the break-even cases for simplicity.

where the players care strongly about the mutually exclusive payoffs. Comparing Figures 2.1 and 2.6, we see that the consensus requirement creates under-experimentation when the priors are diametrically opposite. This is the case because, when p and q converge to 1 and 0, respectively, the organizational planner will choose the experimental approach while the conservative who only considers a mutually inclusive payoff will veto any reform. The consensus requirement does not cause under-experimentation when the priors are slightly different: this is the case because, when p is slightly higher than B and q is slightly lower than B, the choice of the organizational planner and the agreement between the players are the same – they would like to experiment. Linking Figures 2.2 to the comparison, we find that introducing serious concerns about the mutually exclusive payoffs reduces the former under-experimentation when the priors are diametrically opposite, but creates under-experimentation when the priors are slightly different.[18]

To summarize, given the consensus requirement, whether serious consideration of the political implications of experimental learning is desirable to the organization depends on the heterogeneity of beliefs. It is desirable when the beliefs are diametrically opposite, but not appealing when the beliefs are slightly different.

2.7 Robustness: Extending the Contingent, Mutually Exclusive Payoffs to the Big Bang Approach

We have been implicitly assuming that the Big Bang adoption does not bring mutually exclusive payoffs. The justification is that, under the consensus requirement, agreeing to the Big Bang approach could make it very difficult for the two players to claim a contingent reward against each other, and only the experimental approach could serve easily as an agreed test between the two players. For example, when two parties are forming a coalition government, the mutually exclusive payoffs are the shift of popularity between them. When there is a reform following the Big Bang approach, however, is difficult to show voters the existence of different beliefs within the coalition, so it is difficult to generate mutually exclusive payoffs.

[18]For aesthetic simplicity, the specification in Figure 2.6 makes $B = 2C = 2A - 1$, which is not universally true. The discussion always holds, however, because $C < B < A$.

That said, one can still argue that it is possible that the Big Bang approach could bring mutually exclusive payoffs, as the experimental approach does, but on a much larger scale, since the information revealed by the large-scale, Big Bang implementation should be more convincing than small-scale, experimental implementation. This section follows this logic and extends the contingent, mutually exclusive payoffs to the Big Bang approach. We will show that the experimental approach will still be associated with diametrically opposite beliefs as long as the Big Bang approach is not favorable to the conservative.

We assume the following payoff structure to replace the mutually exclusive payoffs, which are assumed in Section 2.4:

Extended contingent, mutually exclusive payoffs If the result of an adoption on the scale s shows the policy is good, then the reformer gets $f(p,q)h(s)$, while the conservative gets $-f(p,q)g(s)$; if the result of reform shows the policy is bad, then the reformer gets $-f(p,q)g(s)$, while the conservative gets $f(p,q)h(s)$. When the adoption follows the Big Bang approach, $s = 1$; when the adoption follows the experimental approach, $s = \rho \in (0,1)$; when there is no adoption and nothing is done, $s = 0$. The indicator function $f(p,q)$ shows whether the payoff structure is *effective*, where $f(p,q) = 1$ if $B_r < p \leq 1$ and $0 \leq q < B_c$; otherwise, $f(p,q) = 0$. The contingent reward and the punishment functions are $h(s) = es^\theta$ and $g(s) = ds^\theta$, where $e > 0$, $d > 0$, and $\theta > 0$.[19]

We call this payoff structure *extended contingent, mutually exclusive payoffs*, because it extends the contingent, mutually exclusive payoffs to the Big Bang approach. Because $\theta > 0$, the scale of the extended contingent, mutually exclusive payoffs is increasing in the scale of the adoption. Sometimes we abbreviate extended contingent, mutually exclusive payoffs as extended mutually exclusive payoffs. When the difference between the contingent, mutually exclusive payoffs and the extended mutually exclusive payoffs is not important, we call both of them mutually exclusive payoffs. Table 2.3 shows the expected payoff from the two approaches and doing nothing when the extended mutually exclusive payoffs are effective.

Similar to Section 2.4, we also define the break-even priors of the trade-off between the

[19]This functional form is assumed to investigate the return to scale of the mutually exclusive payoffs.

Table 2.3: Expected mutually inclusive and weighted extended mutually exclusive payoffs from the three options when the extended contingent, mutually exclusive payoffs are effective

Player	Big Bang approach	Experimental approach	Doing nothing
Reformer	$p[a_r + \beta h(1)] - (1-p)[b_r + \beta g(1)]$	$p[\rho a_r + \delta a_r + \beta h(\rho)] - (1-p)\,[\rho b_r + \beta g(\rho)]$	0
Conservative	$q[a_c - \beta g(1)] - (1-q)[b_c - \beta h(1)]$	$q[\rho a_c + \delta a_c - \beta g(\rho)] - (1-q)\,[\rho b_c - \beta h(\rho)]$	0

In the case of $f(p,q)=1$, i.e. $p \in \left(\frac{b_r}{a_r+b_r}, 1\right]$ and $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$.

experimental approach and doing nothing, for both the conservative and the reformer, by

$$D' = \frac{\rho b_c - \beta h(\rho)}{\rho a_c + \delta a_c + \rho b_c - \beta(h(\rho)+g(\rho))}, \quad E' = \frac{\rho b_r + \beta g(\rho)}{\rho a_r + \delta a_r + \rho b_r + \beta(h(\rho)+g(\rho))}. \tag{2.6}$$

With the two newly-introduced indifference priors, we proceed with Proposition 3.[20]

Proposition 3. *Assume the two players have different preferences between the Big Bang approach and doing nothing when considering only the mutually inclusive payoff. Then the extended contingent, mutually exclusive payoffs are effective. Further assume that the conservative prefers doing nothing over the Big Bang approach for any prior with effective extended contingent, mutually exclusive payoffs. If the players strongly care about the extended contingent, mutually exclusive payoffs, then the following three statements are true:*

i) If the conservative sufficiently disbelieves in the policy while the reformer sufficiently believes in the policy, then the experimental approach will be adopted.

ii) Otherwise, the policy will not be adopted.

iii) The extended contingent, mutually exclusive payoffs have decreasing returns to scale.

Mathematically and more precisely, assume $B_r < p \leq 1$ *and* $0 \leq q < B_c$*. Then* $f(p,q) = 1$*. Further assume* $q\,(a_c - \beta g(1)) - (1-q)\,(b_c - \beta h(1)) < 0$ *holds for any* $q \in [0, B_c)$ *(which is equivalent to assuming* $\beta < \frac{b_c}{h(1)}$ *and* $\frac{a_c}{b_c} < \frac{d}{e}$*). If* $\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{h(\rho)+g(\rho)}, \frac{\rho b_c}{h(\rho)}\right\}$*, then the following three statements are true:*

i) If $0 \leq q < \min\{D', B_c\}$ *and* $\max\{B_r, E'\} < p \leq 1$*, then the experimental approach will be adopted.*

ii) If $D' < q < B_c$ *or* $B_r < p < E'$*, then the policy will not be adopted.*

iii) $\theta < 1$*.*

[20] For simplicity, we only consider the cases in which p and q are not equal to any of the indifference priors.

Appendix A.7 proves Proposition 3. The intuition is simple. When the extended mutually exclusive payoffs are effective and the conservative prefers doing nothing over the Big Bang approach for any prior with effective extended contingent, mutually exclusive payoffs, the conservative will still veto the Big Bang approach as in Proposition 2.[21] When the players strongly care about the extended mutually exclusive payoffs ($\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{h(\rho)+g(\rho)}, \frac{\rho b_c}{h(\rho)}\right\}$), Results i) and ii) then follow the same logic as in Proposition 2. In this case, as an extreme conservative ($q = 0$) prefers the experimental approach over doing nothing and doing nothing over the Big Bang approach, she should prefers the experimental approach over the Big Bang approach. This preference suggests that the extended mutually exclusive payoffs cannot increase very fast in the adoption scale ($\theta < 1$), which is Result iii). Otherwise, the contingent reward from the Big Bang approach would be much larger than that from the experimental approach and the extreme conservative would then like the Big Bang approach even better than the experimental approach. In other words, the mutually exclusive payoffs should dominate the mutually inclusive payoff in the extreme conservative's evaluation of the experimental approach, but *vice versa* in her evaluation of the Big Bang approach.

2.8 Two Historical Illustrations

The Strategic Choice in the Chinese Transition

Our model provides a plausible answer to why China adopted neither a Big Bang nor a do (almost) nothing approach but instead adopted an experimental approach in its transition. In the transition, the first two key assumptions of our model – different priors and the consensus requirement – are well embedded. First, in terms of different priors, it is now well known that, beginning in the late 1970s, there was a fierce debate among the Communist Party leaders about whether and how to introduce reform in China. One group of leaders, represented by Deng Xiaoping, Hu Yaobang, Zhao Ziyang, Wan Li, and others, focused on open markets and placed special emphasis on economic growth rates. The other group, represented by Chen Yun, Li Xiannian, Wang Zhen, Li Peng, Deng Liqun, Hu Qiaomu, Yu

[21] The simple expression of the relative size relies on the specification of $h(s) = es^\theta$ and $g(s) = ds^\theta$. Other specifications, for example, a linear specification of $h(s)$ and $g(s)$, will not derive the same simple expression, but still carry the same intuition.

Qiuli, and others, insisted on restoring the command economy in line with the First Five-Year Plan, a Soviet-style scientific economic plan.[22] The debate was witnessed and documented by Deng Xiaoping's speech (1984), Deng Liqun's autobiography (2006), Li Rui's recollection (2008), Bao Tong's interview (2009), Zhao Ziyang's memoir (2009b, 2009c), and Zhang Lifan's talk (2014), and acknowledged by scholars such as Shirk (1993, 1994), Dittmer and Wu (1995), Vogel (2005, 2011), Heilmann (2011), and Xu (2011), as well as via reports in the media, such as *The Economist* (February 25, 1989).[23] The debate revealed diametrically opposite beliefs held by the two factions inside the Party: Deng Xiaoping's reform faction, and Chen Yun's conservative faction.[24]

Second, the consensus requirement for policy change is one of the most important features of Chinese Communist politics. As Shirk (1993, p. 15) writes, "the Chinese government bureaucracy ...always made decisions by consensus" and "consensus decision making institutions tend to be conservative because radical departures from the status quo are blocked by vetoes from groups who stand to lose." A united image of the Party is required by the single-party authority, and, as Huang (2000, p. 411) documents, its leaders debate among themselves privately but must deny any differences on policy in public. Shirk (1994, p. 16)

[22]The names were all significant in Chinese politics. For the reformer faction, Deng Xiaoping was the core of the second generation leaders of China and the Party; Hu Yaobang was the General Secretary of the Party from 1982 to 1987 and Zhao Ziyang was General Secretary from 1987 to 1989; Wan Li was the Vice Premier of China from 1980 to 1988, and the Chairman of the National People's Congress from 1988 to 1993. For the conservative faction, Chen Yun was the only figure who had equivalent political influence to Deng Xiaoping at the time, acting as the Vice Chairman of the Party from 1978 to 1982, serving in the Politburo Standing Committee of the Party from 1977 to 1987, and then holding the position of Director of the Central Advisory Commission, the office for retired senior Party leaders, from 1987 to 1992; Li Xiannian was the President of China from 1983 to 1988 and Wang Zhen was President from 1988 to 1993; Deng Liqun and Hu Qiaomu were leaders of the propaganda and publicity system; Yu Qiuli was the Vice Premier of China from 1975 to 1982 and the Director of the General Political Department of the People's Liberation Army from 1982 to 1987.

[23]Li Rui was first the secretary of Mao and later the Deputy Head of the Organization Department of the Party from 1983 to 1984. Bao Tong was the Policy Secretary of Zhao Ziyang when Zhao was the Premier of China from 1980 to 1985. Zhang Lifan worked at the Institute of Modern History of Chinese Academy of Social Sciences in the 1980s, and was appointed by Hu Yaobang's family as the witness of Hu Yaobang's funeral in 1989.

[24]Shirk (1993, 1994) thoroughly documents the political issues around the Chinese transition before the early 1990s. Zhao Ziyang (2009b, p. 91–94) documents in detail the differences between the leaders' ideas about the Chinese economy. Xu (2011) cites Deng Xiaoping (1984), Li Rui (2008), Bao Tong (2009), and Zhao Ziyang (2009b) to document the different opinions toward reform within the Party. Heilmann (2011, p. 84) reads: "Deng Xiaoping and Chen Yun ...came to differ substantially with regard to the speed and extent of change."

notes that most reform policies were debated in large working conferences where consensus could be reached among the central leadership, provincial representatives, and department ministers. Although some top figures might have exerted a strong influence in such conferences, during the 1980s, power was almost equally distributed between Deng Xiaoping and Chen Yun. As documented in Vogel (2005, p. 742)'s short biography of Chen Yun, "On important issues relating to the economy, ideology, Party organization, and basic Party Policy, it was expected that Deng would seek the approval or at least the acquiescence of Chen Yun."[25] The metaphor created by Yang (2004) to describe this equilibrium, the *two-peak politics (shuangfeng zhengzhi),* is now well accepted. The consensus requirement in our model is thus plausible for these two well-matched factions.

The presence of different priors and the consensus requirement made the conservatives' beliefs critical to the adoption of any reform. Many sources suggest that the conservatives did not believe in the reforms, thinking it not worthwhile to enact reform policies given their expected defects (e.g., Dittmer and Wu, 1995; Huang, 2000, p. 380). For example, in arguably the most famous speech of his career, Chen Yun (1995) emphasized in 1980 that "the mainstay of our country is a planned economy."[26] Heilmann (2011, p. 84) also writes: "...in contrast to Deng, Chen took a very sceptical stance toward the introduction of non-socialist special economic zones ..." Zhao Ziyang (2009b, p. 92) recollects: "Li Xiannian was fully on Chen Yun's side, and even more extreme and stubborn." This situation corresponds to a very small q in our model.[27]

We can further regard the mutually inclusive payoff in our model as national or Party interests as viewed by each of the two factions. Proposition 1 then predicts that the con-

[25]In the 1956–1966 seven-person Politburo Standing Committee of the Communist Party of China, the most powerful decision making body in China, Chen Yun ranked fifth in influence, and Deng Xiaoping ranked sixth in influence. After the Cultural Revolution (1966–1976), Deng Xiaoping and Chen Yun were the only two members among the seven members of the 1956–1966 Standing Committee remaining alive. For the years after 1978, Huang (2000, p. 363) writes, "More importantly, these arrangements virtually structured new leadership relations in the years to come: the power in decision making was shared by Deng and Chen, with Li Xiannian, and later Peng Zhen, as the balancing weights." Vogel (2005, p. 756) writes, "At the Third Plenum that followed immediately and ratified the new direction laid out at the work conference, Deng Xiaoping, aged 74, sat on the podium with Chen Yun, aged 73."

[26]The statement was spoken during the Central Committee Working Conference on December 16, 1980. It reads *women guojia shi yi jihua jingji wei zhuti de* in Chinese.

[27]In the Chinese transition, the conservatives' belief in the market reform was rather dim, and, as documented in Huang (2000, p. 380), they were always insisting on the central-planned economy as the mainstay. Dittmer and Wu (1995) document that the conservatives' top concerns were economic overheating, inflation, trade deficit, and macro-instability.

servatives should always have vetoed any form of reform proposed by the reformer faction. For example, the conservatives should have rejected expanding the special economic zones in coastal areas, but chosen to keep the scientific, planned system as the economy's mainstay, using a market economic approach only as a supplement.

History simply contradicts this prediction. Note that Proposition 1 comes from adding the consensus requirement to the classic option value–delay cost trade-off between the Big Bang and the experimental approaches. The contradiction suggests that this classic trade-off missed something necessary to explain the experimental transition of China.

As Woo (1994, p. 279–280), Roland (2000, p. 36–37), Cai and Treisman (2006), and Xu (2011) have suggested, China's adoption of the experimental approach might result from the presence of diametrically opposite beliefs toward the reform. Our Proposition 2 supports this explanation: when the two factions hold diametrically opposite beliefs, they are both sufficiently confident of being proven correct in the experimental approach, and thereby gaining the contingent, mutually exclusive payoffs, which drives the experimental transition.

The plausibility of this answer depends on the plausibility of the contingent, mutually exclusive payoffs. By having its position proven correct during the Chinese transition, a faction could not only convince the other faction to adopt its view, but could also affect personnel arrangements, popularize itself among provincial representatives and ministers, and thus gain political power in some outside or future policy discussions.[28] For example, Vogel's biography of Deng Xiaoping (2011, p. 393) notes, "if something was working, that policy or that person garnered support," and "when economic results came in toward the end of each year, for example, they affected the evaluation of the current economic policy and of the officials responsible for the policy." The quotations suggest that the experiment's result affected not only the conclusions about the experiment, but also the careers of relevant officials, and therefore shifted power between the factions.[29] The existence and significance of these contingent, mutually exclusive payoffs are also consistent with the observation that

[28] There is a phrase *zhengzhi ziben* for this kind of political power in Chinese. A straight English translation would be *political capital*.

[29] In another example, Shirk (1994, p. 19) argues that "contending leaders used reform policy to extend new powers and resources to various groups within the selectorate, and leaders adopted particularistic rather than universal forms of policies, which enabled them to claim credit for giving special treatment to particular organizations and localities." Such credit is also contingent on the success of a given reform policy. If the reform policy is proven incorrect, the leaders and the particular organizations, as well as localities, will lose political support and potential promotion.

politicians always avoided association with failed experiments. For example, Vogel (2011, p. 393) documents that, "if something was failing, however, people began to move away and to shun the failure." Shirk (1993, p. 141) also sees that, "if an experimental enterprise somehow turned in a disappointing performance, it was dropped from the program and never mentioned again."

If the contingent, mutually exclusive payoffs were not significant, both factions should hope for a fair experiment through which unbiased information would be revealed. In reality, however, the reformers and the conservatives used their political resources to tilt the experiment toward the outcome they desired, and these tactics suggest the significance of contingent, mutually exclusive payoffs. For example, on the one hand, Shirk (1993, p. 140–141) observes that many of the experiments were "not true experiments but rather 'Potemkin village' models" that were "bolstered with …cheap material inputs, electricity, bank loans, and so on" so that "there was no way an experiment could fail." On the other hand, success of these experiments was never easy since the conservative bureaucrats always used their political resources to sabotage the experiments by imposing "cutthroat" restrictions on these experiments (e.g., Tu, 2008, p. 101–119; Wang, 2008; Li Lanqing, 2009, p. 79–85).[30] In 1981, Chen Yun even proposed removing Ren Zhongyi, who strongly supported the market reform, from the position of the Party secretary of Guangdong Province, where three among the four earliest special economic zones were located. In Chen Yun's words, the experiments should be supervised by people who were "as firm as an unmovable nail," which would create further difficulties against the success of the experimentation (Zhao Ziyang, 2009b, p. 104). Facing these obstacles, the reformers had to fight hard to tilt the experiments back toward the outcome they desired.

Some *ex-post* observations also show the plausibility of the mutually exclusive payoffs. For example, as the experimental reform during the Chinese transition is regarded as a huge success, Deng Xiaoping was venerated as "the chief architect of the socialist opening-up and modernized construction of China" when he died in 1997, while Chen Yun received much less

[30]For example, Tu (2008, p. 101–108) and Wang (2008) document that, after a four-cent bonus effectively encouraged workers in special economic zones to increase productivity, the use of economic incentive was deliberately banned by the central government, resulting in a regression and delay in production. Tu (2008, p. 108–119), Wang (2008) and Li Lanqing (2009, p. 79–85) also discuss the manmade obstacles against special economic zones' investment in transportation and communication technologies. Li Lanqing was the Vice Premier of China from 1998 to 2003 and serving in the Politburo Standing Committee of the Party from 1997 to 2002.

acclaim when he died in 1995, even though he was much more senior than Deng Xiaoping during the early days of the Party.[31] Such a difference in acclaim would not have existed or likely would have "flipped" if the experimental reform had failed, especially given the even matching between the two leaders in the late 1970s and early 1980s.[32]

Some other considerations or alternative explanations could emerge in our illustration. For example, there could be conflicting interests that are not based on different beliefs, e.g., the reform could displace the ministries controlled by the conservative, regardless of the success or failure of the reform. This consideration, however, does not explain why the conservative did not veto the reform to avoid this loss of power.[33] An important alternative explanation, following the logic in Roland (2000, p. 36–37) and Hirsch (Forthcoming), is that conservatives' approval of the experimental reforms could be driven by the desire to convince the reformers to adopt the correct belief. The alternative explanation fails to explain the different attitudes toward the result of experimentation, the effort to tilt the result, or the significant changes in political power after the reform. Another explanation could be logrolling, namely, that one faction might compromise on a policy in exchange for cooperation in other issues. This explanation, however, would conflict with the political-economic cycle in the 1980s. As documented in Dittmer and Wu (1995) and Zhao Ziyang's memoir (2009b, p. 101–104), following problems with the market reform, such as overheating and economic

[31] Vogel (2005, p. 743) notes: "Although Deng was one year older than Chen Yun, Chen Yun had seniority within the Party. From 1931 when he became a member of the Central Committee until 1956, Chen Yun held higher positions than Deng and even after 1956 outranked Deng in the official Party ranking. In 1935, at the famous Zunyi Conference so critical to Mao's rise to pre-eminence, Chen Yun participated not only as a member of the Central Committee but as a member of its standing committee. Deng attended the same meeting as a note taker."

[32] We can also talk a little bit more about the mutually exclusive payoffs from the Big Bang approach. On the one hand, we argue that the result of a Big Bang reform could not give significant contingent, mutually exclusive payoffs to the two factions. The reason should be simple: under the consensus requirement, the conservative would find it hard to claim their victory over the reformers if the Big Bang reform failed, since the reformers could ask "why did you *not* reject the Big Bang approach?" The reformers would also find it difficult to claim their victory if the Big Bang reform succeeded, since the conservative could state "we did approve the Big Bang approach!" The question and the statement would make the victors' claims much weaker. On the other hand, even if the Big Bang approach could bring significant mutually exclusive payoffs, we can argue that the conservative would not dare to try the Big Bang approach, since a failed Big Bang reform could provoke an economic disaster (and it would be very likely to cost the Party's governance position in China). This discussion suggests that either Proposition 2 or 3 is applicable.

[33] Similarly, it could be the case that the two factions had different opinions about the market reform because the conservative were more risk- or loss-averse, but this consideration cannot explain why the conservative did not use their veto power to avoid the risk or potential loss.

crimes, the conservative had more political power to push back not only the economic but also the ideological reforms, which fits our story. The explanation about logrolling, however, would predict that regressive ideological policies should generally coincide with progressive economic policies and not depend on the result of these progressive economic policies.

To summarize, our story about the mutually exclusive payoffs does provide an empirically relevant explanation for the experimental transition of China among the conventional wisdom of one reformer weighing the option value and the delay cost of the experimental approach and other alternative considerations. To bolster our argument, we now discuss a specific, concrete experimental reform:

The generalization of the household-responsibility system. Beginning in 1955, China adopted a system of collectivized agriculture. As early as 1977, some remote, starving rural areas began to decentralize agricultural production and adopt the household-responsibility system (*baochan daohu*). Adopting the new system on a broader level, however, was explicitly prohibited by the Central Committee of the Communist Party of China in 1979.

As Zhao Ziyang (2009c, p. 156–159) documents, in the wake of major success of the reform in starving rural areas, a fierce debate erupted over whether to generalize the reform to the whole country. Within the Central Committee of the Party, the conservative group, represented by Hua Guofeng, Li Xiannian, Chen Yonggui, Wang Renzhong, Hu Qiaomu, and Xu Xiangqian, strongly and publicly opposed the reform on the grounds of ideology, amid concerns about decreasing the scale of agricultural production. This standpoint reflected an extreme conservative belief. In contrast, the reformer group, represented by Deng Xiaoping, Chen Yun, and Wan Li, emphasized the existing success in rural areas, and insisted on generalizing the reform.[34] As readers who are familiar with Chinese history well know, both factions were politically strong, and each could actually veto any proposal if the other insisted on its position.[35]

[34]Vogel (2011, p. 435–442) describes the formation of the reformer group, and Zhao Ziyang (2009c, p. 156–159) lists the names of the leaders who held the conservative view about this specific issue.

[35]The conservative figures were huge in the context: apart from Li Xiannian and Hu Qiaomu whom we have already introduced in Footnote 22, Hua Guofeng was Mao Zedong's designated successor as the paramount leader of the Party and the country; Xu Xiangqian was the second ranked of the only four Marshals alive at the time, among the Ten Marshals who were the most important military leaders; Chen Yonggui and Wang Renzhong were the directors of agriculture in the government.

Moreover, there was also a huge debate among provincial leaders and within the State Agriculture Commission. To discuss whether to generalize the reform, the Central Committee of the Party scheduled a colloquium for provincial officials in September 1980. As recollected by Du Runsheng (2005, p. 117–118), who was the lowest ranked vice director of the State Agriculture Commission at the colloquium, he first presented his support for the generalization, but the Commission then stated that it did not support his position. There was also no unanimous view from provincial officials.[36] Du Runsheng (2005, p. 119) and Zhao Ziyang (2009b, p. 141) both report that the divergence was so huge that neither side could persuade its opponent to change the position. Then came one of the most famous exchanges during Chinese transition:

> You can go your broad way as you want, but I shall definitely go my way, even if you think I am crossing a giant canyon via only a single plank![37]

The exchange suggested that the two factions agreed to disagree and were extremely confident of being proven correct in the future. At the end of the meeting, the Central Committee of the Party (1980) released Directive No. 75. This Directive formally allowed provincial governments to decide whether to adopt the household-responsibility system. Given that the Central Committee of the Party knew from the colloquium exactly which provinces would adopt the system and which would not, the Directive basically introduced an experimental approach to the reform across different Chinese provinces, with some adopting it and some not.

Given that the conservatives were strongly opposed to the reform not only at the central government level but also at the provincial level, how could the experimental approach have been adopted? Proposition 2 suggests that its adoption could have been driven by the presence of diametrically opposite beliefs coexisting with significant mutually exclusive payoffs. This speculation is supported by strong *ex post facto* evidences. For example, as

[36]Du Runsheng (2005, p. 118) and Wu (2012) document that many of them, such as those from Heilongjiang, Jiangsu, Fujian, Shaanxi, and Hebei Provinces, strongly opposed the generalization. Three others, from Guizhou, Inner Mongolia, and Liaoning, strongly favored the proposal.

[37]In Chinese, the saying reads *Ni zou nide yangguandao, wo zou wode dumuqiao.* Du Runsheng (2005, p. 119) and Zhao Ziyang (2009c, p. 158) document this exchange between Yang Yichen, the First Party Secretary of Heilongjiang Province, who rejected the household-responsibility system, and Chi Biqing, the First Party Secretary of Guizhou Province, who supported the household-responsibility system.

mentioned by Du Runsheng (2005, p. 130–131), as the success of the experimental reform was realized, several provincial leaders who had been opposed to the reform were removed from their posts. The State Agriculture Commission, whose ministers (except Du Runsheng) had opposed the reform, was displaced in 1982 by the Division of Rural Policy Research of the Central Committee of the Party and the Center of Rural Development Research of the State Council, which were directed by Du Runsheng (Du Runsheng, 2005, p. 117).[38] It is also fair to say that the success of the reform helped to promote its strongest advocates, e.g., Zhao Ziyang and Wan Li, and to accelerate the retirement of several prominent conservatives, e.g., Hua Guofeng and Chen Yonggui, from the core of Chinese politics.[39] These observations also hint that it would be difficult to argue that the mutually exclusive payoffs did not play a role in the experimental generalization of the household-responsibility system.

Finally, the plausibility of our explanation is also supported by Du Runsheng (2005, p. 118–119)'s remark summarizing the policymaking process. He said:

> The opinions were too opposite for the colloquium to continue. …Directive No. 75 was a compromise result from the debate.

Based on this quote and the earlier "broad way versus single plank" exchange, it is crystal clear that the Directive was a compromise result that was reached because neither of the two factions would compromise, and that the adoption of the experimental approach resulted from the diametrically opposite beliefs and the huge expectations of being proven correct.

Which Way to Germany, and Why Operation Market–Garden?

The aftermath of the Allied victories in Normandy and Paris in August–September 1944 saw a famous argument within the leadership of the Allied Forces as to which strategy should

[38]In Chinese, the Division of Rural Policy Research of the Central Committee of the Party is *Zhonggong Zhongyang Nongcun Zhengce Yanjiu Shi*, and the Center of Rural Development Research of the State Council is *Guowuyuan Nongcun Fazhan Yanjiu Zhongxin*. Du Runsheng would later become one of the most influential and respected leaders of Chinese rural reform. As a disclaimer, we are not suggesting that Du Runsheng was manipulating in the policy debate for his own promotion or reputation. On the contrary, we deeply respect Du Runsheng, for his devotion to rural reform in China, which has shown his unquestionably exceptional character. Our argument, however, applies to the two groups of leaders in the debate.

[39]In June 1981, Hua Guofeng resigned as the Chairman of the Party, while Zhao Ziyang was promoted to become Vice Chairman of the Party. In 1982, Wan Li was promoted to the First Secretary of the 12th Central Committee of the Party, while Chen Yonggui retired from the Committee.

be adopted on the Western Front to defeat Hitler. Dwight Eisenhower, the Supreme Commander of the Allied Forces in Europe (and later President of the United States), proposed crossing the Rhine and reaching the Ruhr on a broad front with the British forces (Field Marshall Bernard Montgomery) coming via the north and the American forces (General of the Army Omar Bradley and General George Patton) via the south of the Ardennes. However, Montgomery, with Churchill's backing, preferred a single, concentrated thrust only through the north. Instead of directly concentrating forces toward the north to implement the single thrust in a Big Bang approach at the strategic level, another option, which came to be called Operation Market–Garden, could be adopted at the operational level by seizing a bridgehead over the Rhine near Arnhem, which is in the north, with an ambitious thrust, but at the cost of delaying the opening of the port of Antwerp. As noted by the renowned historian and grandson of Dwight Eisenhower, David Eisenhower (1986, p. xxiii, 442, 445), this operation "would disrupt Eisenhower's plans ...not decisively" but it "was to be the preliminary in Montgomery's proposed forty-division thrust," and, therefore, could serve as an experiment to "test the validity" of Montgomery's idea.

The first key assumption of our model, the diametrically opposite beliefs of the decision makers, was documented by many witnesses (e.g., Eisenhower, 1948, p. 306–307; Montgomery, 1958, p. 238–257, Ill. 42; Churchill, 1959, p. 877–878) and historians (e.g., Ambrose, 1990, p. 153–159; Murray, 1996; Baxter, 1999, p. 89–100; D'Este, 2002, p. 594–609).[40] Montgomery genuinely believed that the German defense was incapable of any serious resistance in the face of a concentrated attack from the north of the Ardennes, and that his single-thrust strategy would easily open the road to Berlin and finish the war by Christmas 1944. Eisenhower, however, did not buy the idea at all, as he well understood that the Germans still had the ability to make a last-ditch effort and that a broad front by the Allies was necessary to seize the Ruhr. The divergence of their beliefs was so deep that Eisenhower and Montgomery even had a tense face-off on September 10, 1944.[41]

The second key assumption of our model, the consensus requirement, was also present: As Eisenhower was the Supreme Commander, any deviation from his broad-front strategy needed his approval. It is also obvious, as noted by David Eisenhower (1986, p. 445), that the

[40] Also see Murray (1996) and Baxter (1999, p. 89–100) for detailed accounts of the bibliography on this argument.

[41] For details about the meeting, see Ambrose (1990, p. 163) and D'Este (2002, p. 605–606).

single-thrust strategy would not be adopted in any approach unless "Montgomery insisted."

Historical accounts have revealed that Eisenhower dismissed the single thrust at the strategic level, since he could not risk the victory of the Western Allies in the war against Hitler and in the competition with Stalin. He agreed with Montgomery, however, to execute Operation Market–Garden. As we all know now, this operation would, in fact, turn out to be a total disaster.[42] The failure of Market–Garden and the delay of the opening of Antwerp gave the Third Reich a breathing space, and effectively quashed Montgomery's plan at the strategic level and any hope of the Allies to finish the war in 1944. Eisenhower's broad front eventually took place.

As many strategists and historians have noted, Montgomery's proposal of Market–Garden was more foolish than risky. For example, General of the Army Omar Bradley (1951, p. 416) said: "Monty's plan for Arnhem was one of the most imaginative of the war. Just as soon as I learned of Monty's plan, I telephoned Ike and objected strenuously to it."[43] Brighton (2008, p. 334) quotes Major Brian Urquhart, the British intelligence officer who was suspended for warning of the infeasibility of the plan, considering the operation to be "an unrealistic, foolish plan." A famous question in political and military history then arises: Why did Eisenhower "not only approve" but also "insist upon" Montgomery's risky, if not foolish, Market–Garden plan (Dwight Eisenhower, 1970, p. 2135)?

Several potential explanations have been offered. First, Eisenhower might have approved Market–Garden only on military grounds as he might have considered Market–Garden to be a "silver bullet" to seize a strategic bridgehead over the Rhine. However, as the flaws in the plan should have been obvious to Eisenhower, and the blow of Market–Garden was so heavy, this explanation cannot convince historians like Baxter (1999, p. 95), D'Este (2002, p. 603), and Ambrose (2012, p. 513).[44] Brighton (2008, p. 334) also quotes Urquhart as saying that the operation "had been dictated by motives which should have played no part

[42] Coble (2009, p. 1) states that the "casualty count …among three participating Allied airborne divisions …was more than among all Allies on 6 June 1944, the first day of Operation Overlord" – the day of the Normandy landings. The most famous book about Operation Market–Garden could be Ryan (1974)'s *A Bridge Too Far*. Also see Montgomery (1947, 1958), Eisenhower (1948, 1970), Bradley (1951), Wilmot (1952), Churchill (1959), Eisenhower II (1986), Ambrose (1990, 2012), Murray (1996), Baxter (1999), D'Este (2002), and Brighton (2008) and the references they cite.

[43] Montgomery was nicknamed "Monty," while Eisenhower was nicknamed "Ike."

[44] As quoted by Baxter (1999, p. 95) and D'Este (2002, p. 603), Ambrose (2012, p. 513) states that "Eisenhower could not make his decisions solely on military grounds."

in a military operation." This explanation was even refuted by Eisenhower himself, as he wrote to General Hastings Ismay in 1960, as quoted by D'Este (2002, p. 618), that "my staff opposed it but because he was the commander in the field, I approved."

Second, some people believe that Eisenhower approved Market–Garden to appease Montgomery (e.g., Ambrose, 1990, p. 165).[45] As noted by Brighton (2008, p. 335), however, "after the war when this was put to Eisenhower he strongly denied it", and, had Eisenhower "intended Market–Garden to keep Monty quiet, it did not." It is also difficult to believe that Eisenhower invited a huge blow to the American Forces (especially the 82nd and the 101st Airborne Divisions) only to make Montgomery happy. Third, as noted by David Eisenhower (1986, p. 445), his grandfather "could negotiate with Montgomery on the basis of Market–Garden …in hopes of defusing" their argument, but this "would involve making concessions beyond those" Eisenhower "had already made, and set the bad example of rewarding intransigence by negotiating under duress, which could not pass unnoticed by the Americans."

As thoroughly supported by David Eisenhower's Pulitzer-finalist book (1986), another explanation emerges as we examine the political background of the Eisenhower–Montgomery controversy. The argument took place within a larger picture of the competition between the Anglo–American cousins over the leading role within the Allied Forces, the distribution of the historical glory of defeating Hitler, and their influence in Europe after the war. Eisenhower and Montgomery were the representatives of the American and British interests in the political competition.[46] David Eisenhower (1986, p. 444) sharply points out that "Berlin was not what the British had in mind; what they wanted was a dominant voice within the Allied command." If the British did dominate within the Allied command, and if Montgomery's single thrust did succeed with guaranteed strategic priority of the Allied Forces, the British would reap much more glory and postwar political power in Europe than if, as it

[45] Ambrose (1990, p. 165) reads: "But of all the factors that influenced Eisenhower's decisions – to reinforce success, to leap the Rhine, to bring the highly trained but underutilized paratroopers into action – the one that stands out is his desire to appease Montgomery." Brighton (2008, p. 335) writes that "the Americans at SHAEF believed" that Eisenhower "did so as a sop to Montgomery – that, having turned down his plan for a single thrust, he accepted Market–Garden to appease him, and would have turned it down if the plan had been considered on military grounds alone." The SHAEF is the abbreviation of the Supreme Headquarters Allied Expeditionary Force.

[46] See documentation of many historians, e.g., David Eisenhower (1986, p. 445), D'Este (2002, p. 603), Ambrose (2012, p. 504–535), and the references in Baxter (1999, p. 95).

turned out, the American and the British voices were balanced within the Allied command and Eisenhower's broad-front strategy worked out almost as planned. As noted by Ambrose (2012, p. 513) and quoted by Baxter (1999, p. 95) and D'Este (2002, p. 603), however, "under no circumstances would Eisenhower agree to give all the glory to the British."[47] Under this background of the political competition, Montgomery and Eisenhower should both have clearly understood that a successful Market–Garden would divert the competition toward the British, while a failed one would make it more balanced toward the Americans. This is the third key assumption of our model, the contingent, mutually exclusive payoffs.

Many people agree that mutually exclusive payoffs were one of the main reasons for Montgomery's enthusiasm toward the operation. For example, quoted by Brighton (2008, p. 335), Edgar Williams, Montgomery's Chief Intelligence Officer, talked about Montgomery's motive: "He thought that success would tilt the centre of gravity and give the British priority of supplies before the US armies. Probably Monty thought then it was just a question of who put in the final punch against a defeated enemy before a final victory. If this airborne drop succeeded in front of his Second Army drive, his punch not Patton's would be the triumphal road to final victory."[48] It is also natural to propose that one important reason for Eisenhower's approval of Operation Market–Garden was to prove Montgomery and his strategy wrong and therefore gain an advantage for the Americans in the political competition. We are not alone in this proposal; David Eisenhower (1986, p. xxiii) clearly makes his point on his grandfather's motive:

> Eisenhower ...was left with a third course: Calling Montgomery's bluff by au-

[47]D'Este (2002, p. 603) also states: "Although Eisenhower may well have convinced himself his broad front decision was primarily military, the political aspects simply could not have been ignored. 1944 was a presidential election year in a war being fought by allies. From the time he took command of Torch in North Africa his role, indeed the very basis of his success, had been unity in a war, which would be won by allies, not by British or Americans, acting singularly."

[48]General George Patton was mentioned here as the American force that would advance south of the Ardennes under the broad-front strategy that was led by Bradley and Patton. D'Este (2002, p. 610) also writes that "Montgomery was convinced that Eisenhower would be obliged to give priority to this single-thrust concept" once the operation succeeded. Brighton (2008, p. 335) reads: "If Arnhem succeeded, the Allies would in all probability 'go with a winner' and throw everything into the Montgomery thrust into the Ruhr at the expense of all other operations. They would then be operating to Montgomery's single-thrust strategy and, as the army commander on the spot, he could expect that any 'request' for overall command would be granted. We must suspect that he took the risk at Arnhem because it was the only operation that would, in one stroke, allow him to get his way – in command and in strategy – and enable him to direct the war to the early end that he genuinely believed was possible."

> thorizing Market–Garden …but doing so within carefully prescribed limits. Eisenhower's recourse was to allow – indeed, order – Montgomery to proceed with a doomed operation that would test the validity of his idea that the Germans were incapable of further resistance.

According to David Eisenhower (1986, p. xxiii) (summarized by Baxter, 1999, p. 102), his grandfather knew that "Montgomery would be effectively silenced" by "a severe if local setback in Holland" and "must fail and be placed thereafter in [a] subordinate role."[49] In other words, Eisenhower was pursuing mutually exclusive payoffs with the confidence of being proven correct in the experiment, following exactly the logic of our main result. Given these interpretations, Operation Market–Garden was indeed a "silver bullet" for both Eisenhower and Montgomery, but, rather than to defeat Hitler, this "silver bullet" is more for them to win the political competition between the Anglo–American cousins.

The good fit of our model is further strengthened by the aftermath of Operation Market–Garden, which was consistent with the existence of significant mutually exclusive payoffs. Churchill (1959, p. 881) and Montgomery (1947, p. 149) denied that Market–Garden failed, by claiming "a decided victory" that was "ninety per cent successful."[50] As noted by D'Este (2002, p. 618), Montgomery scapegoated Generał Brygady Stanisław Sosabowski, who had seriously opposed the plan beforehand but still commanded the Polish 1st Independent Parachute Brigade with a gallant battle in the operation. Despite taking responsibility as the Supreme Commander, Eisenhower (1970, p. 2135)'s pleasure in being proven correct was clear and consistent: "What this action proved was that the idea of one 'full-blooded thrust' to Berlin was silly."[51] After Market–Garden, Eisenhower gained a much stronger position in his argument with Montgomery and even Churchill. Grigg (1993, p. 110) notes that "there was surely a strong case for removing" Montgomery "after Arnhem." Ambrose (1990, p. 167) also notes that, at that time, "Montgomery knew full well that if Eisenhower told

[49]Coble (2009, p. 32) also comments that "Eisenhower sacrificed an Allied division to allow Montgomery to prove" that the single-thrust strategy was wrong.

[50]Montgomery (1958, p. 265–266) summarized four main reasons for the failure of the operation: 1) low priority of the operation in Eisenhower's agenda; 2) his own mistake in deciding where to drop airborne forces; 3) bad weather; and 4) incorrect estimates of the strength of the German Panzer Corps. He took responsibility for only one of the four reasons. Montgomery (1958, p. 267) further stated that the operation "would have succeeded *in spite of* my mistake", and that "I remain Market–Garden's unrepentant advocate."

[51]Eisenhower (1948, p. 307) also hinted at attributing the decision of Market–Garden to Montgomery, as his memoir reads abruptly: "Montgomery was very anxious to attempt the seizure of the bridgehead."

the CCS it was 'him or me,' Eisenhower would win."[52] For Eisenhower, the Anglo–American balance within the leadership of the Allied Forces became more stable, and the Allied (and the American) interests were better secured. These observations also support our story over a competing explanation, along the line of Hirsch (Forthcoming), that Eisenhower and Montgomery agreed upon Operation Market–Garden only to convince the other: If so, there would not have been such a sharp difference between the attitudes of Eisenhower and Montgomery toward the experiment's result and such a serious impact on the balance between the Anglo–American cousins in ensuring the political competition. We conclude that the setting, prediction, and logic of our model well fit the Eisenhower–Montgomery dispute and the decision concerning Operation Market–Garden.

2.9 Concluding Remarks

In this paper, we propose and formalize the mechanism of Machiavellian experimentation, positing that polarization of beliefs could make decision makers agree to policy experimentation if they are pursuing significant mutually exclusive payoffs from being proven correct by the result of the experimentation. This mechanism contrasts with conventional thinking that experimentation requires moderate but not extreme beliefs.

Several extensions can be made. For example, one can model the micro-foundations of contingent, mutually exclusive payoffs. After the initial strategy adoption problem, there could be a separate bargaining game between the two players, and the mutually exclusive payoffs in the strategy adoption problem could be a potential increase or decrease in the parties' relative bargaining power in the bargaining game. In extreme cases, the result of the experiment could wipe the player proven incorrect out of the bargaining game. More micro-foundational analysis could include reputation concerns (e.g., Levy, 2007a,b), intra-group conflicts (e.g., the survey by Jehn and Bendersky, 2003), and linkage between issues, an important topic in international cooperation and conflict resolution (e.g., Haas, 1980;

[52]The CCS is the abbreviation of the Combined Chiefs of Staff for the western Allies. Ambrose (2012, p. 533) also states that after Market–Garden, "almost all Eisenhower's associates, British and American, agreed that the Supreme Commander was more tolerant of strong dissent from Montgomery than he should have been." "In its way it was a repeat performance of Goodwood, when the feeling at SHAEF and among the American field commanders was that Montgomery should have been relieved." SHAEF is the abbreviation of the Supreme Headquarters Allied Expeditionary Force.

McGinnis, 1986; Davis, 2004).

Another interesting extension would be some comparative statics around the informativeness of the experiment. On the one hand, in terms of the mutually inclusive payoff, if the experiment does not immediately reveal whether the new policy will work, then experimentation will become less favorable for both players, *ceteris paribus.* On the other hand, a less informative experiment should make the mutually exclusive payoffs smaller, since the experiment's result is less convincing. One can pursue this extension further by endogenizing the scale of experimentation.

The key logic of our result can be applied to many other situations. We conclude by mentioning one of them. We consider a transaction in financial markets to be an adoption of an ownership transfer of a financial asset with the mutual consent of the seller and the buyer. The transaction will prove whether the buyer's (or the seller's) belief on a rising (or decreasing) price in the future is correct or incorrect, and being proven correct (or incorrect) results in profit (or loss). The key logic in our model implies straightforwardly that, in the period when the market beliefs about the future change of the price of a financial asset are more heterogeneous, we should see larger trading volume or higher turnover than in the period with less heterogeneous beliefs. This thinking is at the heart of the studies on the implications of heterogeneous beliefs for financial markets (e.g., Varian, 1989; Harris and Raviv, 1993; Kandel and Pearson, 1995; surveys by Hong and Stein, 2007; Xiong, 2013).

Chapter 3

Water-storage Capacities versus Water-use Efficiency: Substitutes or Complements?

3.1 Introduction

Are water conservation or, more precisely, input-efficiency improvement in water use, and water-storage capacities substitutes? By the conventional wisdom the answer is yes: water-use efficiency improvement will decrease the demand for water-storage capacities. In this paper, however, we shall challenge this conventional wisdom and argue that it is possible that water-use efficiency improvement could increase the demand for water-storage capacities and, even more interestingly, this complementarity could happen even if water-use efficiency improvement decreases the water demand.

This paper is under the larger background about water scarcity, which is among the most important constraints limiting social and economic development throughout the world. Climate change will make the constraint even tighter (e.g., the Intergovernmental Panel on Climate Change – Jiménez Cisneros et al., 2014).[1] There have been many approaches in

[1] Jiménez Cisneros et al. (2014, p. 251) state: "water resources are projected to decrease in many mid-latitude and dry subtropical regions, and ...even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage."

water-resource management to tackling water scarcity and adapting to climate change. For example, water infrastructures like dams, reservoirs, and canals can be built to increase water supply (e.g., Yeh, 1985; Simonovic, 1992; Graf, 1999). Conservation in water demand and water-use efficiency improvement, by which we mean increasing input efficiency in water use, e.g., water recycling and reuse, more-efficient irrigation technologies like drip irrigation, and investment in conveyance reducing evaporation and leaking loss, can be adopted (e.g., Caswell, 1991; Chakravorty et al., 1995; Sunding and Zilberman, 2001; Schoengold and Zilberman, 2007). Institutional reforms about water markets and water pricing can be initiated (e.g., Hanke and Davis, 1973; Burness and Quirk, 1979; Sampath, 1992; Easter et al., 1999; Dinar, 2000). Many other approaches are also promising, e.g., research and development in drought-tolerant varieties and biological technologies (e.g., McCue and Hanson, 1990; Kasuga et al., 1999; Wang et al., 2003; Gosal et al., 2009). In this paper, however, we do not focus on any single approach. Instead, we focus on economic relations among different approaches, and, more precisely, we investigate whether higher water-use efficiency will increase or decrease the marginal benefit of or (inverse) demand for water-storage capacities.

This investigation is important to the lasting and important debate about infrastructure investment in water-resource management. Dams, reservoirs, and other water-storage facilities have been providing huge benefits in the agricultural, energy, and urban sectors and contributing substantially to human civilizations, but have also frequently been accompanied with huge environmental, ecological, social, and economic cost.[2] Without fully recognizing these costs, dams have been overbuilt, causing major struggles across the world (e.g., Reisner, 1993; Jackson and Sleigh, 2000; McCully, 2001; Fischhendler and Zilberman, 2005; Duflo and Pande, 2007). Improving water-use efficiency is then increasingly perceived as an important alternative to dam building (e.g., the World Commission on Dams, 2000; Gleick et al., 2003; Cooley et al., 2008; Schwabe and Connor, 2012; the World Wide Fund

[2]Dams have turned deserts in California's Central Valley into one of the most productive agricultural regions in the world, have survived large cities in Northern China like Beijing through the periodic droughts in the area, and, in Reisner (1993, p. 162–164)'s words, have produced "American hydroelectric capacity that could turn out sixty thousand aircraft in four years," which "simply outproduced" the Axis and helped the Allies win the Second World War. The benefits are not costless. For example, when dams are built, the natural environment is seriously altered, in many cases irreversibly, and the salmon and other aquatic species are endangered. Sometimes numerous families are displaced and historic and cultural sites are covered. Huge potential loss associated with the dam failure risk is also created. For the recent debate on the cost-benefit accounting about large dams, see Ansar et al. (2014) and Nombre (2014).

for Nature, 2014; Olen et al., Forthcoming), and the United States Water Resources Council (1983)'s *Principles and Guidelines* for the United States Army Corps of Engineers to assess water projects has also been criticized as often overemphasizing structural measures but overlooking this alternative (e.g., Zilberman et al., 1994; the World Commission on Dams, 2000). Under this background, in many major water-policy debates, e.g., in response to the devastating Californian drought since 2012, water-storage investment and water-use efficiency improvement have been fiercely competing for limited resource.[3] Some even see this competition "as an either-or scenario" between these two approaches (e.g., Tom Stokely quoted by Fimrite, 2014).

This competition has often been resulted from the conventional wisdom that water-use efficiency and water-storage capacities are substitutes (e.g., Gleick et al., 2003, p. 1; Alizadeh and Keshavarz, 2005, p. 101; International Rivers, 2011, p. 4; Chiras, 2012, p. 256; the World Wide Fund for Nature, 2014; Beard, 2015). For example, American Rivers and International Rivers (2004, p. 28) argue that more-efficient irrigation technologies "could increase water efficiency to the level that the need for some dams could be eliminated." The reasoning behind this conventional wisdom is that higher water-use efficiency should decrease the demand for water, the demand for water-storage capacities depends on the demand for water, so higher water-use efficiency should decrease the demand for water-storage capacities (e.g., Cooley et al., 2008; the World Wide Fund for Nature, 2014). We propose two challenges, however, to this conventional wisdom and reasoning. Formalizing these challenges later in the paper, we shall now brief the ideas and their relevance.

First, higher water-use efficiency could increase the water demand. This possibility has been theoretically established (e.g., Caswell and Zilberman, 1986; the survey by Schoengold

[3]Goodhue and Martin (2014) and Howitt et al. (2014, 2015) present estimates of the loss caused by the drought. As a result of the drought, in January 2014, the California Department of Water Resources announced the first zero water allocation from the California State Water Project in the Project's 54-year history. In April 2015, the Governor of California, Jerry Brown, directed the first ever statewide mandatory water reductions. For an example of media coverage on the severeness of the drought, see Serna (2014) and Walton (2015). In response to this Californian drought, lawmakers have been working at both federal and state levels to authorize and fund expansions of water infrastructures, as many studies have documented huge benefit from water projects in reducing the drought impact in the western United States (e.g., Hansen et al., 2011, 2014; Howitt et al., 2011; Zilberman et al., 2011). Opponents of infrastructure expansions, however, think that money should be spent only to subsidize recycling projects and conservation-technology adoption, as they believe that the efficiency improvement will lead to smaller and fewer dams demanded and that dam expansions would severely discourage conservation effort. For examples of the debate, see Calefati (2014), Dunning and Machtinger (2014), Fimrite (2014), and Hanson (2015).

and Zilberman (2007)) and empirically observed across the world (e.g. Scheierling et al. (2006b); Ward and Pulido-Velazquez (2008); the European Commission (2012); Pfeiffer and Lin, 2014; the survey by Berbel et al. (2015)). The reasoning is intuitive: given any water price, higher water-use efficiency decreases the price of effective water, and the effective water use will increase even more than the decrease in the price of effective water, which is the increase in water-use efficiency, if and only if the demand for water is elastic. A larger increase in effective water than the increase in water-use efficiency suggests that a larger amount of gross water use is demanded, usually accompanied by irrigation-land expansion (e.g., Dinar, 2014). Along this logic, since higher water-use efficiency could increase the water demand, it could increase the demand for water-storage capacities. Some scholars have also seen some anecdotes following this logic (e.g., Xu, 2015).

Second, even if higher water-use efficiency decreases the water demand, it could still increase the demand for water-storage capacities, because the marginal benefit of water-storage capacities depends not only on the marginal benefit of water, which is about the water demand, but also on the probability that the dam would reach its full capacity in the future: if the dam would never reach the full capacity, any additional dam capacities would be useless. In this paper, we shall identify sufficient conditions under which higher water-use efficiency will change the control rule of water inventories so that it would be optimal to increase the amount of water to be stored now. When more water is stored now, the dam will have less room to hold future inflows, so it will be more likely to reach the full capacity in the future. If the increase in the full-dam probability is sufficiently significant, then higher water-use efficiency can increase the marginal benefit of water-storage capacities, even if it causes a lower water demand.

Around the relevance of this second challenge some questions might arise. First, are dams ever full? The answer is: yes, and the full-dam probability is often strictly not zero. For example, the main reservoir of the California State Water Project, Lake Oroville, has seen positive overflows in 57% of the years over 1975–2010, when the dam was not able to capture any more water in the wet season for the dry season. Second, how relevant is that higher water-use efficiency will increase the tendency to store in optimal control of water inventories? As the point we make is novel, to our knowledge, in the literature there is no empirical evidence in either way. Our analysis is still useful, because we can help to explain numerical results in practice given linear, isoelastic, exponential, non-parametric, or any arbitrary specifications of the water benefit or demand. Third, could the increase in the full-dam probability, if there is any, really dominate a decrease in the water demand and generate a higher demand for water-storage capacities? In this paper, we address this question with a numerical illustration based on the irrigation water-inventory management problem of the California State Water Project, which, according to the California Department of Water Resources (1963–2013), is "the largest state-built, multipurpose, user-financed water project" in the United States and "irrigates about 750000 acres of farmland" in 2010. In this numerical illustration, using an empirically relevant specification, we show that it is possible that a higher full-dam probability can dominate a lower water demand so that higher water-use efficiency can eventually increase the marginal benefit of water-storage capacities, at least in this specific but important case.

To formalize our ideas, we unfold this paper as follows: We start in Section 3.2 by building a simple model for capacity choices of dams, incorporating stochastic, dynamic control of water inventories and efficiency in water use, while holding constant site selection (e.g., Bıçak et al., 2002; the International Commission on Large Dams, 2007) and other important issues in dam design (e.g., Hall, 1984; the International Union for Conservation of Nature and World Bank, 1997; Hurwitz, 2014). Operation of the dam involves two periods. In each period, the dam first catches water from a wet season (or water-abundant area) and holds it till the dry season (or transfers it to a water-scarce area), fulfilling its *water-catchment* purpose. In the dry season in the first period, the dam can decide to store how much water to prepare for uncertain inflows in the future, fulfilling its *stochastic-control* purpose.

In Section 3.3, we analyze this model and decompose the impact of water-use efficiency on the marginal benefit of water-storage capacities into a *marginal-water-benefit* channel and a *full-dam-probability* channel, which correspond to the *water-catchment* and *stochastic-control* purposes, respectively. For each of these two channels, we identify the conditions about the properties of the water demand and the marginal productivity of effective water under which the direction of this channel is positive. We then derive the conditions for the possibility that higher water-use efficiency will increase the marginal benefit of water-storage capacities.

In Section 3.4 we discuss the implications of our results for economic development, trade policies, specifications of the water demand or productivity, relation between conservation effort and conservation outcomes, and other policy issues in water-resource management. In particular, we show there could be a duality between water-storage capacities and water-use efficiency: A positive impact of water-use efficiency improvement on the marginal benefit of water-storage capacities could suggest a positive impact of water-storage expansion on the incentive for water-use efficiency improvement. Our analysis also implies that, if water-storage capacities and water-use efficiency are complements, then resources should be distributed in a balanced way between water-storage investment and water-use efficiency improvement, instead of being concentrated on either side, as long as these two approaches are both economical.

Section 3.5 extends the planning horizon of our model to more-than-two or infinite periods with parallel results. This extension facilitates the numerical illustration in Section 3.6. Besides showing the relevance of our theoretical analysis, this illustration suggests that, in the case of the irrigation water-inventory management problem of the California State Water Project, the complementarity between water-storage capacities and water-use efficiency is more prominent in the positive impact of water-use efficiency improvement on water-storage expansions, but not the other way around. We provide concluding remarks in Section 3.7.

Contribution to policy debates and literature. Before we dive into the model, we now summarize our contribution to policy debates and literature. Under the background of the debate between water-storage expansions and water-use efficiency improvement, though not arguing about whether building dams and improving water-use efficiency are economical, our analysis suggests that these two approaches could be mutually inclusive and that the relation between these two approaches varies in different circumstances.

To our knowledge, our paper is the first in the literature on capacity choices of water projects (e.g., Rippl, 1883; Revelle et al., 1969; Nayak and Arora, 1971; Dudley and Burt, 1973; Houck, 1979; Manning and Gallagher, 1982; Miltz and White, 1987; Tsur, 1990; Afshar et al., 1991; Fisher and Rubio, 1997; Edirisinghe et al., 2000; Mousavi and Ramamurthy, 2000; Schoengold and Zilberman, 2007; Haddad, 2011; Houba et al., 2014; Xie and Zilberman, 2016; surveys by Yeh, 1985; Simonovic, 1992) to consider the impact of water-use efficiency under stochastically, dynamic control of water inventories. More generally speaking, applying the analytical approach to the comparative statics on the marginal benefit and optimal choices of storage capacities is also rare in this literature and the literature on optimal inventory management of water (e.g., Burt, 1964; Burness and Quirk, 1980; Riley and Scherer, 1979; Gisser and Sánchez, 1980; Dudley and Musgrave, 1988; Tsur and Graham-Tomasi, 1991; Chatterjee et al., 1998; Freebairn and Quiggin, 2006; Brennan, 2008; Hughes and Goesch, 2009; Truong, 2012) and other storable commodities (e.g., Working, 1933; Gustafson, 1958; Samuelson, 1971; Gardner, 1979; Newbery and Stiglitz, 1981; Knapp, 1982; Wright and Williams, 1982, 1984; Scheinkman and Schechtman, 1983; Deaton and Laroque, 1992; Chambers and Bailey, 1996; Bobenrieth et al., 2002; Asche et al., 2014).[4] As we shall show, our analytical effort is not only technically nontrivial but also instrumental in understanding numerical results in the empirical example.

As we shall discuss in Section 3.4, our results about the impact of water-use efficiency improvement on the marginal benefit of water-storage capacities also shed some light to the question whether water-storage expansion will increase or decrease the incentive for water-use efficiency improvement. This implication contributes to the rich literature on irrigation-technology adoption which considers the impacts of many factors on the adoption and water conservation (e.g., Caswell and Zilberman, 1986; Caswell et al., 1990; Dinar and Yaron, 1992; Dinar et al., 1992; Shah et al., 1995; Green et al., 1996; Khanna and Zilberman, 1997; Carey and Zilberman, 2002; Koundouri et al., 2006; Baerenklau and Knapp, 2007; Schoengold and Sunding, 2014; Olen et al., Forthcoming). Case studies by Amarasinghe et al. (2008) and Oberkircher and Hornidge (2011) suggest that intermediate water storage structures could encourage farmers to adopt more-efficient irrigation technologies, while Bhaduri and Manna (2014) analyze the impact of private water storage given a fixed proportional rule in controlling water inventories. Our implication suggests optimally controlled water-storage capacities as a potential factor affecting irrigation-technology adoption and water conservation. This contribution is important given that large dams and reservoirs usually affect a large number of water users.

Our possibility result about complementarity is further related to resource economics in a broader perspective. The potential positive impact of water-use efficiency on the marginal benefit of water-storage capacities is linked to the rebound effect, also named the Jevons

[4] Fisher and Rubio (1997) have made an admirable attempt in this direction on real-time dam renovations, but their analysis is restricted to the mean level of the equilibrium. Our analysis is applied to the whole equilibrium.

(1865) paradox and the Khazzoom (1980)–Brookes (1992) postulate. In the literature, a positive rebound effect on energy or water use could offset the resource-saving effect of efficiency improvement in the use of resources (e.g., Scheierling et al., 2006b; Ward and Pulido-Velazquez, 2008; the European Commission, 2012; Berbel and Mateos, 2014; Pfeiffer and Lin, 2014; Chan and Gillingham, 2015; Cobourn, 2015; surveys by Greening et al., 2000; Alcott, 2005; Hertwich, 2005; Sorrell, 2009; Berbel et al., 2015). We extend the literature by showing that efficiency improvement could still increase the demand for *storage* investment even if it decreases the temporary demand for *gross consumption* of the resource. The implication about the potential positive impact of water-storage capacities on water-use efficiency improvement is also related to the literature on underinvestment in efficiency improvement of energy and other resource use (e.g., surveys by Jaffe and Stavins, 1994; Jaffe et al., 2004; Gillingham et al., 2009; Linares and Labandeira, 2010; Allcott and Greenstone, 2012; Gerarden et al., 2015a,b). Our implication adds underinvestment in storage of resources to the list of potential factors inducing underinvestment in resource-use efficiency.

Last, but not least, our results and implications have some counterintuitive implications for the rich body of literature on the relation between infrastructure investment and resource conservation (e.g., on roads and deforestation, Chomitz and Gray, 1996; Nelson and Hellerstein, 1997; Pfaff, 1999; Cropper et al., 2001; Deng et al., 2011; on roads and groundwater depletion, Chakravorty et al., 2015). In particular, increasing concerns about environmental externality that lead to smaller dams could also lead to less conservation effort like adoption of more-efficient irrigation technologies. At the same time, the huge progress and potential of this adoption across the world (e.g., Postel, 2013) could increase the demand for water-storage investment and will eventually increase consumptive use of water and environmental damage, even though both of the outcomes are optimal from the efficiency perspective that takes market and environment considerations into account. This implication is consistent with and more than the emerging agreement among water economists that adoption of efficient irrigation technologies often leads to higher consumptive/effective use of water (e.g., the International Water Resource Economics Consortium, 2014).

3.2 The Two-period, Stochastic Model

The model has two stages. The second stage is a problem of stochastic, dynamic control of water inventories, given the two key parameters for our purpose – the dam capacity, $\bar{a}$, and water-use efficiency, α. As illustrated by Figure 3.1, we assume that there are two periods, 0 and 1, and that, in each period, a wet season proceeds and a dry season follows. In period 0, the amount of water availability in the wet season, $a_0 > 0$, is stochastic. Given the initial water availability, the dam captures water as much as its capacity allows, $\min\{a_0, \bar{a}\}$. In the dry season, there is no water added to the dam, and the dam chooses how much water to release, $w_0 \in [0, \min\{a_0, \bar{a}\}]$, and how much to store and carry to period 1, $s_0 \equiv \min\{a_0, \bar{a}\} - w_0$. For clarification, we call s_0 the *water storage* and $\bar{a}$ the *dam* or *water-storage capacities*. In period 1, there is a stochastic inflow to the dam in the wet season, $e_1 \in [\underline{e}, \bar{e}]$, where $\underline{e} > 0$. This stochastic inflow is also independent with a_0. The water availability is then

$$a_1 \equiv e_1 + (1 - d)s_0, \tag{3.1}$$

where d is the rate of evaporation between the periods. The dam still captures water of $\min\{a_1, \bar{a}\} \geq 0$. In the dry season, there is still no water added to the dam, and the dam just releases all it has, $w_1 \equiv \min\{a_1, \bar{a}\}$. In each period, the water release, w_t with $t \in \{0, 1\}$, generates the benefit of $B(w_t, \alpha)$.

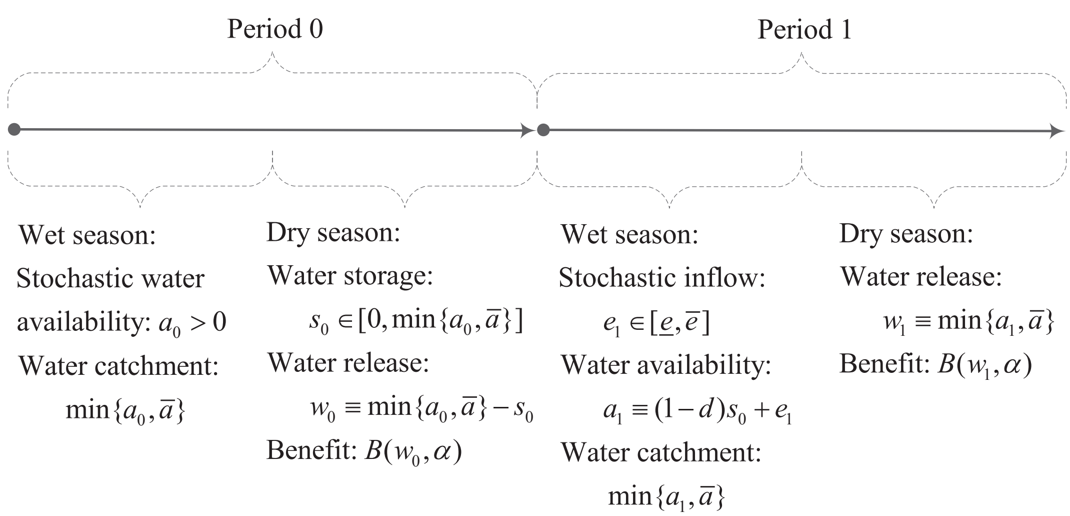


Figure 3.1: Operation of the dam in the two-period, stochastic model

It is important to note that, in this model, the dam capacity has two purposes:

1. The water-catchment purpose: It sets the maximum amount of water that human use deprives from the natural environment and moves between seasons or areas.[5]

2. The stochastic-control purpose: It gives room to control water inventories dynamically and stochastically.

In literature there are alternative ways to model purposes of dam capacities. For example, Fisher and Rubio (1997) and Hughes and Goesch (2009) assume that dams only have the stochastic-control purpose and that spills generate irrigation benefit as regulated water release does. Considering highly seasonal inflows, in our model, we recognize the water-catchment purpose of dams and assume that spills in wet seasons are not captured so it cannot be utilized to generate benefit. This approach is consistent with some economic models (e.g., Truong, 2012) and most dam models in applied probability theory (e.g., Moran, 1959).

It is also important to note that the dam capacity in the model is the maximum of the amount of water that could be captured in wet seasons and held to dry seasons, not the literal volume of the reservoir, and it could be determined by technological, managerial, and institutional constraints. When we state “the dam is full,” we do not mean that the reservoir is literally full; we mean that these technological, managerial, and institutional constraints make any additional water catchment impossible.

Following the idea of Caswell and Zilberman (1986), we further assume that the function of water benefit, $B(w_t, \alpha)$, is the benefit generated by effective water, $\mathcal{B}(\alpha w_t)$. In other words, α measures input efficiency – the proportion of applied water that is effectively used. Adopting more-efficient irrigation technologies and improving conveyance would then increase $\alpha \in [0, 1]$.[6] We assume that regular assumptions, such as $\mathcal{B}''(\cdot) < 0$, $\mathcal{B}''(\cdot)$ is continuous almost everywhere, and $0 < \mathcal{B}'(\cdot) < \infty$, also apply here. For terminology, we

[5] The wet season and the dry season can also be interpreted as a water-abundant area and a water-scarce area.

[6] Chakravorty et al. (1995, 2009) have discussed the optimal design of the distribution and allocation system. As the economics of the distribution and allocation system is not our paper's main focus, we leave the functioning of the system out of the model. The function $B(\cdot, \cdot)$ can include agricultural, industrial, and environmental benefit and any other outcomes of the dams that depend on water storage or release, e.g., drought relief and flood control. For a general description of the various benefit generated by dams, see the World Commission on Dams (2000). The function of the benefit of water release has already accounted for any downstream economic distortions.

call $B_1(w_t, \alpha) \equiv \alpha\mathcal{B}'(\alpha w_t)$ the marginal benefit of (or derived inverse demand for) water (release), which happens only in dry seasons in this model.[7]

Under the stochastic, dynamic control of water inventories, given the distributions of a_0 and e_1, the (gross) value that is generated by the dam is

$$W^*(\bar{a}, \alpha) \equiv \mathbf{E}\left[V^*(\bar{a}, a_0, \alpha)\right], \text{ where}$$

$$V^*(\bar{a}, a_0, \alpha) \equiv \max_{w_0, s_0} \left\{B(w_0, \alpha) + \rho\mathbf{E}_0\left[B(w_1, \alpha)\right]\right\} \qquad \text{s.t.} \tag{3.2}$$

$$s_0 \geq 0,\ w_0 = \min\{a_0, \bar{a}\} - s_0 \geq 0,\ a_1 = (1-d)s_0 + e_1,\ w_1 = \min\{a_1, \bar{a}\}, \tag{3.3}$$

where ρ is the discount factor. The water-inventory management problem given the initial water availability is equivalent to

$$V^*(\bar{a}, a_0, \alpha) \equiv \max_{s_0} \left\{B(\min\{a_0, \bar{a}\} - s_0, \alpha) + \rho\mathbf{E}_0\left[B(\min\{(1-d)s_0 + e_1, \bar{a}\}, \alpha)\right]\right\} \text{ s.t.} \tag{3.4}$$

$$s_0 \geq 0,\ \min\{a_0, \bar{a}\} - s_0 \geq 0. \tag{3.5}$$

The first stage of the model is about the choice of the dam capacity. Taking water-use efficiency, α, and the distributions of a_0 and e_1 as given, the dam designer maximizes the dam generated value, $W^*(\bar{a}, \alpha)$, net of the construction, maintenance, and environmental-damage cost, $C(\bar{a})$, by choosing the dam capacity, $\bar{a}$:

$$\max_{\bar{a} \geq 0} \qquad W^*(\bar{a}, \alpha) - C(\bar{a}). \tag{3.6}$$

This decision can also be interpreted as how much to adjust the total water-storage capacity of a huge water system by introducing a new dam or removing an old dam.[8] Especially for large dams, the dam cost should also include social cost, for example, displacement of residents and demolishing of historical and cultural sites. The environmental-damage cost should also include the opportunity cost of the water that is captured by the dam and would

[7]For generality and simplicity we use this most general specification of the water benefit. It is open to different interpretations. For example, it can be interpreted as the profit earned by a representative water user, $B(w, \alpha)$, who uses up any water release, w, with a zero price, as long as the marginal profit is nonnegative. It can also be interpreted as the sum of the water-price charge and the profit of a representative water user who chooses the amount of water use, x, not larger than water release, w, given water-use efficiency, α, and the water price, $c = B_1(w, \alpha)$, maximizing the water-use benefit, $B(x, \alpha)$ net of the water-price charge, cx.

[8]Readers might think $a_0 \equiv e_0$, the inflow into the dam in the first wet season. For simplicity, we leave a_0 in the dam generated value function without specifying it.

be used instead for other environmental and ecological purposes, for example, surviving aquatic species, in the form of overflows. The marginal-cost function is assumed positive and increasing, which means that $C'(\cdot) > 0$ and $C''(\cdot) > 0$.[9]

The first-order condition for the dam-capacity choice is

$$W_1^*(\bar{a}, \alpha) = C'(\bar{a}). \tag{3.7}$$

The left-hand side is the marginal benefit of or (inverse) demand for dam capacities. The right-hand side is the marginal cost of dam capacities. Assuming interior solution, the optimal dam capacity, $\bar{a} = \bar{a}^*$, should make the marginal benefit and marginal cost break even. A change in water-use efficiency, e.g., adopting drip irrigation or reducing conveyance-leaking loss, will change the marginal benefit of dam capacities, and, therefore, could change the optimal dam capacity.

In this paper, we focus on the impact of water-use efficiency, α, on the left-hand side of this first-order condition – the marginal benefit of dam capacities, $W_1^*(\bar{a}, \alpha)$.

3.3 Analysis and Results

We first look at the marginal benefit of dam capacities. This investigation starts from the problem of stochastic, dynamic control of water inventories. There could be three scenarios of storage–release decisions in period 0:

1. Zero release: $w_0^* = 0$, $s_0^* = \min\{a_0, \bar{a}\}$;

2. Positive storage (and positive release): $w_0^* = \min\{a_0, \bar{a}\} - s_0^* \in (0, \min\{a_0, \bar{a}\})$;

3. Zero storage: $w_0^* = \min\{a_0, \bar{a}\} > 0$, $s_0^* = 0$.

About the three scenarios, first, note that optimal management of water inventories will not allow the zero-release scenario: If all of the captured water in period 0 is stored, the

[9] The assumption is not too unrealistic, since the resource for dam building and maintenance is always limited. As larger dams make the ecological system more vulnerable to further human actions, it is also fair to assume an increasing marginal environmental-damage cost. Furthermore, the assumption makes the dam-capacity problem have solutions.

marginal benefit of water release in period 0 will be so high that releasing even a tiny bit of water will be beneficial.[10]

Second, if the positive-storage scenario happens under optimal management of water inventories, the dam generated value given a_0 will be

$$V^*(\bar{a}, a_0, \alpha) = B(\min\{a_0, \bar{a}\} - s_0^*, \alpha) + \rho \mathbf{E}_0 \left[B(\min\{(1-d)s_0^* + e_1, \bar{a}\}, \alpha)\right] \tag{3.8}$$

with an Euler equation,

$$B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) = \rho(1-d)\mathbf{E}_0 \left[I_{(1-d)s_0^* + e_1 \leq \bar{a}} \cdot B_1((1-d)s_0^* + e_1, \alpha)\right]. \tag{3.9}$$

The left-hand side of this equation is the cost of a marginal increase in the amount of water to be stored, which is the current marginal benefit of water. The right-hand side is the benefit that the marginal increase will generate, which is discounted, expected future marginal benefit of water. Note that the marginal increase will not generate any benefit if the dam is full in the future, because, in this case, the dam will not be able to capture the additional water. The equation implies that the optimal water storage, $s_0^* \equiv s_0^*(\bar{a}, a_0, \alpha)$, should make the two sides – the marginal cost and the marginal benefit of water storage – equal to each other, because, otherwise, the dam operator would be able to improve the dam generated value by adjusting the storage-release decision.

Third, if the zero-storage scenario happens under optimal management of water inventories, the dam generated value given a_0 will be

$$V^*(\bar{a}, a_0, \alpha) = B(\min\{a_0, \bar{a}\}, \alpha) + \rho \mathbf{E}_0 \left[B(\min\{e_1, \bar{a}\}, \alpha)\right] \tag{3.10}$$

with an Euler inequation,

$$B_1(\min\{a_0, \bar{a}\}, \alpha) \geq \rho(1-d)\mathbf{E}_0 \left[I_{e_1 \leq \bar{a}} \cdot B_1(e_1, \alpha)\right], \tag{3.11}$$

which means that it is not beneficial to store even a tiny bit of water.

[10] To see this point, suppose that it is optimal to store all of the captured water in period 0 for period 1. An Euler inequation, $B_1(0, \alpha) \leq \rho(1-d)\mathbf{E}_0 \left[I_{(1-d)\min\{a_0, \bar{a}\} + e_1 \leq \bar{a}} \cdot B_1\left((1-d)\min\{a_0, \bar{a}\} + e_1, \alpha\right)\right]$, must hold. This is impossible, however, because $\rho(1-d)\mathbf{E}_0 \left[I_{(1-d)\min\{a_0, \bar{a}\} + e_1 \leq \bar{a}} \cdot B_1\left((1-d)\min\{a_0, \bar{a}\} + e_1, \alpha\right)\right] \leq B_1(\min\{\underline{e}, \bar{a}\}, \alpha) < B_1(0, \alpha)$.

In the positive-storage and the zero-storage scenarios, the marginal benefit of dam capacities is

$$\begin{aligned} W_1^*(\bar{a}, \alpha) &= \mathbf{E}\left[V_1^*(\bar{a}, a_0, \alpha)\right] \\ &= \mathbf{E}\left[I_{a_0 > \bar{a}} \cdot B_1(\bar{a} - s_0^*, \alpha) + \rho B_1(\bar{a}, \alpha)\mathbf{P}\left[(1-d)s_0^* + e_1 > \bar{a} | a_0\right]\right] \\ &= B_1(\bar{a} - \bar{s}, \alpha) \cdot \mathbf{P}\left[a_0 > \bar{a}\right] + \rho B_1(\bar{a}, \alpha)\mathbf{E}\left[\mathbf{P}\left[(1-d)s_0^* + e_1 > \bar{a} | a_0\right]\right], \end{aligned} \tag{3.12}$$

where $\bar{s}$ denotes $s_0^*(\bar{a}, a_0, \alpha)$ for $a_0 \geq \bar{a}$. This expression carries important intuition: If and only if the dam was full in a wet season, which corresponds to $a_0 > \bar{a}$ or $(1-d)s_0^* + e_1 > \bar{a}$, a marginal increase in dam capacities will help to capture some additional water, generating the marginal benefit of water release in the following dry season, which is $B_1(\bar{a} - \bar{s}, \alpha)$ or $B_1(\bar{a}, \alpha)$.

As illustrated by Figure 3.2, this expression is instrumental in helping us understand the impact of water-use efficiency on the marginal benefit of dam capacities in our model. The marginal benefit of dam capacities, by Equation 3.12, is determined by, first, the marginal benefits of the dry-season water release given the dam was full in the former wet season, $B_1(\bar{a} - \bar{s}, \alpha)$ and $B_1(\bar{a} - \bar{s}, \alpha)$, and, second, the (expected) probabilities that the dam will be full in wet seasons, $\mathbf{P}\left[a_0 > \bar{a}\right]$ and $\mathbf{E}\left[\mathbf{P}\left[(1-d)s_0^* + e_1 > \bar{a} | a_0\right]\right]$. Therefore, if we would like to understand the impact of water-use efficiency on the marginal benefit of dam capacities, we need to know how a change in water-use efficiency will change those marginal benefits, through a *marginal-water-benefit channel,* and how this water-use efficiency change will change those full-dam probabilities, through a *full-dam-probability channel.*

When water-use efficiency improvement will increase/decrease those marginal benefits (or full-dam probabilities), we call that the marginal-water-benefit channel (or the full-dam-probability channel) is positive/negative. If both channels are positive, then we can claim that water-use-efficiency will increase the marginal benefit of dam capacities and water-use efficiency and water-storage capacities are complements. If both channels are negative, then water-use efficiency and water-storage capacities are substitutes. If one of these two channels is positive and the other is negative, then, without the help of numerical investigation, we will not be able to identify whether water-use efficiency and water-storage capacities are substitutes or complements, and it would be extremely unwise to simply rule out the possibility of complementarity (and substitution) at this stage.

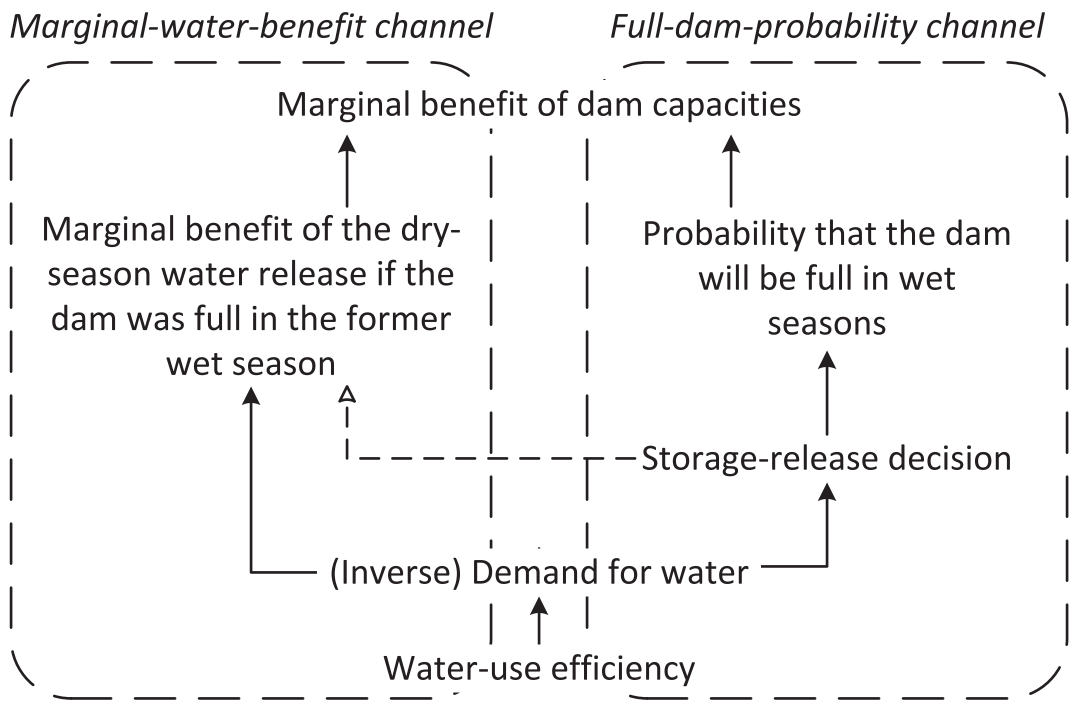


Figure 3.2: Overview of the impact of water-use efficiency on the marginal benefit of dam capacities

That said, what theoretical analysis can provide is to help us identify the directions of the these two channels separately. On the *marginal-water-benefit channel,* as shown by Figure 3.2 and the expressions of $B_1(\bar{a}-\bar{s},\alpha)$ and $B_1(\bar{a}-\bar{s},\alpha)$, an increase in α, water-use efficiency, can change the inverse demand for dry-season water release, $B_1(\cdot,\alpha)$, which will exert a direct impact on the marginal benefits, $B_1(\bar{a}-\bar{s},\alpha)$ and $B_1(\bar{a}-\bar{s},\alpha)$. An increase in α can also affect $B_1(\bar{a}-\bar{s},\alpha)$ indirectly by changing the optimal amount of water to be stored in the first dry season when the dam was full in the first wet season, $\bar{s}$, and, therefore, the optimal amount of water to be released, $\bar{a}-\bar{s}$. As we shall shown soon, the aggregate direction of this marginal-water-benefit channel will be determined by the direction of the direct impact – whether water-use efficiency will shift up or down the inverse demand for water release, which depends on the water-demand elasticity and, equivalently, the elasticity of the marginal productivity of effective water, $\text{EMP} \equiv -\frac{\alpha w \mathcal{B}''(\alpha w)}{\mathcal{B}'(\alpha w)}$ in our model.

On the *full-dam-probability channel,* as shown by Figure 3.2 and the expression of $\mathbf{E}\big[\mathbf{P}[(1-d)s_0^*+e_1>\bar{a}|a_0]\big]$, an increase in α, water-use efficiency, could change the optimal inventory control, s_0^*, by changing the inverse demand for water release, and this change will change the full-dam probability: if more water is stored now, the dam will have less room to hold future inflows and, therefore, it will become more likely to reach its full capacity given the distribution of the future inflows. Again, we shall show soon a sufficient condition under which water-use efficiency improvement will encourage more water to be stored and, therefore, this full-dam-probability channel will be positive. This sufficient condition will turn out to be related to the second-order elasticity of the marginal productivity of effective water, SEMP $\equiv -\frac{\alpha w \mathcal{B}'''(\alpha w)}{\mathcal{B}''(\alpha w)}$, in our model.

We can summarize our overview as the following lemma.

Lemma 1 (Two channels)**.** *The impact of water-use efficiency, α, on the marginal benefit of dam capacities, $W_1^*(\bar{a}, \alpha)$, can be decomposed into the marginal-water-benefit channel and the full-dam-probability channel. Mathematically,*

$$W_{12}^*(\bar{a}, \alpha) = \left(B_{12}(\bar{a} - \bar{s}, \alpha) - B_{11}(\bar{a} - \bar{s}, \alpha) \frac{\partial \bar{s}(\bar{a}, \alpha)}{\partial \alpha} \right) \cdot \mathbf{P}[a_0 > \bar{a}] + \rho B_{12}(\bar{a}, \alpha) \cdot \mathbf{E}\left[\mathbf{P}\left[e_1 > \bar{a} - (1-d) s_0^* | a_0\right]\right] \rho(1-d) B_1(\bar{a}, \alpha) \cdot \mathbf{E}\left[f_{e_1}\left(\bar{a} - (1-d) s_0^*\right) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \right], \tag{3.13}$$

where $s_0^* \equiv s_0^*(\bar{a}, a_0, \alpha)$ is the optimal water storage given the dam capacity, the initial water availability, and water-use efficiency, $F_{e_1}(\cdot)$ is the cumulative distribution function of the future inflow, and $f_{e_1}(\cdot)$ is the probability density function of the future inflow. The marginal-water-benefit channel is represented by the first two terms in the right-hand side of Equation (3.13), while the full-dam-probability channel is represented by the third term.

The Marginal-water-benefit Channel

Proposition 4 (The marginal-water-benefit channel)**.** *The impact of water-use efficiency on the marginal benefit of dam capacities through the marginal-water-benefit channel will be (weakly) positive if and only if water-use efficiency improvement will increase the inverse demand for water. Mathematically, the sum of the first two terms in Equation (3.13) will be (weakly) positive/negative if $B_{12}(w, \alpha)$ is positive/negative for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$, where $\bar{s}$ denotes $s_0^*(\bar{a}, a_0, \alpha)$ for $a_0 \geq \bar{a}$.*

Appendix B.1 proves Proposition 4. The main intuition is that the indirect effect caused by water-use efficiency improvement through the change in the optimal water storage, if there is any, will not be able to revert the direct effect through the shift in the inverse demand for water.

Proposition 4 emphasizes the impact of water-use efficiency improvement on the marginal benefit of or inverse demand for water. Under what conditions water-use efficiency improvement will increase or decrease the inverse demand for water? The classic answer is that water-use efficiency improvement will increase the inverse demand for water if and only if the water demand is elastic. This is because, given any water price, higher water-use efficiency will decrease the price of effective water and increase the amount demanded for effective water. If and only if the water demand is elastic, demanded effective water will increase even more than the decrease in the price of effective water, which is actually the increase in water-use efficiency. In this case, the demanded gross water use increases given any water price, which is equivalent to that the inverse demand for water increases.

We also have another way to look at the conditions under which water-use efficiency improvement will increase or decrease the inverse demand for water. Mathematically, we have

$$B_{12}(w,\alpha) = \frac{d^2\mathcal{B}(\alpha w)}{d\alpha dw} = \mathcal{B}'(\alpha w) + \alpha w \mathcal{B}''(\alpha w). \tag{3.14}$$

Therefore, $B_{12}(w,\alpha) \geq 0$ is equivalent to

$$\text{EMP} \equiv -\frac{\alpha w \mathcal{B}''(\alpha w)}{\mathcal{B}'(\alpha w)} \leq 1, \tag{3.15}$$

where EMP represents the elasticity of the marginal productivity of effective water, which is equal to the inverse of the water-demand elasticity, $-\frac{dw}{dB_1(w,\alpha)} \cdot \frac{B_1(w,\alpha)}{w} = -\frac{\mathcal{B}'(\alpha w)}{\alpha w \mathcal{B}''(\alpha w)}$. Having an elastic water demand or an EMP smaller than one also means that the marginal productivity of effective water declines slow as effective water increases – in other words, the slope of the downward-sloping marginal productivity is flat.

We document this result as a corollary:

Corollary 1 (Demand elasticity, EMP, and slope of the marginal productivity of effective water)**.** *The impact of water-use efficiency on the marginal benefit of dam capacities through the marginal-water-benefit channel will be (weakly) positive if and only if the marginal produc-*

tivity of effective water declines sufficiently slow. Equivalently, the water demand is elastic and the elasticity of the marginal productivity (EMP) of effective water is smaller than one.

Proposition 4 and Corollary 1 follow the established literature on the importance of the EMP in the relation between the water demand and water-use efficiency, which starts with Caswell and Zilberman (1986) and is well noted in other studies (e.g., surveys by Feder and Umali, 1993; Lichtenberg, 2002). Xie and Zilberman (2016) apply this idea to the demand for water projects without inventory management. Proposition 4 and Corollary 1 extend the application to the demand for water-storage capacities with inventory management.

The Full-dam-probability Channel

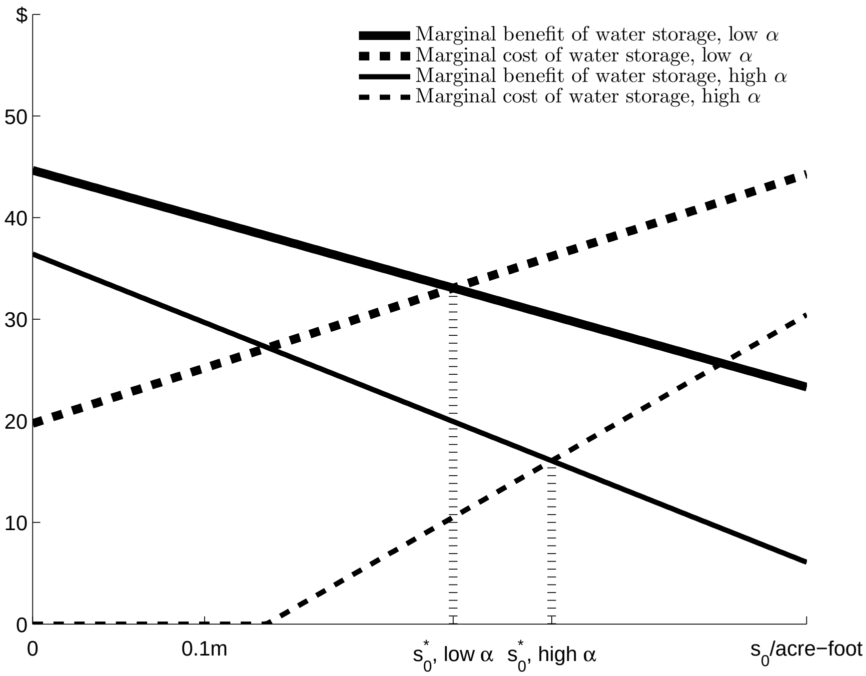
Obviously, if the full-dam probability is zero, or, if it is always optimal to store no water from the first period to the second period, then the full-dam-probability channel will vanish. Therefore, we now assume that the full-dam probability is not zero and there exists some scenario in which it is optimal to store some water in the first dry season. We can then have a sufficient condition under which the full-dam-probability channel is positive.

Proposition 5 (The full-dam-probability channel)**.** *The impact of water-use efficiency on the marginal benefit of dam capacities through the full-dam-probability channel will be (weakly) positive, if water-use efficiency improvement decreases the inverse demand for water and the decrease is larger at larger amounts of water use. Mathematically, the third term in Equation (3.13) will be (weakly) positive if* $B_{12}(w, \alpha) \leq 0$*,* $B_{121}(w, \alpha) \leq 0$*,* $B_{111}(w, \alpha) \leq 0$*, and* $B_{1211}(w, \alpha) \geq 0$ *for any* $w \in [\underline{e}, (1-d)\bar{s} + \bar{e}]$*, where* $\bar{s}$ *denotes* $s_0^*(\bar{a}, a_0, \alpha)$ *for* $a_0 \geq \bar{a}$*.*

Appendix B.2 proves Proposition 5. Figure 3.3 illustrates the intuition in the positive-storage scenario given the initial water availability, a_0, with which it is optimal to store some water in the first dry season. The figure plots the decision of the optimal amount of water to be stored, which is determined by the same Euler equation as Equation (3.9),

$$B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) = \rho(1-d)\mathbf{E}_0 \left[I_{(1-d)s_0^* + e_1 \leq \bar{a}} \cdot B_1((1-d)s_0^* + e_1, \alpha) \right]. \tag{3.16}$$

When water-use efficiency is low, the right-hand side of this equation – the benefit of the marginal increase in the amount of water to be stored – is represented by the bold, solid line. The left-hand side – the cost of the marginal increase – is represented by the bold, dashed line. The optimal amount of water to be stored, $s_0 = s_0^*$, should make these two lines intersect. If higher water-use efficiency decreases the inverse demand for water, both sides of the Euler equation will decrease, just as both of the bold lines will be shifted down to the thin lines. The relative magnitudes of these shifts will then determine how the optimal amount of water to be stored will change.



With $B_{12}(w,\alpha) \leq 0$, $B_{121}(w,\alpha) \leq 0$, $B_{111}(w,\alpha) \leq 0$, and $B_{1211}(w,\alpha) \geq 0$, water-use efficiency improvement will increase the optimal water storage, s_0^*, and the likelihood of the dam reaching the full capacity in the future, $\mathbf{P}[(1-d)s_0^* + e_1 \geq \bar{a}|a_0]$, given a_0. The direction of the full-dam-probability channel is then positive. Specification: $B(w,\alpha) = 181.0 \cdot \alpha x - \frac{1.5\times 10^{-4}}{2} \cdot (\alpha x)^2$, where $x \equiv \min\left\{w, \frac{181.0}{1.5\times 10^{-4}\cdot\alpha}\right\}$, low $\alpha = 0.6$, high $\alpha = 0.8$, $\bar{a} = 2038052$, $a_0 = 0.8\bar{a}$, $d = 0.04$, $\rho = 0.9434$, the probability of $e_1 = 975785$ is 0.8, and the probability of $e_1 = 1536597$ is 0.2

Figure 3.3: An example of water-use efficiency increasing the optimal water storage

For an intuitive explanation, we can roughly consider

$$\mathbf{E}_0\left[B_1((1-d)s_0 + e_1, \alpha)\right] \approx B_1((1-d)s_0 + \mathbf{E}_0\left[e_1\right], \alpha) \tag{3.17}$$

which would be an actual equation if the marginal benefit of water release is linear. The Euler equation can then approximately derive

$$B_1(\min\{a_0, \bar{a}\} - s_0^*, \alpha) \leq B_1((1-d)s_0 + \mathbf{E}_0\left[e_1\right], \alpha). \tag{3.18}$$

This approximation suggests that the current water release, $\min\{a_0, \bar{a}\} - s_0^*$, should roughly be larger than the mean of the future water release, $(1-d)s_0 + \mathbf{E}[e_1]$, because the marginal benefit of water release is declining in the amount of water release. Given this observation, if the decrease in the inverse demand for water caused by water-use efficiency improvement is larger at larger amounts of water use, then the shift in the left-hand side of the Euler equation, which is between the dashed lines, will be larger than the shift in the right-hand side, which is between the solid lines. Therefore, the optimal amount of water to be stored will increase, just as the intersection of the bold lines moves rightwards to the intersection of the thin lines.

Conditions such as $B_{111}(w, \alpha) \leq 0$ and $B_{1211}(w, \alpha) \geq 0$ will help to polish this intuitive argument with technical details, which we leave for Appendix B.2. Finally, this increase in the optimal amount of water to be stored will increase the probability that the dam will be full in the future, because it decreases the room of the dam to hold future inflows.

It is also important to observe that this intuition will hold even if $\rho(1-d)$ is close to one. This observation implies that the different magnitudes of the impacts on the two sides of the Euler equation come from not only the regular "discount-factor effect" but also the properties of the marginal productivity of effective water – the decrease in the inverse demand for water caused by water-use efficiency improvement is larger at larger amounts of water use.

Under what conditions the decrease in the inverse demand for water caused by water-use efficiency improvement is larger at larger amounts of water use? Intuitively, if the decline of the marginal productivity of effective water does not get much slower as effective water increases, then $B_{121}(w, \alpha) \leq 0$. In other words, the marginal productivity of effective water is not extremely convex.

Mathematically, we have

$$B_{121}(w, \alpha) = 2\alpha \mathcal{B}''(\alpha w) + \alpha^2 w \mathcal{B}'''(\alpha w). \tag{3.19}$$

Therefore, $B_{121}(w, \alpha) \leq 0$ is equivalent to

$$\text{SEMP} \equiv -\frac{\alpha w \mathcal{B}'''(\alpha w)}{\mathcal{B}''(\alpha w)} \leq 2, \tag{3.20}$$

where SEMP represents the second-order elasticity of the marginal productivity of effective water.

We document these answers as a corollary.

Corollary 2 (EMP, SEMP, and slope and curvature of the marginal productivity of effective water)**.** *The impact of water-use efficiency on the marginal benefit of dam capacities through the full-dam-probability channel will be (weakly) positive, if the marginal productivity of effective water declines fast and the decline does not get much slower as effective water increases. Equivalently, the elasticity of the marginal productivity (EMP) of effective water is larger than one and the second-order elasticity of the marginal productivity (SEMP) is smaller than two.*

Proposition 5 and Corollary 2 extend the literature's focus on the EMP to the SEMP. This extension is intuitive from the perspective of economic theory. The full-dam-probability channel corresponds to the stochastic-control purpose of dam capacities. An increase in water-use efficiency increases effective water given water use; the change in the control rule of water inventories is determined by the relative impacts of more effective water on the marginal productivity of effective water between the current and the future levels of effective water, so it should be determined by the third-order property of the benefit of effective water. The SEMP is just a measure about the third-order property.

Possibility of Complementarity

Assembling Lemma 1 and Propositions 4 and 5, we can identify the conditions under which complementarity between water-storage capacities and water-use efficiency is possible:

Proposition 6 (Possibility of complementarity)**.** *Water-storage capacities and water-use efficiency could be complements, in the sense that water-use efficiency improvement could increase the marginal benefit of dam capacities:*

- *If the marginal-water-benefit channel is positive, which will happen when water-use efficiency improvement will increase the inverse demand for water;*
- *Or, if the full-dam-capacity channel is positive, which will happen when water-use efficiency improvement will decrease the inverse demand for water and the decrease is larger at larger amounts of water use.*

Mathematically, $W_{12}^{*}(\bar{a}, \alpha)$ *could be positive:*

- *If the sum of the first two terms in Equation (3.13) is positive, which will happen when* $B_{12}(w, \alpha) \geq 0$ *for any* $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$*;*
- *Or, if the third term in Equation (3.13) is positive, which will happen when* $B_{12}(w, \alpha) \leq 0$*,* $B_{121}(w, \alpha) \leq 0$*,* $B_{111}(w, \alpha) \leq 0$*, and* $B_{1211}(w, \alpha) \geq 0$ *for any* $w \in [\underline{e}, (1-d)\bar{s} + \bar{e}]$*.*

Proposition 6 is the main result of this paper. Not only showing the possibility of complementarity, it also shows that the possibility can exist even if water-use efficiency improvement decreases the water demand. As discussed above, this probably counterintuitive result comes from the full-dam-probability channel, which relies on stochastic, dynamic control of water inventories.

We can also write Proposition 6 in terms of the properties of the water demand and the marginal productivity of effective water:

Corollary 3. *Water-storage capacities and water-use efficiency could be complements, in the sense that water-use efficiency improvement could increase the marginal benefit of dam capacities:*

- *If the marginal productivity of effective water declines sufficiently slow;*
- *Or, if it declines fast and the decline does not get much slower as effective water increases.*

Equivalently, dam capacities and water-use efficiency could be complements:

- *If the water demand is elastic, or, equivalently, the EMP is smaller than one;*
- *Or, if water demand is inelastic (or, equivalently, the EMP is larger than one) but the SEMP is smaller than two.*

As Vaux et al. (1981) recognize, the isoelastic and the linear water demands are convenient in econometric studies and influential in policy related researches. We then apply Proposition 6 and Corollary 3 to the two important specifications of the water demand:

Corollary 4 (Isoelastic water demand)**.** *When the water demand is isoelastic, dam capacities and water-use efficiency will be complements, if and only if the water demand is elastic.*

The intuition of Corollary 4 is as follows: A classic result in water-resource economics states that, for isoelastic water demands, water-use efficiency improvement will shift up the marginal benefit of water if and only if the demand is elastic, and this shift will be proportional. Therefore, this shift is just like changing the unit of money so will not change the optimal storage-release decision. The full-dam-probability channel will then disappear. We can then fully identify complementarity through the marginal-water-benefit channel.

Corollary 5 (Linear water demand)**.** *When the water demand is linear, dam capacities and water-use efficiency could be complements:*

- *If the water demand is always in the elastic range, which will be guaranteed when the initial dam capacity is sufficiently small;*
- *Or, if the water demand is always in the inelastic range, which will be guaranteed when the minimum of the inflow is sufficiently large.*

Mathematically, when $\mathcal{B}'''(\cdot) = 0$, $W^*_{12}(\bar{a}, \alpha)$ could be positive:

- *If $\bar{a} \leq \hat{w}$, where $\hat{w}$ solves $-\frac{\alpha\hat{w}\mathcal{B}''(\alpha\hat{w})}{\mathcal{B}'(\alpha\hat{w})} = 1$;*
- *Or, if $\underline{e} \geq \hat{w}$*

The intuition of Corollary 5 is as follows: Another classic result in water-resource economics states that, for linear water demands, first, water-use efficiency improvement will increase the inverse demand for water if and only if the water demand is in the elastic range – the range with small water use and high water prices, which will be guaranteed by a sufficiently small initial dam capacity. Second, along the same logic, a sufficiently large minimum of the inflow will guarantee that water-use efficiency improvement will decrease the inverse demand for water, because the water demand will be in the inelastic range – the range with large water use and low water prices. Third, note that, for linear water demands, the SEMP is always zero, which is smaller than two.

Corollary 5 suggests that, with linear water demand, as long as the elasticity does not vary across one, complementarity between water-storage capacities and water-use efficiency is always possible. It is either because the marginal-water-benefit channel is positive when the water demand is elastic, or because the full-dam-probability channel is positive when the water demand is inelastic and linear.

3.4 Implications

About the Marginal-water-benefit Channel

Our results imply, first, that the marginal-water-benefit channel is important in determining the relation between water-storage capacities and water-use efficiency (especially when the water demand is almost isoelastic). This channel is governed by the first-order impact of water-use efficiency on the inverse demand for water, or, more deeply, whether the marginal productivity of effective water declines slow or fast. Two factors deserve special attentions. The first is land constraints – it is natural to expect and has already been observed that the marginal productivity of effective water should decline much slower, when irrigable land is not constrained and irrigators can expand planted areas, than it does when irrigators have to exploit the constrained irrigable land (e.g., Scheierling et al., 2006b; Berbel and Mateos, 2014; Dinar, 2014; the survey by Berbel et al., 2015). This factor could be important in both of the developed and developing worlds (e.g., the European Commission, 2012; the International Water Resource Economics Consortium, 2014).

The second factor is the stage of the development of water resources. In areas like Western Europe and India where water resources have already been exploited by infrastructure investments (e.g., Shah and Kumar, 2008; Hasanain et al., 2013), it is likely that water-use efficiency improvement will decrease the inverse demand for water use. For areas like sub-Saharan Africa where agriculture is still mainly fed by rain (e.g., Kadigi et al., 2013), the opposite is more likely to hold. Actually, some scholars have already been seeing that, given unconstrained irrigable areas and small initial water-catchment capacities, adoption of more-efficient irrigation technologies is increasing the demand for water and the demand for water-storage projects (e.g., about Xinjiang, a major area of irrigated agriculture in China, Xu, 2015).

Our results also suggest that the elasticity of the water demand is important in determining the direction of the marginal-water-benefit channel. It is well noted that the elasticity of the water demand is highly correlated with the economic properties of the water produced commodity, e.g., irrigated agricultural products or hydropower (e.g., Scheierling et al., 2006a). As an example, the elasticity of the demand for the commodity and the elasticity of the water demand could be positively correlated as long as the production function of the commodity is increasing in water.[11]

This observation carries important policy implications. On the one hand, many small, developing countries are exporting agricultural commodities, and the sector is important for the economy. When their production is small in the world market, they face an almost perfectly elastic demand for the commodity, so the irrigation demand for water could be elastic. In this case, improvements in water-use efficiency, which could result from international aid, could optimally lead to higher demand for irrigation dams needed for the commodity production. This point suggests that the aid tackling water challenges in developing countries should have a joint perspective about international trade, conservation, and water infrastructures.

On the other hand, in cases of dams used to produce nonexported commodities or commodities with low demand elasticities, e.g., electricity and staple food for domestic consumption, the derived demand for water could be inelastic, so dam capacities and water-use efficiency could be substitutes. This point suggests that the joint policy about conservation and water infrastructures should critically depend on the property of the water produced commodity.

About Specifications of the Water Demand

Our results also imply that the functional form of the water demand is critical in determining the complementarity or substitution. Studies find that the irrigation-water demand is usually inelastic (e.g., Moore et al., 1994; Schoengold et al., 2006; Hendricks and Peterson, 2012). An isoelastic, inelastic specification of the water demand suggests that irrigation-dam expansions and conservation-technology adoption should be substitutes. A linear water demand, even if it is inelastic, would still allow the possibility of complementarity.

As Caswell and Zilberman (1986) recognize, the linear water demand is more consistent than the isoelastic demand with the classic three-stage model of the marginal productivity of water in irrigation, in the sense that the EMP varies from zero to infinity as water use increases. The linear water demand is also empirically more relevant, since it can predict heterogenous impact of water-use efficiency improvement on water use with respect to

[11] This argument follows the assumption that the benefit of effective water, $\mathcal{B}(x)$, is equal to the production function of the water produced commodity in effective water, multiplied by the inverse demand for the commodity – the revenue of the commodity production.

different levels of water prices and different amounts of initial water use. Therefore, the linear specification has been considered more proper and has been adopted in describing the irrigation-water demand (e.g., Caswell and Zilberman, 1986; Schoengold et al., 2006; Vicuna, 2007; Quintana Ashwell and Peterson, Forthcoming). Therefore, in the later numerical exercise, we shall emphasize the linear specification more than the isoelastic specification.

Will Larger Dams Decrease the Incentive for Water-use Efficiency Improvement?

Our investigation on how water-use efficiency improvement will change the marginal benefit of dam capacities can also shed some light on how larger water-storage capacities will change the incentive for water-use efficiency improvement. To see this point, consider another model in which the representative water user owning the downstream of the dam is deciding how much to improve water-use efficiency, given water is released from an optimally managed dam with its capacity being $\bar{a}$. Her program will be

$$\max_{\alpha \in [0,1]} \qquad W^*(\bar{a}, \alpha) - G(\alpha), \tag{3.21}$$

where $W^*(\bar{a}, \alpha)$ is the dam generated value in the model that we have analyzed and $G(\alpha)$ is an increasing, convex function, representing the cost at which the water user can make water-use efficiency reach α. The first-order condition of the program is then

$$W_2^*(\bar{a}, \alpha) = G'(\alpha). \tag{3.22}$$

The left-hand side is the marginal contribution of water-use efficiency to the dam generated value, which is the incentive for water-use efficiency improvement, and the right-hand side is the marginal cost of water-use efficiency improvement. Assuming interior solutions, the optimal choice of water-use efficiency, α^*, should make the marginal contribution and the marginal cost intersect with each other.

Obviously, in this model, $W_{21}^*(\bar{a}, \alpha)$ determines whether larger dams will increase or decrease the incentive for water-use efficiency improvement. Note that, as long as the dam generated value, $W^*(\bar{a}, \alpha)$, is well-behaved (almost everywhere), which we show in Appendix B.3, $W_{21}^*(\bar{a}, \alpha)$ should be equal to $W_{12}^*(\bar{a}, \alpha)$, which determines whether higher water-use efficiency will increase or decrease the marginal benefit of dam capacities. In other words, larger dams will increase/decrease the incentive for water-use efficiency improvement, if and only if higher water-use efficiency will increase/decrease the marginal benefit of dam capacities. This duality allows us to state that water-storage capacities and water-use efficiency are complements/substitutes.

The impact of water-storage capacities on the marginal contribution of water-use efficiency can also be decomposed into two sub-impacts, which we brief here. Having larger dams first increases water availability, and whether this increase will increase or decrease the marginal contribution of water-use efficiency will depend on the water-demand elasticity or, equivalently, the EMP, corresponding to the marginal-water-benefit channel in the impact of water-use efficiency on the marginal benefit of dam capacities. Second, having larger dams could change the optimal control rule of water inventories. This change will further change the marginal contribution of water-use efficiency, corresponding to the full-dam-probability channel in the impact of water-use efficiency on the marginal benefit of dam capacities, in the sense that this sub-impact and the full-dam-probability channel both work through the change in the control of water inventories.

Policy Implications given Complementarity or Substitution

When dam capacities and water-use efficiency are complements, first, public water-storage capacities could be expanded without discouraging improvement in water-use efficiency, e.g., adopting more-efficient irrigation technologies and better conveyance technologies. Second, policymakers might believe that subsidizing water users to improve water-use efficiency could make expanding water storage unnecessary, but the subsidies could backfire by increasing the demand for investment in water storage. Third, if policymakers would like to justify water-storage expansions, it would be better if she could use policy tools, e.g., subsidies, technological regulation, and water-pricing reforms, to guarantee water users to improve their efficiency. When dam capacities and water-use efficiency are substitutes, some opposite policy implications would follow.

The case of complementarity also provides some probably counterintuitive relations between conservation effort and conservation outcomes. For example, more effort in conservation, such as more adoption of efficient irrigation technologies, could lead to higher demand for dams and eventually more dam building. Larger dam capacities mean that more water will be captured in the long run, and higher efficiency in water use means that the water catchment will be used more effectively. Therefore, this more conservation effort could lead to more consumptive use of water, which is effective water in our model and also the amount of water that is truly deprived of from the natural environment for human use. More dam building also means more environmental damage. Therefore, more conservation effort could induce worse outcomes of conservation even though these outcomes are efficient with the economy and the environment both considered.

Last but not least, in the case of complementarity, assuming that a policymaker is maximizing the social welfare that is related to water-storage capacities and that dam building and water-use efficiency improvement are both economical, limited resources should be distributed in a balanced way between these two approaches, instead of being concentrated on either side with the other side being ignored. Only extreme substitution could make investing in a single approach an optimal allocation of resources. Appendix B.4 formalizes this implication.

3.5 Extension with Multiple Periods

In this section we extend the simple two-period, stochastic model by incorporating an multi-period horizon of the dam operator. The extension is for two purposes. First, as the simple model assumes only two periods in the dam operation, we shall use the extended model to show that the insight and results from the simple model are robust if a longer horizon is introduced. Second, as the horizon of dam operators is usually long in reality (e.g., Reilly, 1995), the extended model can help us in empirical illustrations.

Assume there are $T+1$ periods and $T \geq 0$. The extension then turns the water-inventory management problem into

$$W^{T*}(\bar{a}, \alpha) \equiv \mathbf{E}\left[V^{T*}(\bar{a}, a_0, \alpha)\right], \text{ where} \tag{3.23}$$

$$V^{T*}(\bar{a}, a_0, \alpha) \equiv \max_{\{w_t\}_{t=0}^{T}, \{s_t\}_{t=0}^{T}} \mathbf{E}_0 \left[\sum_{t=0}^{T} \rho^t B(w_t, \alpha)\right] \qquad \text{s.t.} \tag{3.24}$$

$$s_t \geq 0, w_t \geq 0, w_t + s_t = \min\{a_t, \bar{a}\} \text{ for any } t \geq 0;$$

$$a_0 = e_0;\ a_t = (1-d)s_{t-1} + e_t \text{ for any } t \geq 1;\ w_T = \min\{\bar{a}, a_T\} \tag{3.25}$$

where $e_t \in [\underline{e}, \bar{e}] \sim e$, i.i.d., and all the variables have the same meaning as in the simple model.[12]

Appendix B.5 solves the inventory-management problem. When $T \longrightarrow \infty$, the marginal benefit of dam capacities in the extended model will converge to

$$W_1^*(\bar{a}, \alpha) = \mathbf{E}\left[V_1^*(\bar{a}, a_0, \alpha)\right] = B_1(\bar{a} - \bar{s}, \alpha) \cdot \sum_{t=0}^{\infty} \rho^t \mathbf{E}\left[\mathbf{P}\left[a_t^* > \bar{a} | a_0\right]\right], \tag{3.26}$$

where $\bar{s}$ is the optimal water storage when the dam was full in the former wet season and a_t^* is the water availability at t under optimal storage-release decisions. This expression has exactly the same intuition as in the simple model: The marginal benefit of dam capacities depends on the marginal benefit of the dry-season water release when the dam was full in the former wet season and the probability that the dam will be full in wet seasons. Therefore, the marginal-water-benefit and the full-dam-probability channels will still exist. Appendix B.5 then derives parallel results to the simple model.

3.6 An Empirical Example with Numerical Illustrations

In this section, we present numerical illustrations of our results by simulating the extended model. The simulation is based on the irrigation water-inventory management problem of the California State Water Project. We use three specifications of the irrigation water demand in the illustrations, which are all empirically relevant to the agricultural water demand in California: 1) isoelastic, elastic with the elasticity being -1.21, which is estimated by Frank and Beattie (1979); 2) isoelastic, inelastic with the elasticity being -0.79, which is estimated by Schoengold et al. (2006); and 3) linear with the same elasticity as the second isoelastic, inelastic demand when the demand is equal to the 1975–2010 mean of the annual water deliveries from the Project to agricultural use, which is equivalent to the linear water demand estimated by Schoengold et al. (2006). The three specifications help to confirm our theoretical results and show their empirical relevance. Table 3.1 summarizes the three

[12] The Office of Management and Budget (2011) recommends a constant but not declining discount factor for project evaluation.

demand functions, while Table 3.2 summarizes the specification of the whole simulation. For more details about the specification, see Appendix B.6.

Table 3.1: Specifications of the benefit of water release in the empirical example

Benefit of water release	Demand for water release
$B(w,\alpha) = 3.0 \times 10^7 \cdot (\alpha w)^{1-\frac{1}{1.21}}$	Isoelastic, elastic, $\mu = -1.21$
$B(w,\alpha) = -7.1 \times 10^9 \cdot (\alpha w)^{1-\frac{1}{0.79}}$	Isoelastic, inelastic, $\mu = -0.79$
$B(w,\alpha) = 181.0 \cdot \alpha x - \frac{1.5\times10^{-4}}{2} \cdot (\alpha x)^2$, where $x \equiv \min\left\{w, \frac{181.0}{1.5\times10^{-4}\cdot\alpha}\right\}$	Linear, equivalent to $\mu = -0.79$

The price elasticity of the water demand is denoted as μ.

Table 3.2: Specification of the empirical example

Horizon	$T = \infty$
Inflow in acre-feet	$e_t \sim$ Adjusted, estimated historical inflows, i.i.d.
Evaporation-loss rate	$d = 0.04$
Discount factor	$\rho = 0.9434$
Benefit of water release in \$	$B(w,\alpha) = 3.0 \times 10^7 \cdot (\alpha w)^{1-\frac{1}{1.21}}$
(one in each illustration)	$B(w,\alpha) = -7.1 \times 10^9 \cdot (\alpha w)^{1-\frac{1}{0.79}}$
	$B(w,\alpha) = 181.0 \cdot \alpha x - \frac{1.5\times10^{-4}}{2} \cdot (\alpha x)^2$, where $x \equiv \min\left\{w, \frac{181.0}{1.5\times10^{-4}\cdot\alpha}\right\}$
Baseline water-use efficiency	$\alpha = 0.7135$
Baseline dam capacity in acre-feet	$\bar{a} = 2025335$

For the irrigation water-inventory management problem of the California State Water Project. Based on the California Department of Water Resources (1963–2013, 1976–2014, 1990–2014, 1998–2005, 2008), Frank and Beattie (1979), and Schoengold et al. (2006). Details in Appendix B.6.

For each of the three water demands, we focus on two questions – whether more-efficient technology adoption in irrigation, higher α, will increase or decrease the marginal benefit of dam capacities, $W_1^*(\bar{a},\alpha)$, and whether water-storage expansions, larger $\bar{a}$, will increase or decrease the marginal contribution of water-use efficiency to the dam generated value, $W_2^*(\bar{a},\alpha)$.

Table 3.3 shows results with the benchmark level of storage capacities, 2025335 acre-feet, zero initial water availability, and the benchmark level of water-use efficiency, 0.7135. Panel A is for the isoelastic, elastic demand. A 1% improvement in water-use efficiency from

Table 3.3: The empirical example: Responses to a 1% increase in water-use efficiency or water-storage capacities

Variable	Elasticity w.r.t. α	Elasticity w.r.t. $\bar{a}$
Panel A: Isoelastic, elastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	0.17	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^*>\bar{a}\vert a_0\right]\right]$	0.00	
Marginal benefit of dam capacities, $W_1^*(\bar{a},\alpha)$	0.17	-20.27
Optimal dam capacity, $\bar{a}^*$	$(0,0.01]$	
Marginal contribution of water use efficiency, $W_2^*(\bar{a},\alpha)$	-0.82	0.01
Optimal water-use efficiency, α^*		$(0,0.01]$
Panel B: Isoelastic, inelastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-0.26	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^*>\bar{a}\vert a_0\right]\right]$	0.00	
Marginal benefit of dam capacities, $W_1^*(\bar{a},\alpha)$	-0.26	-13.88
Optimal dam capacity, $\bar{a}^*$	$[-0.02,0)$	
Marginal contribution of water use efficiency, $W_2^*(\bar{a},\alpha)$	-1.25	-0.01
Optimal water-use efficiency, α^*		$[-0.01,0)$
Panel C: Linear demand, inelastic at the mean of water deliveries		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-3.02	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^*>\bar{a}\vert a_0\right]\right]$	4.13	
Marginal benefit of dam capacities, $W_1^*(\bar{a},\alpha)$	0.99	-5.86
Optimal dam capacity, $\bar{a}^*$	$(0,0.17]$	
Marginal contribution of water use efficiency, $W_2^*(\bar{a},a_0,\alpha)$	-1.72	0.05
Optimal water-use efficiency, α^*		$(0,0.03]$

Initial conditions: $\bar{a}=2025335$ and $\alpha=0.7135$. The optimal water storage when the dam reaches the full capacity is denoted by $\bar{s}$. Specification follows Tables 3.1 and 3.2.

0.7135 to 0.7206 will increase the marginal benefit of dam capacities by 0.17%. This positive impact confirms the prediction of complementarity in Corollary 4 for isoelastic, elastic water demands. Moreover, the 0.17% increase in the marginal benefit of dam capacities is solely caused by a 0.17% increase in the marginal benefit of water release when the dam reaches the full capacity, while the net present frequency of the dam reaching the full capacity in the future does not change. This observation confirms the logic of Corollary 4.

How will the 0.17% increase in the marginal benefit of dam capacities be reflected on the optimal choice of storage capacities? Without information about the marginal cost of dam capacities, the most we can do is to estimate the range of the impact: It is obvious that if the marginal cost of dam capacities are perfectly vertical, then the optimal choice of storage capacities will not change. If the marginal cost of dam capacities are assumed perfectly horizontal, then we can derive the upper bound of the increase in optimal storage capacities caused by the 1% improvement in water-use efficiency.[13] In this case, the upper bound will be $-0.17/(-20.27) \approx 8.39 \times 10^{-3}$. In other words, the 1% improvement in water-use efficiency will generate at most a negligible but still positive increase in the optimal storage capacity from the benchmark level if we assume the water demand is isoelastic and elastic.

How will a 1% increase in dam capacities change the incentive for water-use efficiency improvement and the optimal water-use efficiency, if we assume the water demand is isoelastic and elastic? A similar exercise shows that the marginal contribution of water-use efficiency to the dam generated value will increase less than 0.01%, which can be translated into an at most 0.01% improvement in water-use efficiency.

Panel B reports results for the isoelastic, inelastic water demand. They confirm the prediction and the logic of Corollary 4, again: for isoelastic, inelastic demands, dam capacities and water-use efficiency are substitutes, and water-use efficiency improvement decreases the marginal benefit of dam capacities without changing the frequency of the dam reaching the

[13]A little bit algebra can express the upper bound of the elasticity of the optimal choice of storage capacities with respect to water-use efficiency, $\frac{d\bar{a}^*}{d\alpha} \cdot \frac{\alpha}{\bar{a}^*}$, as the elasticity of the marginal benefit of dam capacities with respect to water-use efficiency, $\epsilon_{\alpha}^{W_1^*(\bar{a},\alpha)}$, divided by the elasticity of the marginal benefit with respect to dam capacities, $\epsilon_{\bar{a}}^{W_1^*(\bar{a},\alpha)}$. Mathematically, totally differentiating both side of the first-order condition of the dam-capacity choice gives $W_{11}^*(\bar{a}^*,\alpha)d\bar{a}^* + W_{12}^*(\bar{a}^*,\alpha)d\alpha = C''(\bar{a})d\bar{a}^*$, which derives $0 < \frac{d\bar{a}^*}{d\alpha} = \frac{W_{12}^*(\bar{a}^*,\alpha)}{-W_{11}^*(\bar{a}^*,\alpha)+C''(\bar{a})} < -\frac{W_{12}^*(\bar{a}^*,\alpha)}{W_{11}^*(\bar{a}^*,\alpha)}$. Also, $0 < \frac{d\bar{a}^*}{d\alpha} \cdot \frac{\alpha}{\bar{a}^*} < -\frac{W_{12}^*(\bar{a}^*,\alpha)}{W_{11}^*(\bar{a}^*,\alpha)} \cdot \frac{\alpha}{\bar{a}^*} = -\frac{\alpha W_{12}^*(\bar{a}^*,\alpha)}{V_1^*(\bar{a}^*,\alpha)} \cdot \left(\frac{\bar{a}^* W_{11}^*(\bar{a}^*,\alpha)}{W_1^*(\bar{a}^*,\alpha)}\right)^{-1} \equiv -\, \epsilon_{\alpha}^{W_1^*(\bar{a},\alpha)} \Big/ \epsilon_{\bar{a}}^{W_1^*(\bar{a},\alpha)}$.

full capacity in the future.

Panel C reports results for the linear water demand. With this specification, the inelastic range of the water demand is mostly relevant and the second condition for linear demands in Corollary 5 is almost satisfied.[14] Consistent with theoretical predictions, water-use efficiency improvement will decrease the marginal benefit of water release when the dam has reached the full capacity but will also increase the frequency of the dam reaching the full capacity in the future. Moreover, the full-dam-probability channel does dominate and a 1% improvement in water-use efficiency will increase the marginal benefit of dam capacities by 0.99%. The positive impact suggests complementarity between dam capacities and water-use efficiency if we assume the water demand is linear.

Comparing Panels B and C now confirms the importance of the specification of water demands. The underlying water demands of the two panels both have a price elasticity of -0.79 if the demand is equal to the mean of the 1975–2010 annual water deliveries from the California State Water Project to agricultural use, but differ in their functional forms: The water demand of Panel B is isoelastic while the demand of Panel C is linear. The difference in functional forms leads to different predictions about the economic relation between dam capacities and water-use efficiency. The reason for the difference in predictions is just that water-use efficiency improvement could increase the frequency of the dam reaching the full capacity in the future by optimally increasing water storage, and we can only recognize this impact by recognizing stochastic, dynamic control of water inventories and the full-dam-probability channel.

As we have discussed earlier, irrigation demand for water is usually inelastic, and a linear specification is theoretically more consistent and empirically more relevant to irrigation demands. For the irrigation water-inventory management problem of the California State Water Project, we then emphasize the linear water demand and Panel C more than the other two isoelastic specifications and Panels A and B. Panel C does suggest complementarity between dam capacities and water-use efficiency, which implies balanced distribution of limited resources on water-storage expansions and water-use efficiency improvement.

Table 3.4 tests the robustness of Table 3.3 by calculating responses of the variables of interest to a 5% increase in water-use efficiency or water-storage capacities. All the results

[14] Around 72.2% of the inflow distribution in the empirical example is larger than the critical level of water release, 845597 acre-feet, beyond which the water demand is inelastic.

Table 3.4: The empirical example: Responses to a 5% increase in water-use efficiency or water-storage capacities

Variable	Response to $\Delta\alpha$ (%)	Response to $\Delta\bar{a}$ (%)
Panel A: Isoelastic, elastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	0.85	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^*>\bar{a}\mid a_0\right]\right]$	0.00	
Marginal benefit of dam capacities, $W_1^*(\bar{a},\alpha)$	0.85	-43.86
Optimal dam capacity, $\bar{a}^*$	$(0, 0.10]$	
Marginal contribution of water use efficiency, $W_2^*(\bar{a},\alpha)$	-3.95	0.03
Optimal water-use efficiency, α^*		$(0, 0.04]$
Panel B: Isoelastic, inelastic demand		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-1.29	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^*>\bar{a}\mid a_0\right]\right]$	0.00	
Marginal benefit of dam capacities, $W_1^*(\bar{a},\alpha)$	-1.29	-46.56
Optimal dam capacity, $\bar{a}^*$	$[-0.14, 0)$	
Marginal contribution of water use efficiency, $W_2^*(\bar{a},\alpha)$	-5.99	-0.06
Optimal water-use efficiency, α^*		$[-0.05, 0)$
Panel C: Linear demand, inelastic at the mean of water deliveries		
Marginal benefit of water release with a full dam, $B_1(\bar{a}-\bar{s},\alpha)$	-7.07	
Net present frequency of a full dam, $\sum_{t=0}^{\infty}\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^*>\bar{a}\mid a_0\right]\right]$	12.84	
Marginal benefit of dam capacities, $W_1^*(\bar{a},\alpha)$	4.87	-25.18
Optimal dam capacity, $\bar{a}^*$	$(0, 0.97]$	
Marginal contribution of water use efficiency, $W_2^*(\bar{a},\alpha)$	-8.57	0.31
Optimal water-use efficiency, α^*		$(0, 0.18]$

Initial conditions: $\bar{a} = 2025335$ and $\alpha = 0.7135$. The optimal water storage when the dam reaches the full capacity is denoted by $\bar{s}$. Specification follows Tables 3.1 and 3.2.

in Table 3.3 qualitatively hold and their magnitude becomes larger in Table 3.4. Panel C in Table 3.4 shows that a 5% increase, a reasonable improvement, in water-use efficiency will increase the marginal benefit of dam capacities by around 4.9%, while a 5% increase in water-storage capacities will increase the incentive for water-use efficiency improvement by around 0.3%.

Both Panel Cs in Tables 3.3 and 3.4 show asymmetry in the complementarity between water-storage capacities and water-use efficiency: The impact of dam capacities on the incentive for water-use efficiency improvement is always quite small. It is because that the existing dam capacity is large: First, the contribution of water-use efficiency to the dam generated value depends on the amount of water release in the long run, and so does the marginal contribution – the incentive of water-use efficiency improvement. Second, when the existing dam capacity is large, the amount of water release is large, so the relative increase in the amount of water release by additional dam capacities will be small. Therefore, the impact of the small increase in dam capacities on the incentive of water-use efficiency improvement and the optimal water-use efficiency will be weak. The complementarity between dam capacities and water-use efficiency is then more prominent in the impact of water-use efficiency improvement on the marginal benefit of dam capacities, but not the other way around.

Using the linear demand for water, we finally illustrate the comparison between the value-maximization logic of economists and the cost-minimization logic in the engineering literature (e.g., surveys by Yeh, 1985; Simonovic, 1992). Along the cost-minimization logic, dam designers are choosing the minimal dam capacity, which will incur the minimal cost, to satisfy specific policy objectives. For example, if there is a 5% increase in water-use efficiency, the minimal dam capacity to reach the (gross) value that is generated by the benchmark dam capacity with the benchmark water-use efficiency will be 29.59% smaller than the benchmark dam capacity. This result confirms the intuition that, since the function of the benefit from effective water is increasing, higher water-use efficiency means a higher dam generated value given any dam capacity, so the cost-minimization logic will lead to a smaller capacity choice. In contrast, weighing the marginal benefit and the marginal cost of dam capacities, the optimal dam capacity with the same water-use efficiency improvement, as shown in Table 3.4, will be larger than the benchmark dam capacity by at most 0.97%.

3.7 Conclusion

In this paper, we propose two challenges to the conventional wisdom that higher water-use efficiency will decrease the demand for water-storage capacities. First, higher efficiency in water use can increase the demand for water when the water demand is elastic, so it could increase the demand for water-storage capacities. Second, higher water-use efficiency could change the optimal control of water inventories so that storing more water could be optimal. This possibility, if happens, will make the water-storage capacity constraint more likely to be binding in the future. Along this logic, higher water-use efficiency could increase the demand for water-storage capacities even if it will decrease the demand for water.

We formalize these two challenges in a dam-capacity choice model with stochastic, dynamic control of water inventories. Recognizing the water-catchment and stochastic-control purposes of water-storage capacities, we decompose the impact of water-use efficiency on the marginal benefit of water-storage capacities into a marginal-water-benefit channel and a full-dam-probability channel. We show that the direction of the two channels depends on the properties of the marginal productivity of effective water. Precise information about the marginal productivity of effective water, however, is sometimes difficult to be known. That said, we can still identify the direction of these two channels, as long as we know the properties of the water demand, which are much easier to be estimated in practice.

For simplicity, our model assumes away many important factors in water-inventory management and water-storage design. Our qualitative result about the impact of water-use efficiency on the marginal benefit of water-storage capacities will still hold, as long as the missing factor is not correlated with water-use efficiency, e.g., damages caused by floods. Even if the missing factor is correlated with water-use efficiency, e.g., the return flow of irrigation to groundwater, our qualitative result will not much change, as long as this factor does not much alter the first- and the second-order properties of the marginal productivity of effective water. Even if the missing factor does radically alter the properties of the marginal productivity of effective water, our decomposition of the impact on the marginal benefit of water-storage capacities into the marginal-water-benefit channel and the full-dam-probability channel will still be valid, as long as the focal water-storage facilities have both the water-catchment and the stochastic-control purposes. That said, there are also dams in areas where the peaks of the water endowment and the water demand generally overlap. The water-catchment purpose of these dams are then not important. For these water-storage facilities, however, our analysis about the stochastic-control purpose and the full-dam-probability channel is still applicable.

Our results imply that policymakers should not separately design the two categories of policies – expanding water storage and improving water-use efficiency. In the case of complementarity, resources should not be concentrated only on one category with the other being ignored, if both approaches are economical. This implication is especially important for the countries with small initial water-storage capacities, by which water-use efficiency improvement will increase the demand for water, and the countries with generally abundant inflows and large initial water-storage capacities, by which water-use efficiency improvement will increase the likelihood that dams reach their full capacities.

As the relation between the policies is important in policy debates and could be counterintuitive, it deserves more serious theoretical modeling and empirical investigations. Further effort could be made to specify the improvement in water-use efficiency, e.g., model conservation-technology adoption with heterogeneous water users and specific land constraints. The cost of dams that will be correlated with water-use efficiency improvement, for example, displacement or introduction of specific water users, should also be considered. Our model can also serve as a starting point for a research agenda on the relation between water-storage expansions and other approaches in water-resource management, e.g., introducing water markets to existing systems of water rights and adopting drought-tolerant varieties in agriculture, under the background of climate change, which changes the water demand, evaporation rate, and inflow distribution. In a more general perspective, our analysis on the marginal benefit of storage capacities can be applied and extended to investigate investment decisions in other contexts, such as the joint management of water, food, and energy inventories. Ultimately, introducing political economy into the discussion between water infrastructure and conservation effort would be necessary.

We would like to conclude this paper with a clarification about the use of our analysis and implications. In this paper, we focus on the relation between water-storage capacities and water-use efficiency, but not on whether water-storage expansions or water-use efficiency improvement is economical in any particular case. Therefore, any practical use of our analysis and implications should be accompanied first by substantial empirical works on whether the particular investment in water-storage capacities or water-use efficiency is economical, and our results will then be instrumental in the design of optimal policy portfolios.

Chapter 4

Culture and Collective Action

4.1 Introduction

Are there cultural underpinnings for differences in types of collective action? One may think that countries that have been successful in establishing democracies earlier than other countries had stronger historical traditions of collective action. If this were true, countries that have not yet established democracies are simply lagging in having their population stage a successful revolution to establish democracy. Looking back in human history, things seem, however, quite different from such a simple scheme. Some countries may have had a stronger tradition of collective action than established democracies, but the aims of that collective action may not necessarily have been to establish democracy. In a recent paper, Gorodnichenko and Roland (2013) presented a model and empirical evidence showing that countries with individualist culture would adopt democracy earlier than countries with collectivist culture, even if the latter possibly had better traditions of collective action. In this chapter, we would like to take a closer look at this question and look for micro-foundations of different types of collective action in different cultures. We focus on the comparison between individualism and collectivism, so it is useful in such an endeavor to compare Chinese and European history, which are relatively well documented.

If we compare Chinese history with European history, since the times of the Qin and Han dynasty and the Roman Empire, two stylized facts emerge:

First, peasant and popular revolts played very little role in Europe in leadership change compared to China. In the Roman Empire, it was never the case that an Emperor was overthrown by a popular revolt. All such changes happened inside narrow elite circles (de Ste. Croix, 1981; see also Finer, 1997). In contrast, in China, there are several well known cases of peasant revolts leading to the Emperor being overthrown or even a change in dynasty. The Han dynasty was founded by Liu Bang who was at the head of an army that started as a rebellion of peasant soldiers. Later, around the end of Western Han, the Green Forest rebellion brought an end to the Xin dynasty founded by Wang Mang, and one of the Green Forest leaders, Liu Xiu, founded the Eastern Han Dynasty. The Yellow Turban rebellion played a big role in the collapse of the Eastern Han dynasty as its suppression led to the Three Kingdom periods. At the end of the Sui Dynasty, in 611 AD, large scale peasant revolts weakened the power of the Emperor, leading to the foundation of the Tang Dynasty. Around the end of Tang Dynasty, in 875 AD, Huang Chao led a very strong peasant revolt, which was suppressed by warlords, and one of them, Zhu Wen, then assumed the power of Tang. There followed a period of fragmentation until the foundation of the Song dynasty.

The Red Turban revolt overthrew the Yuan dynasty and one of its leaders, Zhu Yuanzhang, founded the Ming dynasty. The Ming dynasty was actually brought down by a big peasant revolt, led by Li Zicheng, which was then defeated by the Manchus who founded the Qing Dynasty.

Many other revolts, such as the Taiping rebellion in the 19th century nearly overthrew the Qing dynasty, during a bloody civil war that cost 20 million lives. Overall, since the Qin dynasty, there were more than 30 large scale peasant revolts, covering large parts of China's territory.

The second striking fact is that peasant revolts in China aimed most often at replacing a bad emperor (dynasty) with a good emperor (dynasty). In contrast, in Europe and the West, after the Middle Ages, the few big revolutions like the Glorious Revolution in England, the American revolution, the French revolution, the numerous European revolutions of the 19th century aimed most often at changing political institutions to limit the power of the executive and introduce more inclusive political institutions, led gradually to the establishment of democracies based on universal suffrage.

We present in this chapter a model proposing to make sense of these differences. It is a model of collective action, whereby people's potential payoff from collective action is augmented by a social payoff that differs across cultures, and that is rooted in modern cross-cultural psychology. We take as starting point the difference made by Markus and Kitayama (1991) between different notions of the self that are the foundations for cross-cultural psychological analysis of individualism and collectivism: the independent versus the interdependent self where the former is associated more with individualism and the latter more with collectivism.

In the following section, we briefly explain how the notions of independent and interdependent self may affect the social payoffs of collective action in different ways in different cultures. We then present a very simple model incorporating those features to analyze how in a collectivist culture collective action to overthrow an incumbent autocrat and replace him with better ruler is easier, while in an individualist culture collective action to change the existing political institutions and introduce new political institutions is easier. We then extend our model to a multiple player model of collective action, including a global game component. The particular assumptions we make deliver rich results and contribute to the literature on collective action. In the multiple player case, the social payoff from participating in collective action may help alleviate the collective action problem, leading to a unique equilibrium of joint collective action for a large set of parameters of the model. In the global game setup where there is uncertainty about signals received by other players, it is possible that the collective action equilibrium delivers a negative payoff to both players compared to the status quo. These results are, to our knowledge, all novel in the context of collective action games.

4.2 The Independent and the Interdependent Self and Types of Collective Action

The independent self derives its identity only from the inner attributes of the individual. These attributes are considered to reflect the essence of the individual, to be stable across time and context and the combination of these attributes is seen as unique to the individual. These individual inner attributes are significant for defining, regulating and thus predicting the behavior of an individual. The interdependent self, in contrast, derives its identity essentially from relations with others. The self is not a separate identity but is embedded in a larger social group and can be understood only in relation to that larger group. From the point of view of the interdependent self, individual behavior is derived from one's role in different social contexts and from the perception of others' reaction to one's behavior as well as from the perceived effect of one's own actions on others.

These different notions of self have many different implications that can explain the main differences between individualism and collectivism (see the extensive survey in Gorodnichenko and Roland, 2012). Among the many differences, here are just a few that are relevant in the context of this paper. The independent self seeks to know him/herself through inner search of the introspective type. In contrast, the interdependent self seeks to know him/herself through the evaluation of others. People from individualist cultures have a higher need for "self-enhancement" and have a stronger self-serving bias than people from collectivist cultures. In contrast, the need for self-enhancement is less strong for the interdependent self who views him/herself as much more malleable. The interdependent self is concerned more with interpersonal harmony whereas the independent self is concerned with how events affect the individual and helps him or her stand out. A key motivational difference between individualist and collectivist culture is indeed the need to stick out versus to fit in. Both motivations are present everywhere but the former is stronger in individualist than in collectivist cultures where the motivation to fit in is stronger in the latter relative to the individualist culture.

In this chapter, we focus on some implications of the difference between the interdependent and the independent self related to collective action. We will assume that the interdependent self derives a positive payoff from participating in a collective action when such participation corresponds to an existing social norm. As we explain further, such an assumption has roots in Chinese history. The existence of this social payoff can make collective action easier, but only when the revolt is conducted within existing social norms. This is consistent with both the strong frequency of large-scale peasant revolts in China and with its relatively unchanged focus on replacing a bad emperor with a more legitimate one, generating the so-called dynastic cycle.

If the focus of a revolt falls outside existing social norms, however, we will assume that the social payoff for the interdependent self is a risky one. The idea is that participating in a revolt, the purpose of which is not sanctioned by a social norm, can lead to social stigmatization in case of failure. People will be blamed for having participated in actions for "foolish" and "unproven" ideals that have brought repression and misery upon the people. If instead a revolt for a revolutionary ideal, such as democracy, is successful, than we will assume that there can be a positive social payoff of ex post social recognition for having followed a just cause. This risky social payoff will create reluctance to engage in collective action for institutional innovation and institutional experimentation. Because of this, collective action in collectivist cultures will tend to be more conservative in its focus, aiming to change existing political leaders but not the existing political institutions.

On the latter dimension, we will assume that the social payoff to the independent self differs radically from the payoff to the interdependent self. Since the independent self finds gratification in standing out, there will be a positive social payoff to participation in collective action aiming at institutional innovation. The idea is that participation in collective action can help the individual stand out relative to those generations and cohorts that did not have that opportunity.

The existence of a social norm for revolting against a bad emperor in China is rooted in the doctrine of the "Mandate of Heaven" introduced by the Zhou Dynasty (c. 1046–256 BC) to justify its right to rule, which was taken from the Shang Dynasty (c. 1600–1046 BC). The main idea is that the right to rule is bestowed by Heaven upon a ruler, but if the ruler performs badly, then the right will be withdrawn and bestowed on another good ruler. Given this doctrine, revolting against a bad emperor amounts to help to realize the "Mandate of Heaven", and is given strong cultural appreciation. Despite its emphasis on hierarchy and order, Confucianist doctrine's idea that the ruler loses legitimacy if he does not correctly embrace his responsibilities, is emphasized in at least two theories.

First, in the *Analects,* Confucius is recorded to have said: "good governance consists in the ruler being a ruler, the minister being a minister, the father being a father, and the son being a son." This means that everyone must behave in the way they are supposed to behave, given their place in the social relationship, whether senior (a ruler or a father) or junior (a minister or a son). The "Mandate of Heaven" and the norm of revolting against a bad ruler follow from the idea that rulers, despite being on top of the social ladder, have the obligation to behave in a virtuous way.

Second, the Confucianist concept of the "Rectification of Names" states that there should be a close correspondence between names on one hand, and things and actual actions on the other hand; otherwise, social order and stability will be jeopardized. Confucius says that people's behavior should correspond to their name, as senior people like the Emperor have more responsibilities than say a local governor, and the more senior name people carry, the higher their responsibilities. The logic is the same as above.

We are also not alone in noting the "Mandate of Heaven," the norm of revolting against a bad ruler, and their role in Chinese history and political culture. For example, Zhao (2009a) writes, "The strong performance aspect of state legitimacy allowed the ancient Chinese people to judge their ruler in performance terms. …Although most rebellions were ruthlessly repressed, the idea of rising to rebel against an unfit ruler had a legitimate position in Chinese political culture."

To conclude, the norm of revolting against a bad ruler is consistent with Confucianist culture, and the historical literature mentions its importance in Chinese history and political culture.

Collective action has always been difficult to understand, using standard tools of game theory. Because of the externalities to collective action allow people to free-ride on it, collective action has the structure of a prisoner's dilemma. If the payoffs of public action depend, however, on the number of participants, then collective action has the nature of a coordination problem with multiple equilibria: one where all participate, and one where no one participates (see the seminal paper by Palfrey and Rosenthal, 1984). Ostrom (1990) has analyzed how local institutions and norms emerge to solve collective action problems. Closer to our chapter, Gächter and Fehr (1999) have studied in a laboratory setting how social approval affects people's willingness to contribute to a public good.[1] Our chapter is the first to look at differences in social payoffs to collective action in an individualist and in a collectivist culture. The model gives micro-foundations to the more dynamic model of Gorodnichenko and Roland (2013) analyzing the dynamic of democratization and revolt in an autocratic regime. The main result is that collective action to replace the incumbent leader by a new leader is more present in a collectivist culture, while collective action to change the existing political institutions is more present in an individualist culture.

In the next section, we present a very simple model where the people are modeled as a single player. The main purpose is to get simple results to compare typed of collective action in the individualist and the collectivist culture. In the next section, we will introduce the multiple player case, using a game-theoretic setup of collective action.

[1] More generally, Frank (1985) looks at the role of status and status-seeking in economics.

4.3 The Basic Model

Assume that the utility of an agent depends on the economic payoff of risky collective action: $+a$ if successful, $-a$ if unsuccessful. On top of the presence of this standard payoff to collective action, we assume, as explained above, two additional social payoffs derived from the cross-cultural psychology literature.

The first additional payoff to collective action is the opportunity to "stand out" by possibly being regarded as an institutional innovator in the revolution, like the revolutionary figures of the American and French revolution. We call this payoff b and assume that it is independent of the result of the collective action. To the extent that individuals crave for fame and standing out, this payoff is assumed to be intrinsic to the collective action itself. This payoff gives a positive expected psychological reward to the independent self and is assumed to be stronger in an individualist culture that rewards standing out relative to conformity.

We assume that there is a possible additional payoff c to collective action that arises from self-satisfaction with conforming to the social norm of revolting in cases when revolting is seen as the "just" social action. We assume that this payoff is also independent of the success of collective action but derives from the positive self-esteem feedback for having conformed to an existing social norm.[2] We assume that this additional payoff rewards the interdependent self for conformity to existing social norms and is thus mainly present in a collectivist culture.

To this positive payoff for following the norm, we add a risky payoff to the interdependent self: in case of institutional innovation, there is a positive payoff c, but in case of failure, there is a negative payoff $-d$. As explained above, since there is no preexisting norm for participation in collective action under institutional innovation, because of its novelty, its success can create a positive norm rewarding with social recognition those who have partici-

[2]The idea of a social payoff to revolting even in the case of failure can be illustrated by the following well known story in Chinese history. When Chen Sheng and Wu Guang told their men why they had decided to revolt against the Qin dynasty (in 209 BC) because heavy rains prevented them from arriving in time to the Yuyang frontier that they were supposed to guard, Chen Sheng said, to encourage the peasant soldiers to rebel: "Since we'll face death anyway, why don't we die for a grand purpose? If one has to die, one has to die like a man. Are the princes and lords and prime ministers born leaders?" Note that this famous quote also implies that Chen Sheng and Wu Guang had in mind to replace the existing leaders, not to change the existing governance system.

pated. On the other hand, failure of the institutional innovation carries also a social stigma for those who participated in an action not sanctioned by social norms, hence the negative payoff to failure.

Given the game-theoretic difficulties of dealing with joint decisions of collective action, we start by assuming that the decision-making process of the masses is equivalent to the decision-making process of a single agent. We will relax this assumption in the next section.

The expected utility from collective action EU can thus be written:

$$EU = EP + \alpha_k E_{IND}(A) + \beta_k E_{INT}(A), \tag{4.1}$$

Where EP is the expected economic payoff, $E_{IND}(A)$ the expected psychological payoff to the independent self of chosen action A for the independent self, $E_{INT}(A)$ the expected social payoff to the interdependent self of chosen action A, and α_k and β_k are respectively the weights attached to social rewards for the independent self and for the interdependent self where $k = I, C$ is a cultural index where index I stands for individualist culture and index C stands for collectivist culture. By assumption, and given our above discussion, $\beta_C > \beta_I$ and $\alpha_I > \alpha_C$.

We will assume two types of collective action. The first one is a revolt noted R. We define a revolt as a popular uprising to overthrow an existing ruler deemed illegitimate and replacing him by a new ruler deemed more legitimate. We call the other type of collective action institutional innovation, noted I. Under institutional innovation, the collective action leads to the establishment of new political institutions. Monarchy can be replaced by a republic, autocracy can be replaced by democracy, etc. At the time of the institutional change, these institutions are assumed to be new and hitherto untested. They thus historically represent an important institutional innovation.

We assume that the agent receives a signal $q \in [0, 1]$ denoting the probability of success of a revolt R. Similarly, note $\sigma \in [0, 1]$ the probability of success of I.

The status quo has an expected payoff of 0. The decision rule will thus be to choose R over the status quo, I over the status quo or between R and I if both have a positive expected payoff.

Table 4.1 summarizes our assumptions so far.

Given our assumptions, the expected utility of R is

$$EU_R = q(a + \beta_k c) + (1 - q)(-a + \beta_k c) = 2qa + \beta_k c - a. \tag{4.2}$$

Table 4.1: Payoffs of revolt (R) and institutional innovation (I)

Weight	Successful R	Failed R	Successful I	Failed I
	Prob. q	Prob. $1-q$	Prob. σ	Prob. $1-\sigma$
Economic payoff, 1	a	$-a$	a	$-a$
Independent-self payoff, α_k	0	0	b	b
Interdependent-self payoff, σ_k	c	c	c	$-d$

Similarly, the expected utility of I is

$$EU_I = \sigma(2a + \beta_k(e + d)) - a + \alpha_k b - \beta_k d. \tag{4.3}$$

We can then easily define the following thresholds:

$$\underline{q}_k = \frac{1}{2} - \frac{\beta_k c}{2a}, \underline{\sigma}_k = \frac{a - \alpha_k b + \beta_k d}{2a + \beta_k(c + d)}, \tag{4.4}$$

where $\underline{q}_k$ is the minimum threshold for q so that R is preferred to the status quo and $\underline{\sigma}_k$ is the minimum threshold for σ so that I is preferred to the status quo. One sees immediately that $\underline{q}_k$ is decreasing in β_k, This means that the threshold to engage in a revolt is lower in a collectivist culture than in an individualist culture. This is due to the social norm of participating in a just revolt. Note similarly that $\underline{\sigma}_k$ is decreasing in α_k. In other words, the threshold for engaging in institutional innovation is lower in the individualist culture.

Note however that while $\underline{q}_k$ depends on β_k and not on α_k, $\underline{\sigma}_k$ depends both on α_k and on β_k. How does $\underline{\sigma}_k$ vary with β_k? Quick calculations show that $\underline{\sigma}_k$ increases with β_k if $d \geq \frac{a-\alpha_k b}{a+\alpha_k b}c$. Note that $\frac{a-\alpha_k b}{a+\alpha_k b} \leq 1$, so that this condition is in general always satisfied as long as $d \geq c$, i.e., as long as the punishment from the stigma to participating in failed institutional innovation is not lower in absolute terms than the social recognition from success. Note that the condition is always strictly satisfied as long as $\alpha_k > 0$. We thus see that the possible risk of failure associated with institutional innovation may raise the threshold for collective action in that direction in a collectivist culture.

These calculations lead us to our first proposition.

Proposition 7. *The threshold for R is lower under a collectivist than under an individualistic culture and the threshold for I is lower under an individualist compared to a collectivist culture.*

These very simple calculations thus show that there is a greater ease of collective action to replace a bad ruler in a collectivist culture and a greater affinity for collective action for institutional innovation in an individualist culture. These results follow from the assumptions we made giving positive utility to participation in a collective action following an existing social norm under collectivism, but greater reluctance in the absence of a social norm when there is the risk of a social stigma for failure in action for institutional innovation. Conversely, the positive utility from being a participant in collective action for institutional innovation lowers its threshold in an individualist culture.

What are now the conditions to prefer R over I, or vice-versa, in case the threshold for both is satisfied? This is defined in Proposition 8.

Proposition 8. *If $q = \sigma$, and if both I and R are preferred to the status quo, in a collectivist culture, R is preferred over I if $\sigma < 1$ and $\alpha_C \to 0$; in an individualist culture, I is preferred over R if $b > 0$ and $\beta_I \to 0$.*

Proof. The expected payoff of R is greater or smaller than I if

$$\beta_k c + 2qa - a \geq \text{ or } \leq \sigma(2a + \beta_k(c + d)) - a - \beta_k d + \alpha_k b, \tag{4.5}$$

which is equivalent to

$$(1 - \sigma)\beta_k(c + d) + (q - \sigma)2a \geq \text{ or } \leq \alpha_k b. \tag{4.6}$$

If $q = \sigma$, the right-hand side goes to 0 as $\alpha_C \to 0$ and the left-hand side remains positive as long as $\sigma < 1$. Similarly, the left-hand side goes to 0 as $\beta_I \to 0$ and the right-hand side remains positive as long as $b > 0$. □

Proposition 8 shows that under our assumptions, if the likelihood of success of collective action under I and R are the same, then a collectivist culture has a preference for changing leaders but not the regime, in contrast to the individualist culture. Note that if b is large enough, I can be preferred to R in an individualist culture even if $q > \sigma$, i.e. if the probability of success of collective action for R is higher than for I.

To repeat, there are three key assumptions behind these results:

1. R gives a positive social payoff to the interdependent self for following the social norm of revolt, regardless of the success or not of the collective action;

2. I gives a risky payoff to the interdependent self, contingent on the result of the collective action because there is no existing norm (to follow or break) for I.

3. I gives a positive social payoff to the independent self regardless of the success or not of the collective action. This is because of the expected payoff from standing out. Even if everybody participates in the collective action, there is still a benefit from standing out compared to other generations ad cohorts that do not take part in the collective action.

4.4 Extension to Multiple Players

The above analysis assumed that the people behave as one homogenous group. We now relax this assumption. Without loss of generality, we assume that there are two groups of players modeled as two single players. The gist of the results in this section will be roughly the same as in the one player situation, but the results are much richer and there are interesting insights relative to the literature on collective action.

Let us start with the case of revolt R. As we will see, this case can be readily extended to the case of institutional innovation I. We denote again by q the probability of success of a revolt R if all agents decide to engage in collective action. If only one group decides to engage in collective action, then the probability of success is denoted by γq, where $\gamma < 1$. This seems reasonable as the action is less likely to be successful if only part of the population participates.

Like in the previous section, if both players decide on collective action, they will get an expected utility of

$$EU_R = q(a + \beta_k c) + (1 - q)(-a + \beta_k c) = 2qa + \beta_k c - a. \tag{4.7}$$

If only one player decides on collective action, then the expected payoff to that group is $2\gamma qa + \beta_k c - a$. The expected payoff to the other player is assumed to be $2\gamma qa - a$, i.e. that group does not receive the social reward $\beta_k c$ from revolting, but potentially free rides on its benefit, provided $2\gamma qa - a > 0$. Note, however, that free-riding is not the only externality present in this model. If γ is sufficiently small, there is a negative externality imposed on the passive player. Indeed, the decision to engage in collective action may yield a negative payoff for the passive player. Indeed, it is quite possible that $2\gamma qa - a < 0$ while $2\gamma qa + \beta_k c - a > 0$. Table 4.2 shows the payoffs.

Table 4.2: Payoff matrix for revolt (R) versus non revolt (NR) in the two player case

Action	R	NR
R	$2qa + \beta_k c - a, 2qa + \beta_k c - a$	$2\gamma qa - a + \beta_k c, 2\gamma qa - a$
NR	$2\gamma qa - a, 2\gamma qa - a + \beta_k c$	$0, 0$

As above, we assume that $q \geq \underline{q}_k = \frac{1}{2} - \frac{\beta_k c}{2a}$. Otherwise, not revolting jointly is always a dominant strategy. All the action here will be taken by variation of γ. Assume first that γ is high, close to 1. Let us look at the strategies of player 1. Suppose player 2 decides not to revolt. Player 1 is strictly better off revolting if $2\gamma qa - a + \beta_k c > 0$. This inequality give us a lower bound on γ such that as $\gamma > \underline{\gamma}_{kR} = \underline{q}_k q^{-1}$. Suppose player 2 decides to revolt. Then player 1 is strictly better off revolting because of the additional utility $\beta_k c$ from following the social norm of revolt. A symmetric reasoning can be held for player 2 showing that it is also a dominant strategy to revolt. There is thus a unique Nash equilibrium as long as $\gamma > \underline{\gamma}_{kR} = \underline{q}_k q^{-1}$. Note that $\underline{\gamma}_{kR}$ decreases with q.

Below $\underline{\gamma}_{kR}$, it is easy to see that there will be two equilibria: revolting and not revolting. Indeed, if player 2 revolts, player 1 is better off revolting, again because of the additional utility $\beta_k c$ from following the social norm of revolt. However, if player 2 does not revolt, then player 1 is better off not revolting, since by definition of $\underline{\gamma}_{kR}$, the payoff to revolting $2\gamma qa - a + \beta_k c$ will be strictly negative.

Note that in this game while a player may free-ride on the decision by the other player to revolt, the player benefits even more from participating, due 1) to the increased likelihood of success of collective action (q instead of γq) and 2) to the benefit to the interdependent self $\beta_k c$ from doing so.

Note that without the presence of $\beta_k c$, the lower bound on γ to obtain a unique equilibrium is $\frac{1}{2}q^{-1}$, which is always higher than $\underline{\gamma}_{kR}$, which is $\left(\frac{1}{2} - \frac{\beta_k c}{2a}\right) q^{-1}$, as long as $\beta_k c$ is positive. The higher $\beta_k c$, the further away below $\underline{\gamma}_{kR}$ can be from $\frac{1}{2}q^{-1}$. It is thus possible to generate collective action even when $\underline{\gamma}_{kR}$ is relatively low.

Note finally that $\underline{\gamma}_{kR}$ is decreasing with β_k, as it is a positive function of $\underline{q}_k$, which is decreasing with β_k. Given $\beta_C > \beta_I$, the threshold $\underline{\gamma}_{kR}$ is lower in the collectivist culture.

We can do a similar analysis for the decision to engage in institutional innovation I. Table 4.3 below shows the different payoffs.[3]

Table 4.3: Payoff matrix for institutional innovation (I) or not (NI) in the two player case

Action	I	NI
I	$(2a+\beta_k(c+d))\sigma - a + \alpha_k b - \beta_k d$, $(2a+\beta_k(c+d))\sigma - a + \alpha_k b - \beta_k d$	$(2a+\beta_k(c+d))\gamma\sigma - a + \alpha_k b - \beta_k d$, $2\gamma\sigma a - a$
NI	$2\gamma\sigma a - a$, $(2a+\beta_k(c+d))\gamma\sigma - a + \alpha_k b - \beta_k d$	0, 0

As in the previous section, we assume that $\sigma \geq \underline{\sigma}_k = \frac{a-\alpha_k b+\beta_k d}{2a+\beta_k(c+d)}$. The condition for I to be a unique equilibrium is that $(2a+\beta_k(c+d))\sigma - a + \alpha_k b - \beta_k d > 0$, which is verified if $\gamma > \underline{\gamma}_{kI} = \underline{\sigma}_k \sigma^{-1}$. Below $\underline{\gamma}_{kI}$, there are two equilibria, I and NI. One verifies easily that $\underline{\gamma}_{kI}$ decreases with α_k. By a similar reasoning to that in the previous section, one also verifies that $\underline{\gamma}_{kI}$ increases with β_k as long as $d \geq c$. Given these two conditions, it is thus the case that $\underline{\gamma}_{kI}$ is lower in the individualist compared to the collectivist culture, given $d \geq c$.

The results for R and I are summarized in the following proposition.

Proposition 9. *There exist thresholds for γ, $\underline{\gamma}_{kR}$ and $\underline{\gamma}_{kI}$ above which there is a unique equilibrium, respectively R and I. Threshold $\underline{\gamma}_{kR}$ is lower in the collectivist culture and threshold $\underline{\gamma}_{kI}$ is lower in the individualist culture.*

In what follows, we want to look more carefully at what happens below thresholds $\underline{\gamma}_{kR}$ and $\underline{\gamma}_{kI}$. The above result is a classic one of multiple equilibria in a coordination game, in the spirit of Palfrey and Rosenthal (1984). If we now assume that there is some uncertainty among players about q, we can use the global game technology and eliminate multiplicity of equilibria . The two player case is the easiest for the sake of exposition and is in the spirit of Carlsson and van Damme (1993), but we will later extend the analysis to multiple players, and indeed to a continuum of players as in Morris and Shin (2003).

Assume thus that variable q is a random variable and that each player (group of players) receives a private signal q_i, $i = 1, 2$ such that $q_i = q + \epsilon_i$, where ϵ_i has normal distribution $N(0, \delta^2)$. We assume that q, ϵ_1, and ϵ_2 are statistically independent from each other.

[3] Table 4.3 is mistyped in Roland and Xie (2016, p. 54, Tab. 4.3).

Let us now derive the equilibrium of this global game, first for the case of R. Having received signal q_1, player 1 forms the view that signal q_2 (conditional on q_1) has distribution $N(q_1, 2\delta^2)$. Indeed, since $q_1 = q + \epsilon_1$, we have that $(q|q_1) = q_1 - \epsilon_1 \sim N(q, \delta^2)$. Since $q_2 = q + \epsilon_2$, we then have

$$(q_2|q_1) = q_1 - \epsilon_1 + \epsilon_2 \sim N(q_1, 2\delta^2). \tag{4.8}$$

For any x, agent 1 then assigns $P(q_2 \leq x|q_1) = \Phi\left(\frac{x-q_1}{\sqrt{2}\delta}\right)$.

Consider now that player 2 has a switching strategy and decides to revolt only if $q_2 \geq \underline{q}_2$. Given this decision rule, player l's expected payoff of revolting conditional on the signal received is given by

$$\begin{aligned} &\mathbf{E}\left[\left(1-\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)\right)(2qa-a+\beta c)+\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)(2\gamma qa-a+\beta c)|q_1\right] \\ &= 2aq_1\left(1-(1-\gamma)\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)\right)-a+\beta_k c \equiv f(q_1,\underline{q}_2). \end{aligned} \tag{4.9}$$

The expected payoff of not revolting conditional on the signal received is given by

$$\begin{aligned} &\mathbf{E}\left[\left(1-\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)\right)(2\gamma qa-a)+\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)\cdot 0|q_1\right] \\ &= \left(1-\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)\right)(2\gamma q_1 a-a) \equiv g(q_1,\underline{q}_2). \end{aligned} \tag{4.10}$$

Player 1 should thus revolt if and only if $f(q_1, \underline{q}_2) - g(q_1, \underline{q}_2) > 0$.

Note that

$$\begin{aligned} &f(q_1,\underline{q}_2)-g(q_1,\underline{q}_2) \\ &= a\left[2(1-\gamma)q_1\left(1-\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)\right)+(2\gamma q_1-1)\Phi\left(\frac{\underline{q}_2-q_1}{\sqrt{2}\delta}\right)\right]+\beta_k c \end{aligned} \tag{4.11}$$

is increasing monotonically in q_1 if $\gamma < \frac{1}{2q_1}$. Given that $\underline{\gamma}_{kR} < \frac{1}{2}$, and that the analysis with global games is done for those values of γ for which there are multiple equilibria, i.e. below $\underline{\gamma}_{kR}$, this condition will always be satisfied. Then given q_2, there will be a threshold level for q_1 solving $f(q_1, \underline{q}_2) - g(q_1, \underline{q}_2) = 0$, above which player 1 will prefer to revolt.

We can make a similar reasoning for player 2.

There will then be a Nash equilibrium $(\underline{q}_1^*, \underline{q}_2^*)$ that will thus solve

$$f(\underline{q}_1^*, \underline{q}_2^*) - g(\underline{q}_1^*, \underline{q}_2^*) = 0, f(\underline{q}_2^*, \underline{q}_1^*) - g(\underline{q}_2^*, \underline{q}_1^*) = 0. \tag{4.12}$$

The solution is then calculated to be $\underline{q}_1^* = \underline{q}_2^* = \underline{q}^* = \frac{1}{2} - \frac{\beta_k c}{a}$. Note that this threshold is lower than in the one-player case. This is an interesting observation, meaning that players are individually more willing to engage individually in collective action when its probability of success is lower! This seems surprising given that usually free-riding is the externality associated to collective action. As we saw above, free-riding is also present in this model as the passive player benefits from the action of the other player. However, there is also a negative externality associated with the fact that, while participating in the possible upside and downside of collective action, the passive player does not enjoy the social payoff from the collective action, leading thus to prefer switching to participate in the revolt, even when q is relatively low compared to the single player threshold. Let us call this effect the "reluctant revolutionary" effect. This effect is stronger in the collectivist culture as $\underline{q}^*$ decreases with β_k. If $\beta_k = 0$, the threshold is the same as in the one-player game.

An implication of the above reasoning is that the R equilibrium may be inefficient, i.e. deliver a negative expected payoff for both players compared to the status quo! This is because of the "reluctant revolutionary" effect mentioned above. If one player decides on collective action, the other one prefers to participate in the revolt because of the negative externality the other player would otherwise impose. Given that q is low enough, both nevertheless get a negative expected outcome. To our knowledge, this is the first model to deliver the surprising result that the collective action equilibrium can be the unique equilibrium even though both players receive negative payoffs in equilibrium. An intuitive way of seeing it is that even though both suffer under the collective action, deviating is not a profitable action for either player. This result is specific to the global game. With uncertainty about the signal received by the other player, a player may decide to engage in revolt to avoid the even more negative payoff received when remaining passive if the other player decides to revolt.

Looking now at the case of I, we get the corresponding

$$\begin{aligned} & f(\sigma_1, \underline{\sigma}_2) - g(\sigma_1, \underline{\sigma}_2) \\ = a & \left[2(1-\gamma)\sigma_1 \left(1 - \Phi\left(\frac{\underline{\sigma}_2 - \sigma_1}{\sqrt{2}\delta} \right) \right) + (2\gamma\sigma_1 - 1)\Phi\left(\frac{\underline{\sigma}_2 - \sigma_1}{\sqrt{2}\delta} \right) \right] \\ & + \beta_k(c+d)\sigma_1 \left[1 - (1-\gamma)\Phi\left(\frac{\underline{\sigma}_2 - \sigma_1}{\sqrt{2}\delta} \right) \right] + \alpha_k b - \beta_k d. \end{aligned} \tag{4.13}$$

This expression is increasing in σ_1 when $\gamma < \frac{1}{2\sigma_1}$, which is automatically satisfied, using a similar reasoning as above.[4] Then given $\underline{\sigma}_2$), there will be a threshold σ_1 solving $f(\sigma_1, \underline{\sigma}_2) - g(\sigma_1, \underline{\sigma}_2) = 0$, above which player 1 will prefer to engage in institutional innovation. The Nash equilibrium $(\underline{\sigma}_1^*, \underline{\sigma}_2^*)$ will thus solve

$$f(\underline{\sigma}_1^*, \underline{\sigma}_2^*) - g(\underline{\sigma}_1^*, \underline{\sigma}_2^*) = 0, f(\underline{\sigma}_2^*, \underline{\sigma}_1^*) - g(\underline{\sigma}_2^*, \underline{\sigma}_1^*) = 0. \tag{4.14}$$

The solution is then $\underline{\sigma}_1^* = \underline{\sigma}_2^* = \underline{\sigma}^* = \frac{a-2\alpha_k b+2\beta_k d}{2a+(1+\gamma)\beta_k(c+d)}$, which is decreasing in α_k, and increasing in β_k, as long as $d \geq \frac{(1+\gamma)a-2\alpha_k b(1+\gamma)}{(3-\gamma)a+2\alpha_k b(1+\gamma)}$, which is satisfied as soon as $d \geq c$.

This reasoning leads us to formulate the following proposition:

Proposition 10. *If there is uncertainty over q and σ, and if the noisy signals received by players are statistically independent, for smaller values of γ, there exists a unique equilibrium threshold $\underline{q}^* = \frac{1}{2} - \frac{\beta_k c}{a}$ and $\underline{\sigma}^* = \frac{a-2\alpha_k b+2\beta_k d}{2a+(1+\gamma)\beta_k(c+d)}$ above which players decide to engage in collective action respectively for R and I. The threshold is lower for R in a collectivist culture and for I in an individualist culture.*[5]

Let us now go a bit deeper in the comparison of thresholds for the collectivist and individualist culture. Given the assumptions of our model, in the individualist culture, β_k is small. We can see that as $\beta_k \to 0$, $\underline{q}^* > \underline{\sigma}^*$. The threshold for I is thus lower than for R. Similarly, for the collectivist culture, as $\alpha_k \to 0$, $\underline{\sigma}^* \to \frac{a-2\beta_k c+2\beta_k(c+d)}{2a+(1+\gamma)\beta_k(c+d)} > \frac{a-2\beta_k c}{2a} = \underline{q}^*$. We thus have the opposite results: the threshold for R is lower than for I.

We saw above that the threshold for q in the case of R is lower in the global game than in the single player game, leading potentially to an inefficient equilibrium under R compared to NR. What about for I? Here the answer is different for individualism and for collectivism. In the individualist culture, as $\beta_k \to 0$, the threshold in the single player game $\underline{\sigma} = \frac{a-\alpha_k b+\beta_k d}{2a+\beta_k(c+d)} \to \frac{a-\alpha_k b}{2a}$ whereas in the global game we have $\underline{\sigma}^* = \frac{a-2\alpha_k b+2\beta_k d}{2a+(1+\gamma)\beta_k(c+d)} \to \frac{a-2\alpha_k b}{2a}$. Given that $\frac{a-2\alpha_k b}{2a} < \frac{a-\alpha_k b}{2a}$, $\underline{\sigma}^* < \underline{\sigma}$.

In other words, the I threshold is lower in the global game than in the single player case in the individualist culture. This is a similar effect as for R. The psychological effect b of participating in 1 is not reaped when not participating in collective action. The risk of missing out on this, and only getting the expected economic payoff, thus leads a player to

[4] Equation (4.13) is mistyped in Roland and Xie (2016, p. 57).
[5] Proposition 10 corrects the typo in Roland and Xie (2016, p. 57, Prop. 4).

engage in collective action, even for low values of a compared to the single player case. In the collectivist culture, however, as $\alpha_k \to 0$,

$$\underline{\sigma} = \frac{a - \alpha_k b + \beta_k d}{2a + \beta_k(c+d)} \to \frac{a + \beta_k d}{2a + \beta_k(c+d)} \tag{4.15}$$

and

$$\underline{\sigma}^* = \frac{a - 2\alpha_k b + 2\beta_k d}{2a + (1+\gamma)\beta_k(c+d)} \to \frac{a + 2\beta_k d}{2a + (1+\gamma)\beta_k(c+d)}. \tag{4.16}$$

Comparing both expressions, we see that $\underline{\sigma}^* > \underline{\sigma}$. The reason is related to the extra risk involved in engaging in I in the collectivist culture. In case of failure, there is the stigma d attached to it, which is at least as high as the benefit c. If d were equal to 0, we would have $\underline{\sigma}^* < \underline{\sigma}$ and get a similar result to the ones above.

These results give us the following proposition.

Proposition 11. *In the global game defined in Proposition 10, i) in the individualist culture, $\underline{q}^* > \underline{\sigma}^*$, and in the collectivist culture, $\underline{\sigma}^* > \underline{q}^*$; ii) the threshold for R is lower than in the single-player game for both individualism and collectivism, but the threshold for I is higher than in the single-player game for collectivism, but lower for individualism.*

To conclude this discussion of two player collective action, the main difference with the one player case is thus the threshold for collective action for both R and I. The results are nevertheless remarkably richer than those of the one player case. We have the "reluctant revolutionary" effect on top of the standard free-riding effect on collective action and the standard coordination problem. Moreover, in the global game the collective action equilibrium may be inefficient and dominated by the status quo.

Coming back to one of the main themes of the chapter, the comparison of types of collective action, an important conclusion that also follows from the whole discussion is that Proposition 8, stating that R is preferred over I under collectivism, and vice-versa under individualism, once the thresholds for both R and I are both exceeded, remains completely valid in the two player case once one adjusts for the thresholds.

4.5 Conclusion

We have presented in this chapter a model of different types of collective action to compare the propensity to engage in collective action for a collectivist and for an individualist culture. We have considered two types of collective action: one where the incumbent leader is replaced by another one, say a bad autocrat replaced by a better one, but without institutional change; and another form of collective action aiming at changing the political institutions. We have introduced social payoffs to participation in collective action for the independent self and for the interdependent self, where the former is mainly present in the individualist culture and the latter mainly present in the collectivist culture. This may shed light on the different histories of collective action in both cultures, as illustrated by the comparison between Chinese and European history since the Qin and Han dynasties and the Roman Empire.

The model also yields new insights on the collective action game, relative to the literature. In the multiple player case, these social payoffs lead to an alleviation of the collective action problem, differentially for the two types of collective action in the individualist and collectivist culture. These social payoffs create a "reluctant revolutionary" effect that can more than offset the traditional freerider effect and push a player to participate in collective action in order not to lose out on the social payoff. This effect may even lead, in the context of a global game, to a payoff of collective action that is lower than the status quo for all players.

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Appendix A

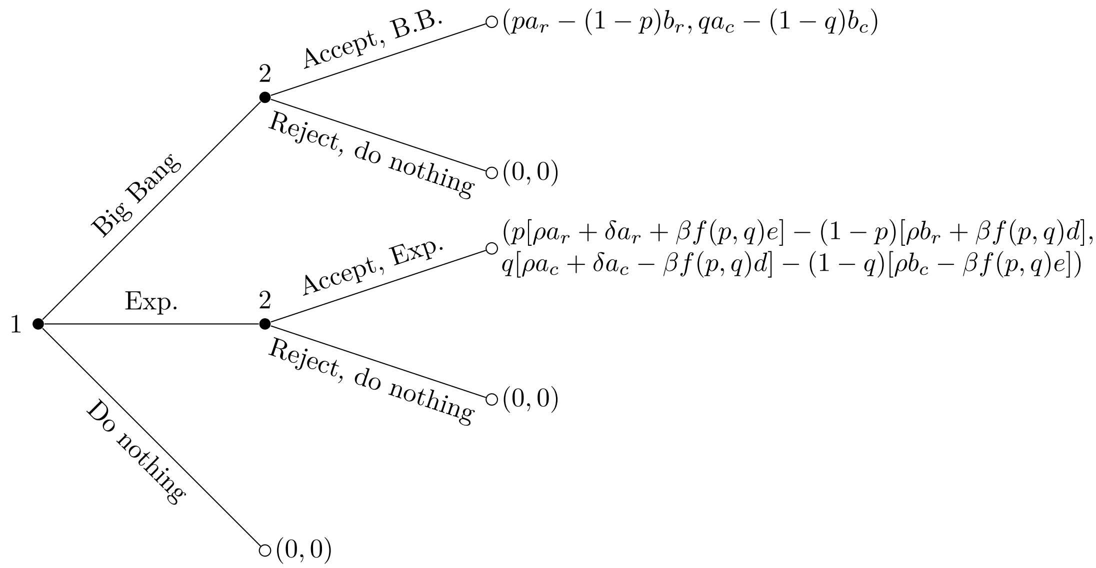
Appendices of *Machiavellian Experimentation*

A.1 An Example of Equivalent Non-cooperative Games

This section presents an example of the non-cooperative games that can replicate and refine the results from the cooperative game. We include both the mutually inclusive payoff and the unextended mutually exclusive payoffs here.

We assume all of the priors and payoffs are common knowledge. There are two stages of the game: at the first stage, the reformer provides a proposal, which includes one of the three options – Big Bang approach, experimental approach, or doing nothing; at the second stage, the conservative decides to accept the proposal or reject it. Figure A.1 shows the extensive form of this game.

The outcomes of the subgame perfect Nash equilibrium with pure strategies are almost the same as the core of the cooperative game in the main text. The only difference is that there is a situation where the Big Bang and the experimental approaches are both in the core of the cooperative game, while only the Big Bang approach will be adopted in this non-cooperative game, since the reformer is the first mover.



1: Reformer; 2: Conservative. $f(p,q) = 1$ if $p \in \left(\frac{b_r}{a_r+b_r}, 1\right]$ and $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$; otherwise $f(p,q) = 0$.

Figure A.1: The extensive form of the non-cooperative game

A.2 Proof of Proposition 1

Since $A_r > B_r > C_r$, we can divide the reformer's preference between the three options into four ranges: if $A_r < p \leq 1$, then the Big Bang approach is the best while doing nothing the worst; if $B_r < p < A_r$, then the experimental approach is the best while doing nothing still the worst; if $C_r < p < B_r$, then the experimental approach is the best while the Big Bang approach the worst; if $0 \leq p < C_r$, then doing nothing is the best while the Big Bang approach still the worst. We can also apply the similar treatments to the conservative.

Proposition 1 is then proved by some algebra.

A.3 Proof of Proposition 2

Consider $f(p,q) = 1$, which yields $p \in \left(\frac{b_r}{a_r+b_r}, 1\right]$ and $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$. Also assume $\beta > \frac{\rho(a_c+b_c)+\delta a_c}{e+d}$.

The experimental approach will be adopted if, and only if,

$$p(\rho a_r + \delta a_r + \beta e) - (1-p)(\rho b_r + \beta d) > 0 \text{ and}$$
$$q(\rho a_c + \delta a_c - \beta d) - (1-q)(\rho b_c - \beta e) > 0. \tag{A.1}$$

Otherwise nothing will be done.

Proposition 2 is then proved by some algebra.

A.4 Extension: Contingent, Mutually Exclusive Payoffs with N Players

In this section, we generalize the model with contingent, mutually exclusive payoffs for N players, where $N \geq 2$. We shall show that the result in Section 2.4 still hold. The model in Section 2.4 is simply a special case for the discussion in this section with $N = 2$. We shall also show that the role of contingent, mutually exclusive payoffs becomes more significant when more players participate in decision-making process.

We employ the same model structure and model settings as described in Section 2.2. The N players come together to discuss whether and how the organization should adopt a policy. Each player believes the policy has a probability p_i $(i = 1, 2, \ldots, N)$ to be good. There are still three options for the decision: adopting the policy in a Big Bang approach, adopting the policy in an experimental approach, and doing nothing. The first two approaches require consensus from the N players, in the sense that any of them could choose doing nothing as she wants.

The mutually inclusive payoff and the break-even priors A_i, B_i, and C_i for each player are defined in the same way as in Section 2.3.[1] We label the players with $B_i < p_i \leq 1$ *reformers*, and those with $0 \leq p_i < B_i$ *conservatives*.[2] Each player is then either a reformer or a conservative. The corresponding contingent, mutually exclusive payoffs are defined as follows:

If the N players agree to the experimental approach: If the experiment's result shows the policy is good, then the reformers get $f(p_1, p_2, \ldots, p_N)e$, while the conserva-

[1]More specifically, $A_i = \frac{(1-\rho)b_i}{(1-\rho)a_i - \delta a_i + (1-\rho)b_i}$, $B_i = \frac{b_i}{a_i + b_i}$, and $C_i = \frac{\rho b_i}{\rho a_i + \delta a_i + \rho b_i}$.

[2]For simplicity, we ignore the case in which $p_i = B_i$.

tives get $-f(p_1, p_2, \ldots, p_N)d$, where $d > 0$ and $e > 0$. If the experiment's result shows the policy is bad, then the reformers get $-f(p_1, p_2, \ldots, p_N)d$, while the conservatives get $f(p_1, p_2, \ldots, p_N)e$. The indicator function $f(p_1, p_2, \ldots, p_N)$ shows whether the payoff structure is effective, where $f(p_1, p_2, \ldots, p_N) = 1$ if there are at least one reformer and one conservative; otherwise, $f(p_1, p_2, \ldots, p_N) = 0$.[3]

Consistent with Section 2.4, we assume that players value the contingent, mutually exclusive payoffs with a weight β over the mutually inclusive payoff, where $0 \leq \beta \leq +\infty$. Similarly, the adoption of policy in any approach requires: this approach brings positive weighted sum of the expected mutually inclusive and mutually exclusive payoffs to the N players, and the other approach cannot give all the players higher weighted sum of the expected mutually inclusive and mutually exclusive payoffs than this approach does.[4]

With a similar argument, the break-even priors D_i for the reformers and E_j for the conservatives are respectively defined for the trade-off between an experimental approach and doing nothing.[5] With the definition of the indifference priors, we proceed with Proposition 12.

Proposition 12. *Label the players who prefer the Big Bang approach to doing nothing the reformers, and those who prefer doing nothing to the Big Bang approach the conservatives, when considering only the mutually inclusive payoff. Assume there are at least one reformer and one conservative. Then contingent, mutually exclusive payoffs are effective. Further assume the players strongly care about the contingent, mutually exclusive payoffs. Then the following two statements are true:*

i) If all of the conservatives sufficiently disbelieve in the policy while the reformers sufficiently believe in the policy, then the experimental approach will be adopted.

ii) Otherwise, the policy will not be adopted.

Mathematically and more precisely, define sets $\phi \equiv \{i : B_i < p_i \leq 1, i = 1, 2, \ldots, N\}$ *and* $\varphi \equiv \{j : 0 \leq p_j < B_j, j = 1, 2, \ldots, N\}$. *Assume* $\phi \cup \varphi = \{1, 2, \ldots, N\}$, $\phi \neq \varnothing$, *and*

[3] In this setting, contingent, mutually exclusive payoffs capture the different voices across all the players, and they are effective if, and only if, there exists sufficiently different views toward the policy. In other words, there should be at least one player who prefers the Big Bang approach to doing nothing, and another player who prefers doing nothing to the Big Bang, for the mutually exclusive payoffs to be effective.

[4] For simplicity, we ignore the break-even cases.

[5] More specifically, $D_i = \frac{\rho b_i - \beta e}{\rho a_i + \delta a_i + \rho b_i - \beta(e+d)}$ and $E_j = \frac{\rho b_j + \beta d}{\rho a_j + \delta a_j + \rho b_j + \beta(e+d)}$.

$\varphi \neq \varnothing$. Then $f(p_1, p_2, \ldots, p_N) = 1$. Further assume $\beta > \max_{j\in\varphi}\left\{\frac{\rho(a_j+b_j)+\delta a_j}{e+d}, \frac{\rho b_j}{e}\right\}$. Then the following two statements are true:

i) If $0 \leq p_j < \min\{D_j, B_j\}$ for any $j \in \varphi$ and $\max\{B_i, E_i\} < p_i \leq 1$ for any $i \in \phi$, then the experimental approach will be adopted.

ii) If $\exists j \in \varphi$ such that $D_j < p_j < B_j$ or $\exists i \in \phi$ such that $B_i < p_i < E_i$, then the policy will not be adopted.

Proposition 12 comes from both the contingent, mutually exclusive payoffs and the consensus requirement. The intuition and results are very similar to Proposition 2 in Section 2.4. More details can be found in Appendix A.5. Another interesting observation is that, if all the players hold identically, independently, and uniformly distributed priors, then it is more likely for opposite ideas to exist with newly-added players, and furthermore, when the number of players increases, the mutually exclusive payoffs are even more likely to be effective. As an example, Appendix A.6 details the evolution of the outcome structure when we introduce a third player to the two-player model.

A.5 The Intuition of Proposition 12

When the mutually exclusive payoffs are effective, players can be split into two groups, one regarded as reformers and the other as conservatives. To be noted, the conservatives always prefer doing nothing over the Big Bang approach, and thus the Big Bang approach will never be adopted. In this case, if the conservatives sufficiently disbelieve in the policy ($\forall j \in \varphi, 0 \leq p_j < \min\{D_j, B_j\}$), then they will regard that they are sufficiently likely to be proved correct in an experimental approach, and thus gain positive mutually exclusive payoffs from the experimental approach. Furthermore, if they sufficiently care about the mutually exclusive payoffs ($\beta > \max_{j\in\varphi}\left\{\frac{\rho(a_j+b_j)+\delta a_j}{e+d}, \frac{\rho b_j}{e}\right\}$), then the mutually exclusive-payoff consideration will dominate their mutually inclusive payoff consideration about the experimental approach, and they will prefer the experimental approach over doing nothing. On the other hand, the experimental approach still will not be adopted if any of the reformers does not sufficiently believe in the policy ($\exists i \in \phi, B_i < p_i < E_i$), since she will be afraid of losing too much in the experimental approach, and the expected loss will threat her to prefer doing nothing over the experimental approach. Therefore, the experimental approach will be adopted only if all of the N players have opposite and sufficiently extreme priors; otherwise, no policy will be adopted.

To illustrate Proposition 12, Figure A.2 shows the solution to a game with $N = 3$. In Figure A.2, the mutually exclusive payoffs are effective near the six cube vertices except $(0, 0, 0)$ and $(1, 1, 1)$.[6] When the mutually exclusive payoffs are effective, the Big Bang approach cannot be reached as an outcome because of the requirement of consensus. Under this situation, the conservative always regard doing nothing better than the Big Bang approach, and will thus veto the Big Bang approach. On the other hand, as Proposition 12 states, given effective mutually exclusive payoff, if, and only if, each player holds extreme prior toward the policy, they will agree to an experimental approach. In other words, "experimental approach" occupied the corners of six vertices shaded by the same color, whose locations are denoted as italic "Experiment" with three in the front and three on the back.[7] Meanwhile, there is no policy adoption if any of the players hold a moderate belief toward the policy, given that the mutually exclusive payoffs are effective. In Figure A.2, we can see that no policy adoption is achieved near the middle of edges.

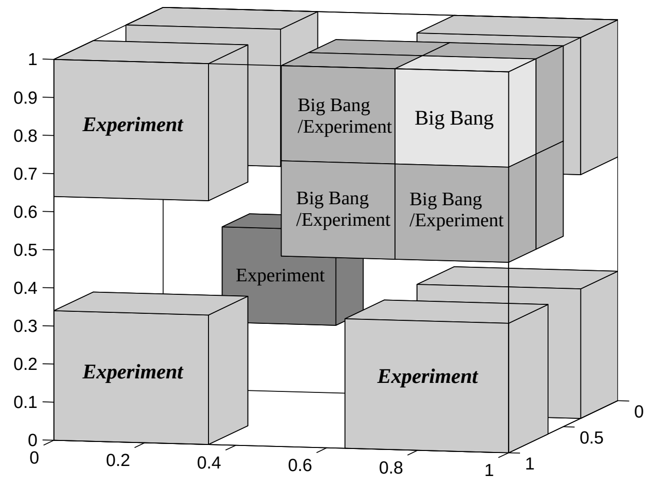
A.6 Details about Extending the Two-player Model to a Three-player Model

We further our analysis to how introducing a third player can largely change the outcome structure of the two-player model. We first demonstrate Figure A.3, which generalizes Figure 2.2 without assuming $p > q$. It illustrates the outcome structure of the two-player model with mutually exclusive payoffs and a large β. We then compare it with the subfigures in Figure A.4, showing the outcome structure of the three-player model by introducing a third player into the two-player model, given different values of Player 3's prior.[8]

[6] The six cube vertices are $(0, 0, 1)$, $(0, 1, 0)$, $(1, 0, 0)$, $(0, 1, 1)$, $(1, 0, 1)$ and $(1, 1, 0)$.

[7] Besides these six areas, there are two small areas with the experimental approach, which are located near the center of the cube, and are shaded by black. They capture the situation when there is no opposite extreme belief across players, i.e. $\phi \neq \varnothing$ and $\varphi \neq \varnothing$ are not satisfied simultaneously. At this time, mutually exclusive payoffs do not exit in players' consideration, and only when all of the players hold similar moderate beliefs, the experimental approach can be achieved, which corresponding to Proposition 1. In Figure A.2, due to three dimensions, we can only see one of the areas from this view.

[8] The six subfigures are cross sections of Figure A.2, which include all the different possible cross sections.

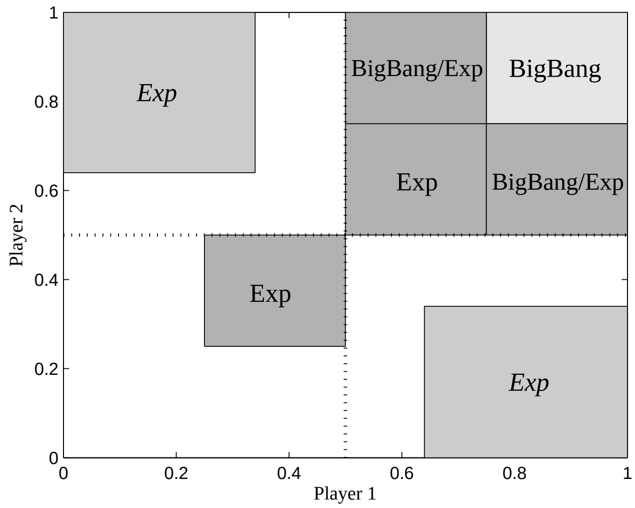


$$a_i = b_i = 2,\ i = 1, 2, 3,\ e = 1,\ d = 2,\ \rho = 0.25,\ \delta = 0.50,\ \beta = 10$$
$$A_i = 0.75,\ B_i = 0.5,\ C_i = 0.25,\ D_i = 0.34,\ E_i = 0.64$$

Figure A.2: The typical case of $N = 3$ with large β

First of all, let's focus on when contingent, mutually exclusive payoffs are effective. For contingent, mutually exclusive payoffs to be effective, there should exist opposite ideas about the trade-off between the Big Bang approach and doing nothing. In Figures A.3 and A.4, the break-even prior is 0.5. We denote this prior with dotted lines, and we divide each of Figure A.3 and the Subfigures in Figure A.4 into four parts by the dotted lines. For Figure A.3, the mutually exclusive payoffs are effective in the left-top part and the right-bottom part. For each of Subfigures A.4a, A.4b and A.4c, since Player 3 is a conservative, mutually exclusive payoffs are ineffective in the left-bottom part among the four parts, while effective in the other three. For each of Subfigures A.4d, A.4e and A.4f, since Player 3 is a reformer, mutually exclusive payoffs are ineffective in the right-top part among the four parts, while effective in the other three. Comparing Figures A.3 and A.4, introducing Player 3 greatly enlarges the area where contingent, mutually exclusive payoffs are effective from two parts to three parts among the total four parts. The intuition is simple: with a newly-added player, if all the players hold identically, independently, and uniformly distributed priors, it is more likely for opposite ideas to exist, and furthermore, when the number of players increases, the mutually exclusive payoffs are even more likely to be effective.

In the subfigures, the areas with the experimental approach being adopted and mutually



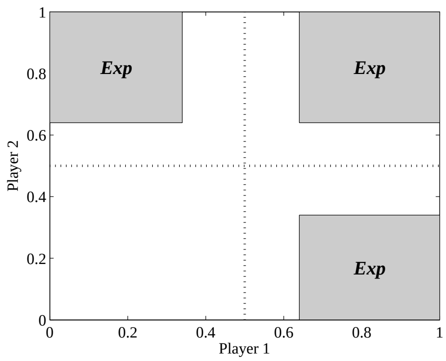
$a_1 = a_2 = b_1 = b_2 = 2$, $e = 1$, $d = 2$, $\rho = 0.25$, $\delta = 0.50$, $\beta = 10$
$A_1 = A_2 = 0.75$, $B_1 = B_2 = 0.5$, $C_1 = C_2 = 0.25$, $D = 0.34$, $E = 0.64$
The areas with the experimental approach adopted and mutually exclusive payoffs effective are marked by italic "*Exp*"; the areas with the experimental approach adopted but mutually exclusive payoffs ineffective is marked by normal "Exp"; the areas in white denotes that the policy is not adopted.

Figure A.3: The case for two players with large β

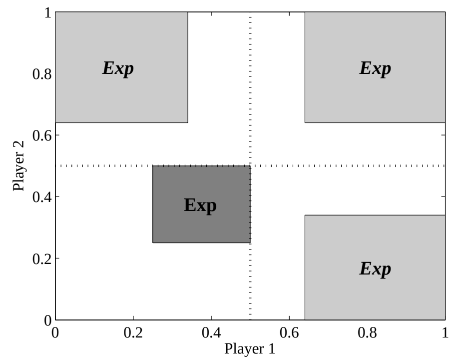
exclusive payoffs being effective are marked by italic "*Exp*"; the area with the experimental approach being adopted but mutually exclusive payoffs being ineffective is marked in normal "Exp". When Player 3 is very conservative toward the policy ($p_3 < 0.34$), as shown in Subfigures A.4a and A.4b, the experimental approach is reached at the area where Player 1 or Player 2 is strongly optimistic toward the policy, the area with diametrically opposite beliefs and effective mutually exclusive payoffs.[9] The absence of a normal "Exp" area in Subfigure A.4a when the mutually exclusive payoffs are ineffective is because of player 3's extremely conservative prior: without effective mutually exclusive payoffs, Player 3 is so conservative that she will veto the adoption of policy.

When Player 3 holds moderate belief toward the policy ($0.34 < p_3 < 0.64$), she will

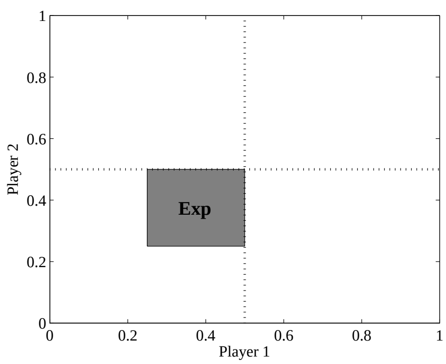
[9] Compared with Figure A.3, note that the right-top corners in Subfigures A.4a and A.4b become the experimental approach instead of the Big Bang approach. The reason comes from the interaction of consensus and mutually exclusive payoff. Since Player 3 will always veto the Big Bang approach, there is no Big Bang approach at the right-top corner ($p_1 > 0.64$, $p_2 > 0.64$, and $p_3 < 0.34$) anymore. Instead, contingent, mutually exclusive payoffs provide incentives for all the players to agree on experiment here.



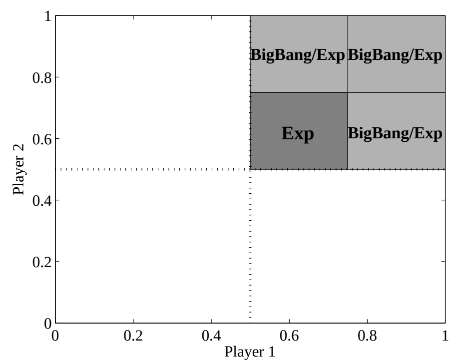
(a) Player 3: $p_3 = 0.1$



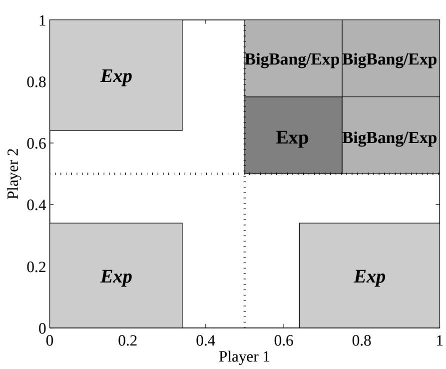
(b) Player 3: $p_3 = 0.3$



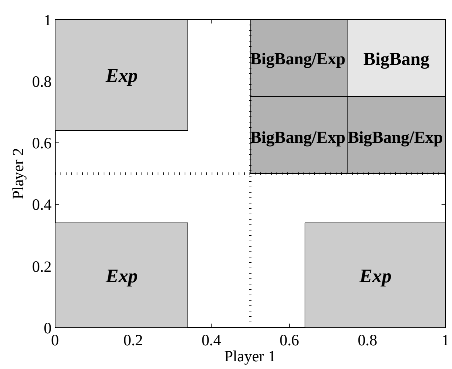
(c) Player 3: $p_3 = 0.4$



(d) Player 3: $p_3 = 0.6$



(e) Player 3: $p_3 = 0.7$



(f) Player 3: $p_3 = 0.9$

$$a_i = b_i = 2,\ i = 1, 2, 3,\ e = 1,\ d = 2,\ \rho = 0.25,\ \delta = 0.50,\ \beta = 10$$
$$A_i = 0.75,\ B_i = 0.5,\ C_i = 0.25,\ D_i = 0.34,\ E_i = 0.64$$

The areas with the experimental approach adopted and mutually exclusive payoffs effective are marked by italic "*Exp*"; the areas with the experimental approach adopted but mutually exclusive payoffs ineffective is marked by normal "Exp"; the areas in white denotes that the policy is not adopted.

Figure A.4: Typical cases for the first two players given different p_3, the third player's prior reject the experimental approach once the mutually exclusive payoffs are effective. The intuition is that when the mutually exclusive payoffs are effective, Player 3 is not confident enough of being proved correct in the experimental approach, and thus would rather choose doing nothing. As shown in Subfigure A.4c and A.4d, the experimental approach is not adopted in the three parts with effective mutually exclusive payoffs among the four parts divided by the dotted lines. When the mutually exclusive payoffs are ineffective, if Player 3 is a conservative ($p_3 < 0.5$), then she will always veto the Big Bang approach, and the experimental approach can only be adopted if all the players share moderate conservative beliefs; if Player 3 is a reformer ($p_3 > 0.5$), then either the experimental approach or the Big Bang approach can be achieved, since all of the players are reformers. This outcome structure with ineffective mutually exclusive payoffs follows the classic logic in Section 2.3.

We conclude this section by detailing the outcome change from the two-player case to the three-player case when Player 3 is strongly optimistic toward the policy ($p_3 > 0.64$). In Figure A.3, the left-bottom corner of the unit square is not occupied by any approach of policy adoption: when both players are extremely conservative, the policy is not adopted. In Subfigures A.4e and A.4f, however, the left-bottom corners of the unit squares are occupied by "*Exp*": with the newly-introduced, extremely-optimistic Player 3, the extremely conservative Players 1 and 2 would like to agree to the experimental approach. We can regard such comparison as a story in which the two extreme conservatives form an ally in the sense that they gain or lose with the mutually exclusive payoffs together, and just against Player 3. This ally is contingent on the players' priors.[10]

A.7 Proof of Proposition 3

When the conservative prefers doing nothing over the Big Bang approach,

$$q[a_c - \beta g(1)] - (1-q)[b_c - \beta h(1)] < 0, \text{ i.e. } q[a_c + b_c - \beta(g(1) + h(1))] < b_c - \beta h(1). \quad \text{(A.2)}$$

Inequation (A.2) derives the following Lemma.

Lemma 2. *If Inequation (A.2) holds for any* $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$*, then* $b_c - \beta h(1) > 0$*, and either 1)* $a_c + b_c - \beta(h(1) + g(1)) < 0$*, or 2)* $a_c + b_c - \beta(h(1) + g(1)) > 0$ *and* $\frac{b_c - \beta h(1)}{a_c + b_c - \beta(g(1) + h(1))} > \frac{b_c}{a_c + b_c}$.

[10]The difference between the right-top corners of Subfigures A.4e and A.4f, two areas without effective mutually exclusive payoffs, is slight and depends on how optimistic Player 3 is.

The intuition of the two cases follows the same logic as our discussion for Proposition 2. Now let's consider the two Cases.

Case 1 This case requires $a_c + b_c - \beta(h(1) + g(1)) < 0$ and $b_c - \beta h(1) > 0$. The requirement derives $\beta < \frac{b_c}{h(1)}$.

With $\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{h(\rho)+g(\rho)}, \frac{\rho b_c}{h(\rho)}\right\}$, Statement i) and ii) follow straightforwardly.

Also note that $\beta < \frac{b_c}{h(1)}$ and $\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{h(\rho)+g(\rho)}, \frac{\rho b_c}{h(\rho)}\right\}$ derive $\frac{\rho b_c}{h(\rho)} < \beta < \frac{b_c}{h(1)}$, which implies $\theta < 1$, Statement iii).

Note $a_c + b_c - \beta(h(1) + g(1)) < 0$ and $b_c - \beta h(1) > 0$ also derive $\frac{a_c+b_c}{h(1)+g(1)} < \beta < \frac{b_c}{h(1)}$, which is equivalent to $\frac{a_c}{b_c} < \frac{d}{e}$.

Case 2 This case requires $b_c - \beta h(1) > 0$, $a_c + b_c - \beta(h(1) + g(1)) > 0$, and $\frac{b_c - \beta h(1)}{a_c+b_c-\beta(g(1)+h(1))} > \frac{b_c}{a_c+b_c}$. The requirement needs straightforwardly $\beta < \frac{b_c}{h(1)}$.

With $\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{h(\rho)+g(\rho)}, \frac{\rho b_c}{h(\rho)}\right\}$, Statement i) and ii) follow straightforwardly.

Note that $\beta < \frac{b_c}{h(1)}$ and $\beta > \max\left\{\frac{\rho(a_c+b_c)+\delta a_c}{h(\rho)+g(\rho)}, \frac{\rho b_c}{h(\rho)}\right\}$ derive $\frac{\rho b_c}{h(\rho)} < \beta < \frac{b_c}{h(1)}$, which is equivalent to $\theta < 1$, Statement iii).

Also, given $a_c + b_c - \beta(h(1) + g(1)) > 0$ and $b_c - \beta h(1) > 0$,

$$\frac{b_c - \beta h(1)}{a_c + b_c - \beta(g(1) + h(1))} > \frac{b_c}{a_c + b_c} \Rightarrow \frac{a_c}{b_c} < \frac{d}{e}. \tag{A.3}$$

The analysis above already prove the three statements and one direction in the equivalence between "Inequation (A.2) holds for any $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$" and "$\beta < \frac{b_c}{h(1)}$ and $\frac{a_c}{b_c} < \frac{d}{e}$." Now we prove the other direction in the equivalence:

Reverse Case 1 $b_c - \beta h(1) > 0$, $\frac{a_c}{b_c} < \frac{d}{e}$, and $a_c + b_c - \beta(h(1) + g(1)) < 0$ derives that Inequation (A.2) holds for all $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$:

$b_c - \beta h(1) > 0$ means $q[a_c + b_c - \beta(g(1) + h(1))] < b_c - \beta h(1)$ holds for $q = 0$. $a_c + b_c - \beta(h(1) + g(1)) < 0$ means $q[a_c + b_c - \beta(g(1) + h(1))]$ is decreasing in q, so $q[a_c + b_c - \beta(g(1) + h(1))] < b_c - \beta h(1)$ holds for all $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$.

Reverse Case 2 $b_c - \beta h(1) > 0$, $\frac{a_c}{b_c} < \frac{d}{e}$, and $a_c + b_c - \beta(h(1) + g(1)) > 0$ derives that Inequation (A.2) holds for all $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$:

$a_c + b_c - \beta(h(1) + g(1)) > 0$ means $q[a_c + b_c - \beta(g(1) + h(1))]$ is increasing in q. Now consider the situation where $q = \frac{b_c}{a_c+b_c}$. In this situation, $q[a_c+b_c-\beta(g(1)+h(1))] = \frac{b_c}{a_c+b_c}[a_c+b_c - \beta(g(1)+h(1))]$. Note $\frac{a_c}{b_c} < \frac{d}{e}$ is equivalent to $\frac{b_c}{a_c+b_c}[a_c+b_c-\beta(g(1)+h(1))] < b_c - \beta h(1)$, so $q[a_c + b_c - \beta(g(1) + h(1))] < b_c - \beta h(1)$ holds for all $q \in \left[0, \frac{b_c}{a_c+b_c}\right)$.

Collecting the two reverse cases finishes the proof of Proposition 3.

Appendix B

Appendices of *Water-storage Capacities versus Water-use Efficiency: Substitutes or Complements?*

B.1 Proof of Proposition 4

Proof. The first term in Equation 3.13 is $\left(B_{12}(\bar{a}-\bar{s},\alpha) - B_{11}(\bar{a}-\bar{s},\alpha)\frac{\partial \bar{s}(\bar{a},\alpha)}{\partial \alpha}\right) \cdot \mathbf{P}[a_0 > \bar{a}]$, which is zero if $\mathbf{P}[a_0 > \bar{a}] = 0$. Now consider the case in which $\mathbf{P}[a_0 > \bar{a}] > 0$. We would like to analyze $B_{12}(\bar{a}-\bar{s},\alpha) - B_{11}(\bar{a}-\bar{s},\alpha)\frac{\partial \bar{s}(\bar{a},\alpha)}{\partial \alpha}$ given a_0.

When a_0 is in the zero-storage scenario, $B_{12}(\bar{a}-\bar{s},\alpha) - B_{11}(\bar{a}-\bar{s},\alpha)\frac{\partial \bar{s}(\bar{a},\alpha)}{\partial \alpha} = B_{12}(\bar{a}-\bar{s},\alpha)$, so it will be positive if and only if $B_{12}(\bar{a}-\bar{s},\alpha) \geq 0$.

When a_0 is in the positive-storage scenario, consider, more generally, $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial \alpha}$. By the Euler equation,

$$
\begin{aligned}
B_1(\min\{a_0,\bar{a}\} - s_0^*,\alpha) &= \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq \bar{a}} \cdot B_1((1-d)s_0^*+e_1,\alpha)\right] \\
&= \rho(1-d)\int_{-\infty}^{\bar{a}-(1-d)s_0^*} f_{e_1}(x) B_1((1-d)s_0^*+x,\alpha)dx, \qquad \text{(B.1)}
\end{aligned}
$$

we have

$$\begin{aligned}
&- B_{11}(\min\{a_0, \bar{a}\} - s_0^*, \alpha)ds_0^* + B_{12}(\min\{a_0, \bar{a}\} - s_0^*, \alpha)d\alpha \\
=& \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{11}((1-d)s_0^*+e_1, \alpha)\right] ds_0^* \\
&- \rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)s_0^*)B_1(\bar{a}, \alpha)ds_0^* \\
&+ \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{12}((1-d)s_0^*+e_1, \alpha)\right] d\alpha,
\end{aligned} \tag{B.2}$$

so

$$\begin{aligned}
&\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial\alpha} \\
=& \Big(B_{12}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{12}((1-d)s_0^*+e_1, \alpha)\right]\Big) \\
&\cdot \Big[B_{11}(\min\{a_0, \bar{a}\} - s_0^*, \alpha) + \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{11}((1-d)s_0^*+e_1, \alpha)\right] \\
&- \rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)s_0^*)B_1(\bar{a}, \alpha)\Big]^{-1}.
\end{aligned} \tag{B.3}$$

We then know

$$\begin{aligned}
&B_{12}(\bar{a}-s_0^*, \alpha) - B_{11}(\bar{a}-s_0^*, \alpha)\frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial\alpha} \\
=& B_{12}(\bar{a}-s_0^*, \alpha) - B_{11}(\bar{a}-s_0^*, \alpha) \\
&\cdot \Big(B_{12}(\bar{a}-s_0^*, \alpha) - \rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{12}((1-d)s_0^*+e_1, \alpha)\right]\Big) \\
&\cdot \Big[B_{11}(\bar{a}-s_0^*, \alpha) + \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{11}((1-d)s_0^*+e_1, \alpha)\right] \\
&- \rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)s_0^*)B_1(\bar{a}, \alpha)\Big]^{-1} \\
=& \Big[\rho(1-d)^2 B_{12}(\bar{a}-s_0^*, \alpha)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{11}((1-d)s_0^*+e_1, \alpha)\right] \\
&- \rho(1-d)^2 B_{12}(\bar{a}-s_0^*, \alpha) f_{e_1}(\bar{a}-(1-d)s_0^*)B_1(\bar{a}, \alpha) \\
&+ \rho(1-d)B_{11}(\bar{a}-s_0^*, \alpha)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{12}((1-d)s_0^*+e_1, \alpha)\right]\Big] \\
&\cdot \Big[B_{11}(\bar{a}-s_0^*, \alpha) + \rho(1-d)^2\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\le\bar{a}} \cdot B_{11}((1-d)s_0^*+e_1, \alpha)\right] \\
&- \rho(1-d)^2 f_{e_1}(\bar{a}-(1-d)s_0^*)B_1(\bar{a}, \alpha)\Big]^{-1}.
\end{aligned} \tag{B.4}$$

Denote $s_0^*(\bar{a}, a_0, \alpha) \equiv \bar{s}(\bar{a}, \alpha)$ or just $\bar{s}$ when $a_0 \geq \bar{a}$. Then we have

$$\begin{aligned}
& B_{12}(\bar{a} - s_0^*, \alpha) - B_{11}(\bar{a} - s_0^*, \alpha) \frac{\partial s_0^*(\bar{a}, a_0, \alpha)}{\partial \alpha} \\
= & \Big[\rho(1-d)^2 B_{12}(\bar{a} - \bar{s}, \alpha) \mathbf{E}_0 \left[I_{(1-d)\bar{s}+e_1 \leq \bar{a}} \cdot B_{11}((1-d)\bar{s} + e_1, \alpha) \right] \\
& - \rho(1-d)^2 B_{12}(\bar{a} - \bar{s}, \alpha) f_{e_1}(\bar{a} - (1-d)\bar{s}) B_1(\bar{a}, \alpha) \\
& + \rho(1-d) B_{11}(\bar{a} - \bar{s}, \alpha) \mathbf{E}_0 \left[I_{(1-d)\bar{s}+e_1 \leq \bar{a}} \cdot B_{12}((1-d)\bar{s} + e_1, \alpha) \right] \Big] \\
& \cdot \Big[B_{11}(\bar{a} - \bar{s}, \alpha) + \rho(1-d)^2 \mathbf{E}_0 \left[I_{(1-d)\bar{s}+e_1 \leq \bar{a}} \cdot B_{11}((1-d)\bar{s} + e_1, \alpha) \right] \\
& - \rho(1-d)^2 f_{e_1}(\bar{a} - (1-d)\bar{s}) B_1(\bar{a}, \alpha) \Big]^{-1}.
\end{aligned} \tag{B.5}$$

By the Euler equation we know

$$B_1(\bar{a} - \bar{s}, \alpha) = \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)\bar{s}+e_1 \leq \bar{a}} \cdot B_1((1-d)\bar{s} + e_1, \alpha) \right] \leq B_1((1-d)\bar{s} + \underline{e}, \alpha), \tag{B.6}$$

so $\bar{a} - \bar{s} \geq (1-d)\bar{s} + \underline{e}$. Note $B_1(w, \alpha) > 0$ and $B_1(w, \alpha) < 0$ by $\mathcal{B}'(\cdot) > 0$ and $\mathcal{B}''(\cdot) < 0$. Therefore, we can sign that

$$B_{12}(\bar{a} - \bar{s}, \alpha) - B_{11}(\bar{a} - \bar{s}, \alpha) \frac{\partial \bar{s}(\bar{a}, \alpha)}{\partial \alpha} \geq 0 \tag{B.7}$$

if $B_{12}(w, \alpha) \geq 0$ for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$;

$$B_{12}(\bar{a} - \bar{s}, \alpha) - B_{11}(\bar{a} - \bar{s}, \alpha) \frac{\partial \bar{s}(\bar{a}, \alpha)}{\partial \alpha} \leq 0 \tag{B.8}$$

if $B_{12}(w, \alpha) \leq 0$ for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$.

Collecting the two scenarios we know that, given any a_0, $B_{12}(\bar{a}-\bar{s}, \alpha) - B_{11}(\bar{a}-\bar{s}, \alpha)\frac{\partial \bar{s}(\bar{a}, \alpha)}{\partial \alpha}$ will be positive/negative if $B_{12}(w, \alpha)$ is positive/negative for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$.

Collecting the two cases about whether $\mathbf{P}[a_0 > \bar{a}] = 0$, the first term in Equation (3.13) will be (weakly) positive/negative if $B_{12}(w, \alpha)$ is positive/negative for any $w \in [(1-d)\bar{s} + \underline{e}, \bar{a}]$.

The second term in Equation (3.13) is $\rho B_{12}(\bar{a}, \alpha) \cdot \mathbf{E}[\mathbf{P}[e_1 > \bar{a} - (1-d)s_0^* | a_0]]$. If $\mathbf{E}[\mathbf{P}[e_1 > \bar{a} - (1-d)s_0^* | a_0]] = 0$, this term will be zero. If $\mathbf{E}\left[\mathbf{P}\left[e_1 > \bar{a} - (1-d)s_0^* | a_0\right]\right] > 0$, then $\rho B_{12}(\bar{a}, \alpha) \cdot \mathbf{E}\left[\mathbf{P}\left[e_1 > \bar{a} - (1-d)s_0^* | a_0\right]\right] \geq 0$ if and only if $B_{12}(\bar{a}, \alpha) \geq 0$. Collecting these two cases about whether $\mathbf{E}\left[\mathbf{P}\left[e_1 > \bar{a} - (1-d)s_0^* | a_0\right]\right] = 0$, the second term in Equation (3.13) will be (weakly) positive/negative if $B_{12}(\bar{a}, \alpha)$ is positive/negative.

Collecting the results about these two terms, we prove the result. □

B.2 Proof of Proposition 5

Proof. The third term in Equation (3.13) is $\rho(1-d)B_1(\bar{a},\alpha)\cdot\mathbf{E}\left[f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\right]$.

If $f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)$ is always zero given any a_0, or, equivalently, if the dam will never reach the full capacity in the second period, then this term will be zero. If any a_0 is in the zero-storage scenario, this term will be zero, too. Now we consider $f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}$ given a_0 in the case excluded from the two mentioned cases.

If $f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)=0$ or a_0 is in the zero-storage case, $f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}$ will be zero.

If $f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)>0$ and a_0 is in the positive-storage case, we would like to sign $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}$, so we follow Appendix B.1's expression of $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}$. When $B_{12}(w,\alpha)\leq 0$ for $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$,

$$\begin{aligned}&B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right]\\ \leq\ &B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\mathbf{E}_0\left[B_{12}((1-d)s_0^*+e_1,\alpha)\right].\end{aligned}\tag{B.9}$$

When $B_{12}(w,\alpha)\leq 0$ and $B_{1211}(w,\alpha)\geq 0$ for $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$, by Jensen (1903)'s inequality,

$$\begin{aligned}&B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right]\\ \leq\ &B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\mathbf{E}_0\left[B_{12}((1-d)s_0^*+e_1,\alpha)\right]\\ \leq\ &B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-B_{12}((1-d)s_0^*+\mathbf{E}_0\left[e_1\right],\alpha).\end{aligned}\tag{B.10}$$

When $B_{111}(w,\alpha)\leq 0$ for any $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$, by the Euler equation and Jensen (1903)'s inequality,

$$\begin{aligned}B_1(\min\{a_0,\bar{a}\}-s_0^*,\alpha)&=\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_1((1-d)s_0^*+e_1,\alpha)\right]\\ &\leq\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_1((1-d)s_0^*+e_1,\alpha)\right]\\ &\leq\mathbf{E}_0\left[B_1((1-d)s_0^*+e_1,\alpha)\right]\\ &\leq B_1((1-d)s_0^*+\mathbf{E}_0\left[e_1\right],\alpha),\end{aligned}\tag{B.11}$$

so $\min\{a_0,\bar{a}\}-s_0^*\geq(1-d)s_0^*+\mathbf{E}_0\left[e_1\right]$. When $B_{12}(w,\alpha)\leq 0$, $B_{1211}(w,\alpha)\geq 0$, and $B_{111}(w,\alpha)\leq 0$ for $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$ and $B_{121}(w,\alpha)\leq 0$ for any $[(1-d)s_0^*+\mathbf{E}_0\left[e_1\right],\min\{a_0,\bar{a}\}-$

$s_0^*]$,

$$\begin{aligned}
&B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right]\\
&\leq B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-B_{12}((1-d)s_0^*+\mathbf{E}_0\left[e_1\right],\alpha)\\
&\leq 0. \qquad\qquad (B.12)
\end{aligned}$$

Note that $\min\{a_0,\bar{a}\}-s_0^*\leq(1-d)\bar{s}+\bar{e}$ and $(1-d)s_0^*+\mathbf{E}_0\left[e_1\right]\geq\underline{e}$. We can then state that, when $B_{12}(w,\alpha)\leq 0$, $B_{121}(w,\alpha)\leq 0$, $B_{1211}(w,\alpha)\geq 0$, and $B_{111}(w,\alpha)\leq 0$ for any $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$,

$$B_{12}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{12}((1-d)s_0^*+e_1,\alpha)\right]\leq 0, \qquad (B.13)$$

which means $\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\geq 0$ for any a_0 in this case.

Collecting all the cases above we know that, if $B_{12}(w,\alpha)\leq 0$, $B_{121}(w,\alpha)\leq 0$, $B_{1211}(w,\alpha)\geq 0$, and $B_{111}(w,\alpha)\leq 0$ for any $w\in[\underline{e},(1-d)\bar{s}+\bar{e}]$, the third term in Equation (3.13), $\rho(1-d)B_1(\bar{a},\alpha)\cdot\mathbf{E}\left[f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\right]$, will be (weakly) positive. □

B.3 Equivalence between $W_{21}^*(\bar{a},\alpha)$ and $W_{12}^*(\bar{a},\alpha)$

First note that $W_{21}^*(\bar{a},\alpha)=\mathbf{E}\left[V_{31}^*(\bar{a},a_0,\alpha)\right]$ and $W_{12}^*(\bar{a},\alpha)=\mathbf{E}\left[V_{13}^*(\bar{a},a_0,\alpha)\right]$, so their equivalence can be induced by the equivalence between $V_{13}^*(\bar{a},a_0,\alpha)$ and $V_{31}^*(\bar{a},a_0,\alpha)$ given a_0. With some algebra, we can show that

$$\begin{aligned}
V_{13}^*(\bar{a},a_0,\alpha)=I_{a_0>\bar{a}}\cdot&\left(B_{12}(\bar{a}-s_0^*,\alpha)-B_{11}(\bar{a}-s_0^*,\alpha)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha}\right)\\
&+\rho B_{12}(\bar{a},\alpha)\left[1-F_{e_1}\left(\bar{a}-(1-d)s_0^*\right)\right]\\
&+\rho(1-d)B_1(\bar{a},\alpha)f_{e_1}\left(\bar{a}-(1-d)s_0^*\right)\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\alpha} \qquad (B.14)
\end{aligned}$$

and

$$\begin{aligned}
V_{31}^*(\bar{a},a_0,\alpha)=I_{a_0>\bar{a}}\cdot B_{21}(\bar{a}-s_0^*,\alpha)&+\rho B_{21}(\bar{a},\alpha)\left[1-F_{e_1}\left(\bar{a}-(1-d)s_0^*\right)\right]\\
-\frac{\partial s_0^*(\bar{a},a_0,\alpha)}{\partial\bar{a}}&\Big[B_{21}(\min\{a_0,\bar{a}\}-s_0^*,\alpha)\\
&-\rho(1-d)\mathbf{E}_0\left[I_{(1-d)s_0^*+e_1\leq\bar{a}}\cdot B_{21}((1-d)s_0^*+e_1,\alpha)\right]\Big]. \qquad (B.15)
\end{aligned}$$

Observe that the derivatives, $V_{13}^*(\bar{a},a_0,\alpha)$ and $V_{31}^*(\bar{a},a_0,\alpha)$, are continuous almost everywhere. Therefore, by Young (1910)'s Theorem, $V_{13}^*(\bar{a},a_0,\alpha)=V_{31}^*(\bar{a},a_0,\alpha)$ almost everywhere. We can then have $W_{21}^*(\bar{a},\alpha)=W_{12}^*(\bar{a},\alpha)$.

B.4 Resource Allocation between Water-storage Expansions and Water-use Efficiency Improvement

Consider the problem of resource allocation between increasing dam capacities by $\Delta\bar{a}$ and improving water-use efficiency by $\Delta\alpha$:

$$\max_{\Delta\bar{a}\geq 0,\Delta\alpha\geq 0} \quad W^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha) \qquad \text{s.t.} \qquad p_{\bar{a}}\cdot\Delta\bar{a}+p_\alpha\cdot\Delta\alpha\leq b, \tag{B.16}$$

where $p_{\bar{a}}\equiv C'(\bar{a})+D'(\bar{a})$ is the price for dam expansion, $p_\alpha\equiv G'(\alpha)$ is the price for water-use efficiency improvement, and b is the policy budget. An interior solution with $\Delta\bar{a}>0$ and $\Delta\alpha>0$ corresponds to a balanced distribution of the budget, while a corner solution with $\Delta\bar{a}=0$ or $\Delta\alpha=0$ corresponds to concentrating the budget on either dam expansion or water-use efficiency improvement with the other being ignored. An interior solution will be reached as long as the isovalue curve, $W^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)=v$, is tangent with the budget-constraint line, $p_{\bar{a}}\cdot\Delta\bar{a}+p_\alpha\cdot\Delta\alpha=b$, at a point with $\Delta\bar{a}>0$ and $\Delta\alpha>0$, in a $\Delta\bar{a}$-$\Delta\alpha$ span. Assuming both options are economical, it is equivalent to say that the slope of the isovalue curve in $\Delta\bar{a}$, $-\frac{W_1^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)}{W_2^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)}$, increases and becomes less negative as $\Delta\bar{a}$ increases. Mathematically, it is equivalent to

$$\frac{d\left(-\frac{W_1^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)}{W_2^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)}\right)}{d\Delta\bar{a}} = \underbrace{-\frac{W_{11}^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)}{W_2^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)}}_{(+)} + \underbrace{\frac{W_1^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)}{W_2^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)^2}}_{(+)} \cdot W_{12}^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)>0. \tag{B.17}$$

Note that complementarity between dam expansion and water-use efficiency improvement is equivalent to $W_{12}^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)>0$, so, if both options are economical, the complementarity will guarantee an interior solution to the resource allocation problem, which means that balanced distribution between the policies will be optimal. Assuming both options are economical, only extremely strong substitution with $W_{12}^*(\bar{a}+\Delta\bar{a},\alpha+\Delta\alpha)\ll 0$ could make ignoring either dam expansions or water-use efficiency improvement optimal.

B.5 Analysis and Results for the Extended Model

The extended model carries the same logic as in the simple model. The Euler (in)equations of the water-inventory management problem are

$$\begin{aligned} &B_1(w_0^{T*},\alpha) \geq \rho(1-d)\mathbf{E}_0\left[V_2^{T-1*}(\bar{a},(1-d)s_0^{T*}+e_{t+1},\alpha)\right] \text{ if } s_0^{T*}=0; \\ &B_1(w_0^{T*},\alpha) = \rho(1-d)\mathbf{E}_0\left[V_2^{T-1*}(\bar{a},(1-d)s_0^{T*}+e_{t+1},\alpha)\right] \text{ if } s_0^{T*}>0 \text{ and } w_0^{T*}>0, \end{aligned} \tag{B.18}$$

where w_0^{T*} and s_0^{T*} are the optimal water release and water storage at period 0 given the water availability, a_0, respectively, and $w_0^{T*}+s_0^{T*} \equiv \min\{a_0,\bar{a}\}$, the amount of water that is captured at period 0. The left-hand sides of the (in)equations are the marginal cost of water storage and the right-hand sides are the marginal benefit of water storage. The equation holds when the optimal water release and the optimal water storage are both positive.

Proposition 13 (Possibility of complementarity in the extended model)**.** *For any $T \geq 0$ or $T=\infty$, dam capacities and water-use efficiency could be complements:*

- *If the marginal-water-benefit channel is positive: Water-use efficiency improvement will increase the inverse demand for water;*
- *Or, if the full-dam-capacity channel is positive: Water-use efficiency improvement will decrease the inverse demand for water and the decrease is larger at larger amounts of water use.*

Mathematically, the CEMV could be positive:

- *If $B_{12}(w,\alpha) \geq 0$ for any $w \in [\underline{e},\bar{a}]$;*
- *Or, if $B_{12}(w,\alpha) \leq 0$, $B_{121}(w,\alpha) \leq 0$, $B_{111}(w,\alpha) \leq 0$, and $B_{1211}(w,\alpha) \geq 0$ for any $w \in [\underline{e},(1-d)\bar{a}+\bar{e}]$.*

Parallel corollaries then follow.

Proof. The Bellman (1957) equation is

$$V^{T*}(\bar{a},a_0,\alpha) \equiv \max_{s_0}\left\{B(\min\{a_0,\bar{a}\}-s_0,\alpha)+\rho\mathbf{E}_0\left[V^{T-1*}(\bar{a},(1-d)s_0+e_1,\alpha)\right]\right\} \quad \text{s.t.} \tag{B.19}$$

$$s_0 \geq 0, \min\{a_0, \bar{a}\} - s_0 \geq 0, a_0 \text{ is given.} \tag{B.20}$$

Given a_0, we have

$$\begin{aligned} V_1^{T*}(\bar{a}, a_0, \alpha) = {} & I_{a_0 > \bar{a}} \cdot B_1(\bar{a} - s_0^{T*}, \alpha) - B_1(\min\{a_0, \bar{a}\} - s_0^{T*}, \alpha) \frac{\partial s_0^{T*}(\bar{a}, a_0, \alpha)}{\partial \bar{a}} \\ & + \rho \mathbf{E}_0 \left[V_1^{T-1*}(\bar{a}, (1-d)s_0^{T*} + e_1, \alpha) \right] \\ & + \rho(1-d) \mathbf{E}_0 \left[V_2^{T-1*}(\bar{a}, (1-d)s_0^{T*} + e_1, \alpha) \right] \frac{\partial s_0^{T*}(\bar{a}, a_0, \alpha)}{\partial \bar{a}} \end{aligned} \tag{B.21}$$

Similar to the simple model, there are three scenarios:

Suppose $s_0^{T*} = \min\{a_0, \bar{a}\}$. Then an Euler inequation,

$$\begin{aligned} B_1(0, \alpha) & \leq \rho(1-d) \mathbf{E}_0 \left[V_2^{T-1*}(\bar{a}, (1-d)\min\{a_0, \bar{a}\} + e_1, \alpha) \right] \\ & = \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)\min\{a_0, \bar{a}\} + e_1 \leq \bar{a}} \cdot B_1(w_1^{T*}, \alpha) \right], \end{aligned} \tag{B.22}$$

must hold, but it is impossible, because

$$B_1(0, \alpha) \leq \rho(1-d) \mathbf{E}_0 \left[I_{(1-d)\min\{a_0, \bar{a}\} + e_1 \leq \bar{a}} \cdot B_1(w_1^{T*}, \alpha) \right] < B_1(0, \alpha) \tag{B.23}$$

makes a contradiction. Therefore, $s_0^{T*} \in [0, \min\{a_0, \bar{a}\})$.

Supposing $s_0^{T*} = 0$, we have

$$V_1^{T*}(\bar{a}, a_0, \alpha) = I_{a_0 > \bar{a}} \cdot B_1(\bar{a}, \alpha) + \rho \mathbf{E}_0 \left[V_1^{T-1*}(\bar{a}, e_1, \alpha) \right]. \tag{B.24}$$

Supposing $s_0^{T*} \in (0, \min\{a_0, \bar{a}\})$, an Euler equation,

$$B_1(\min\{a_0, \bar{a}\} - s_0^{T*}, \alpha) = \rho(1-d) \mathbf{E}_0 \left[V_2^{T-1*}(\bar{a}, (1-d)s_0^{T*} + e_1, \alpha) \right], \tag{B.25}$$

must hold. Then we have

$$V_1^{T*}(\bar{a}, a_0, \alpha) = I_{a_0 > \bar{a}} \cdot B_1(\bar{a} - s_0^{T*}, \alpha) + \rho \mathbf{E}_0 \left[V_1^{T-1*}(\bar{a}, (1-d)s_0^{T*} + e_1, \alpha) \right]. \tag{B.26}$$

Collecting the two scenarios of $s_0^{T*} \in [0, \min\{a_0, \bar{a}\})$, given any a_0, we have

$$\begin{aligned} V_1^{T*}(\bar{a}, a_0, \alpha) & = I_{a_0 > \bar{a}} \cdot B_1(\bar{a} - s_0^{T*}, \alpha) + \rho \mathbf{E}_0 \left[V_1^{T-1*}(\bar{a}, (1-d)s_0^{T*} + e_1, \alpha) \right] \\ & \equiv I_{a_0 > \bar{a}} \cdot B_1(\bar{a} - \bar{s}^{T}, \alpha) + \rho \mathbf{E}_0 \left[V_1^{T-1*}(\bar{a}, (1-d)s_0^{T*} + e_1, \alpha) \right], \end{aligned} \tag{B.27}$$

where we denote the water storage when the dam reaches the full capacity in period 0 as $\bar{s}^T(\bar{a},\alpha)$ or simply $\bar{s}^T$. By iteration,

$$\begin{aligned} V_1^{T*}(\bar{a},a_0,\alpha) &= I_{a_0>\bar{a}}\cdot B_1(\bar{a}-\bar{s}^T,\alpha)+\rho\mathbf{E}_0\left[V_1^{T-1*}(\bar{a},(1-d)s_0^{T*}+e_1,\alpha)\right] \\ &= I_{a_0>\bar{a}}\cdot B_1(\bar{a}-\bar{s}^T,\alpha)+\sum_{t=1}^{T}\rho^t\mathbf{E}_0\left[I_{a_t^*>\bar{a}}\cdot B_1(\bar{a}-\bar{s}^{T-t},\alpha)\right] \\ &= B_1(\bar{a}-\bar{s}^T,\alpha)\cdot I_{a_0>\bar{a}}+\sum_{t=1}^{T}B_1(\bar{a}-\bar{s}^{T-t},\alpha)\rho^t\mathbf{E}_0\left[I_{a_t^{T*}>\bar{a}}\right] \\ &= B_1(\bar{a}-\bar{s}^T,\alpha)\cdot I_{a_0>\bar{a}}+\sum_{t=1}^{T}B_1(\bar{a}-\bar{s}^{T-t},\alpha)\rho^t\left(1-F_{a_t^{T*}|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)\right). \end{aligned} \tag{B.28}$$

Therefore, the marginal benefit of dam capacities is

$$W_1^{T*}(\bar{a},\alpha)=\mathbf{E}\left[V_1^{T*}(\bar{a},a_0,\alpha)\right]=\sum_{t=0}^{T}\left(B_1(\bar{a}-\bar{s}^{T-t},\alpha)\cdot\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^{T*}>\bar{a}|a_0\right]\right]\right), \tag{B.29}$$

where $a_0=e_0$. When $T\longrightarrow\infty$, it will converge to

$$W_1^{*}(\bar{a},\alpha)=\mathbf{E}\left[V_1^{*}(\bar{a},a_0,\alpha)\right]=B_1(\bar{a}-\bar{s},\alpha)\cdot\sum_{t=0}^{\infty}\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^{*}>\bar{a}|a_0\right]\right]. \tag{B.30}$$

The CPD is then

$$\begin{aligned} W_{12}^{T*}(\bar{a},\alpha) = &\sum_{t=0}^{T}\left[\frac{dB_1(\bar{a}-\bar{s}^{T-t},\alpha)}{d\alpha}\cdot\rho^t\mathbf{E}\left[\mathbf{P}\left[a_t^{T*}>\bar{a}|a_0\right]\right]\right] \\ &-\sum_{t=0}^{T}\left(B_1(\bar{a}-\bar{s}^{T-t},\alpha)\cdot\rho^t\mathbf{E}\left[\frac{\partial F_{a_t^{T*}|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)}{\partial\alpha}\right]\right). \end{aligned} \tag{B.31}$$

The first term is the marginal-water-benefit channel. The second term is the full-dam-probability channel.

About the marginal-water-benefit channel, we want to prove: If $B_{12}(w,\alpha)\geq 0$ for any $w\in[\underline{e},\bar{a}]$, $\frac{dB_1(\bar{a}-\bar{s}^{T-t},\alpha)}{d\alpha}\geq 0$ for any $t\in\{0,1,2,\dots,T\}$. If $B_{12}(w,\alpha)\leq 0$ for any $w\in[\underline{e},\bar{a}]$, $\frac{dB_1(\bar{a}-\bar{s}^{T-t},\alpha)}{d\alpha}\leq 0$ for any $t\in\{0,1,2,\dots,T\}$.

Instead, we now try to prove a stronger result: If $B_{12}(w,\alpha)\geq 0$ for any $w\in[\underline{e},\bar{a}]$, $\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha}\geq 0$ for any a_0 and any $t\in\{0,1,2,\dots,T\}$. If $B_{12}(w,\alpha)\leq 0$ for any

$w \in [\underline{e}, \bar{a}]$, $\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha} \leq 0$ for any a_0 and any $t \in \{0, 1, 2, \ldots, T\}$. We can prove this result by mathematical induction:

When $t = T$, $\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha} = \frac{dB_1(\min\{a_0,\bar{a}\}-s_0^{0*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha}$. Note $s_0^{0*}(\bar{a}, a_0, \alpha) = 0$, so $\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha} = B_{12}(\min\{a_0, \bar{a}\}, \alpha)$. Therefore, when $t = T$, the claim is true.

Suppose the claim is true when $t = T-k$. Consider $t = T-k-1$. Note $\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha} = \frac{dB_1(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha}$. If $s_0^{k+1*}(\bar{a}, a_0, \alpha) = 0$, the claim will be true. If $s_0^{k+1*}(\bar{a}, a_0, \alpha) > 0$, the optimal storage $s_0^{k+1*}(\bar{a}, a_0, \alpha)$ and $\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha}$ are determined by the Euler equation,

$$\begin{aligned} B_1(\min\{a_0, \bar{a}\} - s_0^{k+1*}(\bar{a}, a_0, \alpha), \alpha) &= \rho(1-d)\mathbf{E}_0\left[V_2^{k*}(\bar{a}, (1-d)s_0^{k+1*}(\bar{a}, a_0, \alpha) + e_1, \alpha)\right] \\ &= \rho(1-d)\mathbf{E}_0\big[I_{(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1<\bar{a}} \\ &\quad \cdot B_1(w^{k*}(\bar{a}, (1-d)s_0^{k+1*}(\bar{a}, a_0, \alpha) + e_1, \alpha), \alpha)\big]. \end{aligned} \tag{B.32}$$

The left hand side will also increase/decrease with α, given any $s_0^{k+1*}(\bar{a}, a_0, \alpha)$, if $B_{12}(w, \alpha)$ is positive/negative for any $w \in [\underline{e}, \bar{a}]$. Since the claim is true when $t = T-k$, the right hand side of this equation will increase/decrease with α, given any $s_0^{k+1*}(\bar{a}, a_0, \alpha)$, if $B_{12}(w, \alpha)$ is positive/negative for any $w \in [\underline{e}, \bar{a}]$. Therefore, $\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha} = B_1(\min\{a_0, \bar{a}\} - s_0^{k+1*}(\bar{a}, a_0, \alpha), \alpha)$ will increase/decrease with α, if $B_{12}(w, \alpha)$ is positive/negative for any $w \in [\underline{e}, \bar{a}]$. Collecting the cases of $s_0^{k+1*}(\bar{a}, a_0, \alpha) = 0$ and $s_0^{k+1*}(\bar{a}, a_0, \alpha) > 0$, the claim is true when $t = T - k - 1$.

By mathematical induction, the claim is true for any $t \in \{0, 1, 2, \ldots, T\}$. The result about the marginal-water-benefit channel is a special case of this claim where $a_0 \geq \bar{a}$.

About the full-dam probability channel, we want to prove: If $B_{12}(w, \alpha) \leq 0$, $B_{121}(w, \alpha) \leq 0$, $B_{111}(w, \alpha) \leq 0$, and $B_{1211}(w, \alpha) \geq 0$ for any $w \in [\underline{e}, (1-d)\bar{a} + \bar{e}]$, $\frac{\partial F_{a_t^{T*}|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)}{\partial \alpha} \leq 0$ for any $t \in \{0, 1, 2, \ldots, T\}$.

First we try to prove: If $B_{12}(w, \alpha) \leq 0$, $B_{121}(w, \alpha) \leq 0$, $B_{111}(w, \alpha) \leq 0$, and $B_{1211}(w, \alpha) \geq 0$ for any $w \in [\underline{e}, (1-d)\bar{a} + \bar{e}]$, $\frac{\partial s_0^{T-t*}(\bar{a},a_0,\alpha)}{\partial \alpha} \geq 0$ for any a_0 and any $t \in \{0, 1, 2, \ldots, T\}$. We will prove this claim by mathematical induction.

When $T = t$, $s_0^{T-t*}(\bar{a}, a_0, \alpha) = s_0^{0*}(\bar{a}, a_0, \alpha) = 0$. The claim is true.

Suppose the claim is true when $t = T - k$. Consider $t = T - k - 1$. If $s_0^{k+1*}(\bar{a}, a_0, \alpha) = 0$, the claim will be true. If $s_0^{k+1*}(\bar{a}, a_0, \alpha) > 0$, the optimal storage $s_0^{k+1*}(\bar{a}, a_0, \alpha)$ and

$\frac{dB_1(w_0^{T-t*}(\bar{a},a_0,\alpha),\alpha)}{d\alpha}$ are determined by the Euler equation,

$$\begin{aligned} B_1(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha) &= \rho(1-d)\mathbf{E}_0\left[V_2^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)\right] \\ &= \rho(1-d)\mathbf{E}_0\big[I_{(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1<\bar{a}} \\ &\quad \cdot B_1(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\big]. \end{aligned} \tag{B.33}$$

Given $s_0^{k+1*}(\bar{a},a_0,\alpha)$, the impact of α on the left-hand side is $B_{12}(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha)$. The impact on the right-hand side is $\rho(1-d)\mathbf{E}_0\big[I_{(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1<\bar{a}}\cdot\big(B_{12}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)-B_{11}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\frac{\partial s_0^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)}{\partial\alpha}\big)\big]$. The impact on the left-hand side net of that on the right-hand side is

$$\begin{aligned} & B_{12}(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha) \\ & -\rho(1-d)\mathbf{E}_0\big[I_{(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1<\bar{a}}\cdot\big(B_{12}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha) \\ & -B_{11}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\frac{\partial s_0^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)}{\partial\alpha}\big)\big] \\ \le & B_{12}(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha) \\ & -\rho(1-d)\mathbf{E}_0\big[I_{(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1<\bar{a}}\cdot B_{12}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\big] \\ \le & B_{12}(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha)-\mathbf{E}_0\big[B_{12}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\big] \\ \le & B_{12}(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha)-B_{12}(\mathbf{E}_0\big[w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)\big],\alpha) \end{aligned} \tag{B.34}$$

By the Euler equation,

$$\begin{aligned} B_1(\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha) &= \rho(1-d)\mathbf{E}_0\big[I_{(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1<\bar{a}} \\ &\quad \cdot B_1(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\big] \\ &\le \mathbf{E}_0\big[B_1(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\big] \\ &\le B_1(\mathbf{E}_0\big[w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)\big],\alpha). \end{aligned} \tag{B.35}$$

Therefore, $\min\{a_0,\bar{a}\}-s_0^{k+1*}(\bar{a},a_0,\alpha)\ge\mathbf{E}_0\big[w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)\big]$. Therefore, the impact on the left-hand side net of that on the right-hand side is

$$\begin{aligned}
&B_{12}(\min\{a_0,\bar{a}\} - s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha) \\
&- \rho(1-d)\mathbf{E}_0\big[I_{(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1<\bar{a}} \cdot \big(B_{12}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha) \\
&- B_{11}(w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha),\alpha)\frac{\partial s_0^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)}{\partial\alpha}\big)\big] \\
\le & B_{12}(\min\{a_0,\bar{a}\} - s_0^{k+1*}(\bar{a},a_0,\alpha),\alpha) - B_{12}(\mathbf{E}_0\big[w^{k*}(\bar{a},(1-d)s_0^{k+1*}(\bar{a},a_0,\alpha)+e_1,\alpha)\big],\alpha) \\
\le & 0.
\end{aligned} \tag{B.36}$$

Therefore, $s_0^{k+1*}(\bar{a},a_0,\alpha)$ will increase with α. Collecting the cases of $s_0^{k+1*}(\bar{a},a_0,\alpha)=0$ and $s_0^{k+1*}(\bar{a},a_0,\alpha)>0$, the claim is true when $t=T-k-1$.

By mathematical induction the claim is proved.

Now we try to prove the result about the full-dam probability channel by mathematical induction. When $t=0$, $F_{a_t^{T*}|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)=I_{a_0<\bar{a}}$, which is independent on α. The claim is true.

Suppose the claim is true when $t\le k$. Consider $t=k+1$. Note $a_t^{T*}=a_{k+1}^{T*}=(1-d)s_0^{T-k*}(\bar{a},a_k^{T*},\alpha)+e_{k+1}=(1-d)s_0^{T-k*}(\bar{a},(1-d)s_0^{T-k+1*}(\bar{a},a_{k-1}^{T*},\alpha)+e_k,\alpha)+e_{k+1}$. Since $s_0^{T-k*}(\bar{a},a_0,\alpha)$ is increasing in a_0 and α, we have $\frac{\partial F_{a_t^{T*}|\bar{a},a_0,\alpha}(\bar{a};\bar{a},a_0,\alpha)}{\partial\alpha}\le 0$ when $t=k+1$.

By mathematical induction, the result about the full-dam probability channel is then proved.

Collecting the two channels we prove the proposition for $T<\infty$. The result will hold in the limit for $T\longrightarrow\infty$. □

B.6 Specification of the Numerical Illustrations

The California State Water Projects captures water from the Sierra Nevada through the Feather River into Lake Oroville, the main storage facility of the Project.[1] In each year, inflows and spills are predominately during winter and spring (January–May). Water stored in Lake Oroville is released into the Oroville-Thermalito Complex (Thermalito Forebay), then transported from the Complex southward through the Feather River, the Sacramento

[1]The Project starts from three reservoirs in the Upper Feather area – Antelope Lake, Frenchman Lake, and Lake Davis. Spills and releases from the three reservoirs flow into the Feather River.

River, and the California Aqueduct, and stored in reservoirs locating along the Project from the north to the south. Around May–June, the Project decides water allocation for contractors in the current year, which generates irrigation benefit in the second half of the year. Around November–December, observing storage in principal reservoirs, the Project announces a preliminary plan for water allocation in the next year. This operation pattern fits our model and we can use the calendar year as the time unit in the specification of the model.

The 1974–2010 data of the end-of-calendar-year storage in principal reservoirs of the California State Water Project are available from the California Department of Water Resources (1963–2013, 1976–2014). The Department (1963–2013) reports the 1975–2010 data of the project wide deliveries. According to the Department (1976–2014), the average annual evaporation-loss rate of the water storage in the five primary storage facilities – Antelope Lake, Frenchman Lake, Lake Davis, Lake Oroville, and the San Luis Reservoir – in 1976, 1981, 1986, 1991, 1996, and 2001 is 0.038, which is approximately 0.04. The Department (1976–2014; 1990–2014) also reports the 1975–2010 data of the amount of spills from Lake Oroville. Given the evaporation-loss rate, the 1974–2010 end-of-calendar-year storage data, the 1975–2010 delivery data, and the 1975–2010 spill data, we can find the corresponding 1975–2010 inflows by calculation, which have a mean of 3891587 acre-feet and a corrected sample standard deviation of 1444480 acre-feet. The total amount of water that is captured by the Project, which is the end-of-calendar-year storage plus the project wide deliveries, has a mean of 7285378 acre-feet for the 20 years that saw positive spills among the 36 years. We set the storage capacity that is equivalent to our model as 7285378 acre-feet.[2]

The Department (1963–2013) records the 1975–2010 data of the annual deliveries to agricultural use, which have a mean of 936098 acre-feet or, equivalently, 27.80% of the total delivery. We use this percentage to adjust the inflow distribution and the storage capacity, which means that, for agricultural use, the baseline storage capacity is $0.2780 \times 7285378 = 2025335$ acre-feet and the inflow distribution has a mean of $0.2780 \times 3891587 = 1081861$ acre-feet and a corrected sample standard deviation of $0.2780 \times 1444480 = 401565$ acre-feet. The distribution of the adjusted, estimated historical inflows, which we use in the illustrations,

[2]The Department (1963–2013) reports that the project wide storage capacity is 5.4038 million acre-feet at the end of 2010. This is not the capacity equivalent to our model.

is uniform with 36 possible values.[3]

The Department (1998–2005) publishes its annual estimates of irrigated crop areas, consumed fractions, and applied water per unit of area. The latest data available online are for 2005. We calculate the benchmark water-use efficiency in the following procedure: First, we focus on the county-level data for the 18 counties that were served by the 29 long-term contracting agencies of the California State Water Project at the end of 2010.[4] Second, for each county and each crop among the 20 categories of crops, we calculate the total amount of applied water in 2005 by multiplying the irrigated crop area with the applied water per unit area.[5] Third, for each county and each crop, we calculate the total amount of effective water by multiplying the total amount of applied water with the consumed fraction. Finally, we aggregate the total amounts of applied and effective water by counties and crops, and calculate the overall water-use efficiency by dividing the total amount of effective water over the total amount of applied water, which is 0.7135.

A recent estimate of the price elasticity of the water demand for irrigation in California by Schoengold et al. (2006) is -0.79 with panel data in which the mean price is \$46.49 per thousand cubic meters, which is approximately \$57 per acre-foot.[6] We then assume that, in our specification, the water demand should be 936098 acre-feet if the water price is \$57 per acre-foot and the water-use efficiency is 0.7135.[7] Given this assumption, we specify three functions of the benefit of water release satisfying, respectively, that 1) the derived water demand (or marginal benefit of water release) is isoelastic and has an elasticity of -1.21, 2) the derived water demand is isoelastic and has an elasticity of -0.79, and 3) the derived water demand is linear and has an elasticity of -0.79 when the demand is 936098 acre-feet. We also

[3]The 36 values are 239001, 345959, 538214, 584182, 611960, 632764, 683223, 794128, 824611, 824867, 846706, 888651, 894498, 928424, 968210, 999585, 1052469, 1059629, 1106896, 1108130, 1111920, 1151602, 1186559, 1210988, 1309659, 1336180, 1398546, 1403399, 1409113, 1432491, 1473347, 1486822, 1609242, 1761617, 1813942, and 1919462.

[4]The 18 counties include Alameda, Butte, Kern, Kings, Los Angeles, Napa, Orange, Plumas, Riverside, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Santa Clara, Solano, Stanislaus, Ventura, and Yuba Counties. The 29 agencies are listed in the California Department of Water Resources (1963–2013, Bulletin 132-11, p. 11).

[5]The 20 categories include grain, rice, cotton, sugar beets, corn, beans, safflower, other field crops, alfalfa, pasture, tomatoes for processing, tomatoes for market, cucurbits, onions and garlic, potatoes, other truck crops, almonds and pistachios, other deciduous fruit crops, subtropical fruits, and vines.

[6]We read the variable cost of water in Schoengold et al. (2006)'s Table 2 as the price.

[7]Note that only the relative price but not the absolute price matters, so the number of the price does not matter for the results that we illustrate.

assume free disposal of water so that the marginal benefit of water will never be negative. The three functions of the benefit of water release are then shown as in Table 3.1.

In water project evaluations, the annual discount rate recommended by the California Department of Water Resources (2008) is 0.06. The discount factor is then $(1 + 0.06)^{-1} = 0.9434$. We then finish specifying the empirical example, as shown in Table 3.2.

Appendix C

Lien-Tsao Hsieh 谢琏造 謝璉造

C.1 A Brief Chronology

- December 11, 1915: Born in Yixing, China.
- 1922–1928: Studied at a primary school in Yixing.
- 1928–1931: Studied at Provincial I-Shing High School in Yixing.
- September 18, 1931: Japan invaded northeastern China.
- 1931–1934: Continued studying at Provincial I-Shing High School.
- 1934–1935: Studied in the Cotton Cultivation Program at the College of Agronomy, National Central University, Nanjing, China.
- 1935–1937: Worked as an associate at the Central Institute of Cotton Production Improvement at Nanjing.
- July 7, 1937: The Second Sino-Japanese War began.
- 1938–1939: Worked as an associate at the Department of Cotton Cultivation, the Central Research Institute of Agriculture (former Central Institute of Cotton Production Improvement) at Nanjing.
- 1939: Left the Central Research Institute of Agriculture under political repression.

- February 1940–July 1941: Studied at the Great China University, Guiyang, China.
- September 1941: Started studying at the National Southwestern Associated University, Kunming, China.
- December 7, 1941: The Pacific War began.
- January 1944: Received the Bachelor of Arts in History from the National Southwestern Associated University.
- February 1944: Started working for the Bureau of Foreign Affairs of the Military Affairs Commission of the Republic of China in Kunming as a translator in the United States Army training program for the Republic of China National Army.
- May 1945: Transferred from the Bureau of Foreign Affairs to the United States Department of the Army in Kunming as a translator in future training programs in the United States for the Republic of China National Army.
- June 18, 1945: Arrived at Washington, D.C. from Kunming after flying over the Himalayas and stopping at New Delhi, India, Cairo, Egypt, and Casablanca, Morocco.
- June 19–July 2, 1945: Assigned from Washington, D.C. to Minter Field Army Airfield, CA by train.
- July 2–August 1945: Worked at Minter Field Army Airfield.
- August 1945: Started working at Lowry Air Force Base, CO and studying at the University of Denver, CO.
- August–September 1945: Japan surrendered, the Second Sino-Japanese War, Pacific War, and Second World War ended, and the Chinese Civil Water began.
- April 1946: Ended working at Lowry Air Force Base and started working at Bergstrom Air Force Base, TX.
- August 1946: Ended working at Bergstrom Air Force Base and studying at the University of Denver.

- September 1946–July 1948: Studied at the University of Colorado, Boulder, CO, and joined the Cosmopolitan Club and the Graduate Club at the University of Colorado, Boulder.[1]

- August 1948: Received the Master of Arts in History from the University of Colorado, Boulder with the thesis, *American Contributions to the Study of Chinese History,* approved by Frank Earl Swisher (Chair) and Colin B. Goodykoontz.[2]

- September 1948: Started writing the Ph.D. dissertation in History at the University of South Carolina, Columbia, SC on a fellowship, living at 2322 Terrace Way, Columbia, SC.[3] The dissertation would be on the history of Chinese immigrants in America.

- September 1949: Started working as a research assistant at the Bancroft Library of the University of California, Berkeley, CA and an editor of *Chung Sai Yat Po (China West Daily)* in San Francisco, CA, living at 735 Clay Street, San Francisco, CA.[4]

- October 1, 1949: The People's Republic of China was founded.

- June 25, 1950: The Korean War began.

- June 30, 1950: Left San Francisco for China by sea.

- September 12, 1950–April, 1952: Worked as an Associate Research Fellow at the Institute of Modern History of the Chinese Academy of Science, Beijing, China.

- April–October 1952: Participated in the negotiation of the Korean Armistice Agreement at Panmunjom, Korea as a member of the Chinese delegation.

- October 1952: Returned from Panmunjom and continued working at the Institute of Modern History.

- July 27, 1953: The Korean Armistice Agreement was signed.

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[1]See the University of Colorado, Boulder (1947, 1948a,b) for reference. The Cosmopolitan Club at the University of Colorado (2016a,b) "is one of the oldest student organizations at the University of Colorado at Boulder," which "began as [a] social club to as a place of welcome, social activities, and inter-cultural and international understanding" at the University of Colorado, Boulder in the early 1920s.

[2]See Hsieh (1948) for reference.

[3]The Gamecock (1949) reports the fellowship appointment.

[4]See the University of California (1949–1950, p. 123) for reference.

- 1962: Attended the Pakistan Historical Society's Pakistan History Conference at Lahore, Pakistan.[5]
- March 14, 1962: Died of cancer in Beijing, survived by his wife, Ninghua Qu, son, Yuanhui, and daughters, Yuanan and Yuankai.[6]

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[5]This attendance is documented by Khan (1978, p. 24–25).
[6]Ninghua Qu was Shih-Ying Chü (1926)'s first child. Yuanhui Xie is Yang Xie's father.

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