WACCShed: A Platform for the Study of Watersheds as Dynamic Coupled Natural and Human Systems

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Abstract

This study describes the development of the *W*ater *A*nd *C*limate *C*hange Water*shed (WACCShed)* Platform, an agent-based software platform that permits the systematic study of interactions among hydrology, climate, and strategic human decision-making in a watershed over time. To illustrate the capabilities of the platform, findings are reported for a base-case application reflecting, in simplified form, the structural attributes of the Squaw Creek watershed in central Iowa. Attention is focused on the alignment of welfare outcomes as a prerequisite for effective watershed governance. Key treatment factors include farmer and city manager decision modes for land and budget allocations, farmer targeted savings, and the effectiveness of city levee investments for the mitigation of city flood damage. Welfare misalignment is found to arise across a broad spectrum of settings for these treatment factors.

Keywords: Watershed, agent-based software, dynamic coupled natural and human system, strategic human decision-making, environmental uncertainty

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1. Introduction

1.1. Study Scope and Organization

Sustainable access to adequate water ranks among the most serious challenges facing the world in the 21st century. Finding solutions requires coordinated efforts by natural and social scientists, engineers, water managers, policy-makers, and stakeholders from the broader community. These groups have diverse interests, values, histories, and disciplinary perspectives. Changing climate, demographics, and economic demands add to the challenge by presenting a moving target. Complicating matters further are the complex and seemingly contradictory messages the public receives about expected changes, especially concerning climate (Barsugli et al., 2013; Hewitson et al, 2014). This poor communication allows parties to focus on messages that align best with their views, ignoring other viewpoints (Sarewitz, 2004).

Cohesive planning for sustained water resources with community support will thus require continual co-development of knowledge and problem solutions (Rosenzweig et al., 2014). Software frameworks permitting water sustainability issues to be studied from multiple viewpoints by means of systematic computational experimentation can potentially enhance this co-development.

This paper describes the development of the *W*ater *A*nd *C*limate *C*hange Water*shed (WACCShed)* Platform, an agent-based software framework for the modeling of watersheds as dynamic coupled natural and human systems (Liu et al., 2007). As depicted in Fig. 1, the platform facilitates the study of hydrology, climate, and human decision-making processes in a watershed over time. It permits the modeling of the physical and institutional environment that shapes and channels the actions of human watershed participants. In turn, as advocated by An (2012), it permits a watershed environment to be affected by the actions and interactions of its human participants.

To illustrate the capabilities of the WACCShed Platform, findings are reported for a base-case application that captures, in highly simplified form, the structural attributes of the Squaw Creek watershed in central Iowa (Wendt, 2007). The base case omits institutional arrangements and policies, such as credit systems and crop insurance programs, in order to highlight more clearly the types of risks faced by human watershed participants arising from uncertain physical and economic conditions. The base case also restricts attention to a small number of decision-makers in order to identify with care

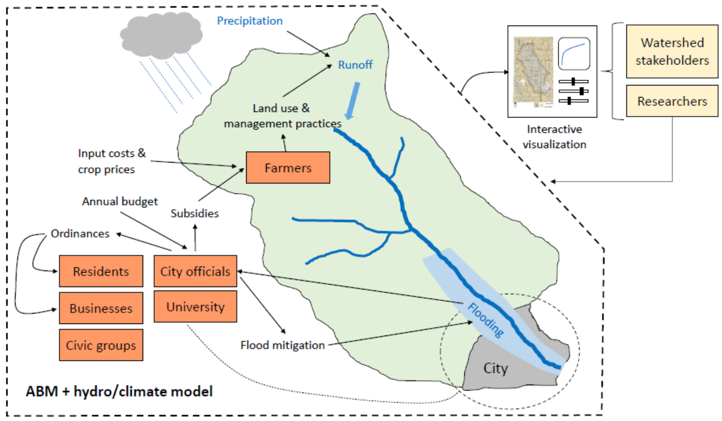

Figure 1: WACCShed: An agent-based software framework for the study of watersheds

the manner in which their risk-management practices result in an intrinsic dynamic coupling of natural and human systems.

The base-case watershed consists of a farmer who owns and manages upstream farmland and a city manager who oversees a downstream city susceptible to flooding. The principal focus of attention is the dynamic interplay among strategic goal-directed human decision-making, crop production, and hydrological processes. In pursuit of consumption and savings objectives, the farmer annually divides her farmland into three portions: cropland; land left fallow; and retention land, i.e., land for which management practices result in higher water retention (lower water runoff) than cropland and fallow land. The city manager annually allocates the city budget among city social services, retention-land subsidy payments, and levee investments in pursuit of city social welfare objectives.

The land and budget allocation decisions of the farmer and city manager are complicated by environmental uncertainty regarding precipitation patterns, input costs, and crop prices, and by behavioral uncertainty regarding the future decisions of the other agent. Strategic interaction arises because the farmer's land allocations depend on the subsidy rates for retention land set by the city manager, and the city manager considers this dependence when determining these subsidy rates.

Alignment of welfare outcomes is a critical prerequisite for the effective governance of watershed systems since it permits stakeholders to agree on coordinated actions for their common betterment (Ostrom, 1990). This study reports welfare alignment findings for the base-case watershed under systematically varied settings for four treatment factors. The first factor is the specification of farmer and city manager decision modes, either OFF or ON. Under the OFF mode, the decision maker determines annual land or budget allocations by means of a simple myopic decision rule. Under the ON mode, the decision maker determines annual land or budget allocations by solving an expected welfare maximization problem. The second factor is the farmer's risk tolerance. The third factor is the farmer's targeted savings level for the end of her planning period. The fourth factor is the effectiveness of levee quality in preventing city flood damage.

A key finding is that welfare misalignment is a common occurrence across a broad range of tested treatments; that is, farmer welfare and city social welfare tend to be negatively correlated. For example, all else equal, the welfare of the farmer tends to be highest when the farmer's targeted savings level is moderate; but city social welfare tends to be highest when the farmer's targeted savings level is low, forcing her to rely on water-retention land subsidy payments for the purchase of inputs for crop production.

Section 1.2 clarifies the relationship of this study to the existing literature. Section 2 outlines key aspects of WACCShed's software architecture. The base-case application of the WACCShed Platform is presented in summary form in Section 3 and in more detailed form in Section 4. Section 5 presents a sensitivity design for base-case computational experiments, with a focus on welfare comparisons. Dynamic feedback loops affecting welfare comparisons under this sensitivity design are discussed and illustrated in Section 6, and detailed welfare outcomes under this sensitivity design are reported in Section 7. Concluding remarks are given in Section 8. Technical details are provided in appendices, along with a nomenclature table listing definitions for key base-case variables and functional forms.

1.2. Relationship to Existing Literature

Agent-Based Modeling (ABM) is well suited for the study of dynamic coupled natural and human (CNH) systems (An, 2012; Heckbert et al, 2010; Muller et al., 2014; Tesfatsion, 2015). ABM permits researchers to tailor models to real-world systems rather than forcing researchers to simplify system representations purely for analytical tractability. It enables researchers to develop empirically-based frameworks that capture the salient physical, biological, and institutional aspects of a real-world system and then pose the following types of questions: Given these environmental characteristics, what do the human participants do? What could they do? What should they do, given their various purposes?

As detailed in (Axelrod and Tesfatsion, 2006; Borrill and Tesfatsion, 2011; Chen, 2016), an ABM study of a dynamic system begins with assumptions about the agents (persistent entities) constituting the system and their potential interactions, and then uses computer simulations to generate histories that reveal the dynamic consequences of these assumptions. The agents can range from physical and biological entities with no cognitive function, such as rivers and crops, to individual and group decision-makers with sophisticated learning and communication capabilities.

ABM researchers use computer experiments to investigate how large-scale effects arise from the micro-level interactions of agents, starting from initial conditions, much as a biologist might study the dynamic properties of a culture in a petri dish. The first step is to construct a computational world suitable for the purpose at hand. The world should incorporate relevant physical conditions and institutional arrangements, and it should be populated with decision-making agents endowed with realistic behavioral dispositions and learning capabilities who interact subject to these conditions and arrangements. The second step is to specify initial conditions for the computational world. The final step is to permit the computational world to evolve over time driven solely by agent interactions, with no further intervention from the modeler.

ABM researchers taking a normative approach to the study of institutional arrangements are interested in two basic types of questions. First, do current or proposed arrangements promote efficient, fair, and orderly social outcomes over time, despite possible attempts by system participants to game these arrangements for their own advantage? Second, under what conditions might these arrangements give rise to adverse unintended consequences? See Tesfatsion (2011) for a detailed discussion of this type of study.

Researchers are increasingly using ABM to study how human decisions influence hydrological processes. Examples include ABM studies of watersheds (Valkering et al., 2005; Ng et al., 2011; Nikolic et al., 2013), large river basins (Barthel et al., 2005; Nickel et al., 2005), and urban area water infrastructure (Giacomoni et al., 2013; Kanta and Zechman, 2014; Smith et al., 2015). Several ABM researchers have used CNH models to study the interaction of farmers with water resources. Topics have included: the crop-yield effects of coordination among farmer associations (Lansing and Kremer, 1993); the connection between upstream water management and the viability of downstream farming (Becu et al., 2003); the effects of subsistence farming on deforestation (Bithell and Brasington, 2009); and the impacts of farming input costs, crop prices, carbon allowances, and biofuel adoption on farmer behavior and stream nitrate loads (Ng et al., 2011).

These studies demonstrate the power of coupling ABM with models of hydrology, but they also illustrate some of the challenges. A key challenge is the trade-off between realism and depth of understanding. As models become more realistic with regard to their modeling of structure, institutions, and human behavior, the resulting complexity of the models can limit the ability to understand the potential effects of changes in these factors (Bithell and Brasington, 2009; Filatova et al., 2013; Morgan et al., 2015).

As will be clarified in subsequent sections, the WACCShed Platform facilitates the balancing of realism and understanding. The platform can be used to develop and study a spectrum of watershed models ranging from relatively simple conceptual thought-experiments to detailed empirically-grounded representations. The flexible modular architecture of the platform eases the transition from one form of modeling to the next.

2. WACCShed Software Architecture

WACCShed is a software platform developed entirely in Java. It is expressly designed to support the systematic study of coupled interactions among hydrological, climate, and human decision-making processes over time.

WACCShed is a modified version of GLOWA-Danube (Barthel et al, 2008; GLOWA-Danube Project, 2014). The latter platform is a complex software framework consisting of over 30 Java packages developed specifically for the study of the Danube River watershed. To obtain the WACCShed Platform, the packages comprising GLOWA-Danube were substantially reduced in number and simplified in form.

As depicted in Fig. 2, WACCShed consists of five principal types of software components:

- *Configuration:* This component reads configuration files into the system and sets up three configuration classes (SimulationConfiguration, AreaMetaData, and ComponentMetaData).

- *Modules:* Each module is run iteratively by invoking the following four methods: ProvideData(), StoreData(), GetData(), and Compute(). Each module has: (i) a table of module-specific watershed area units;

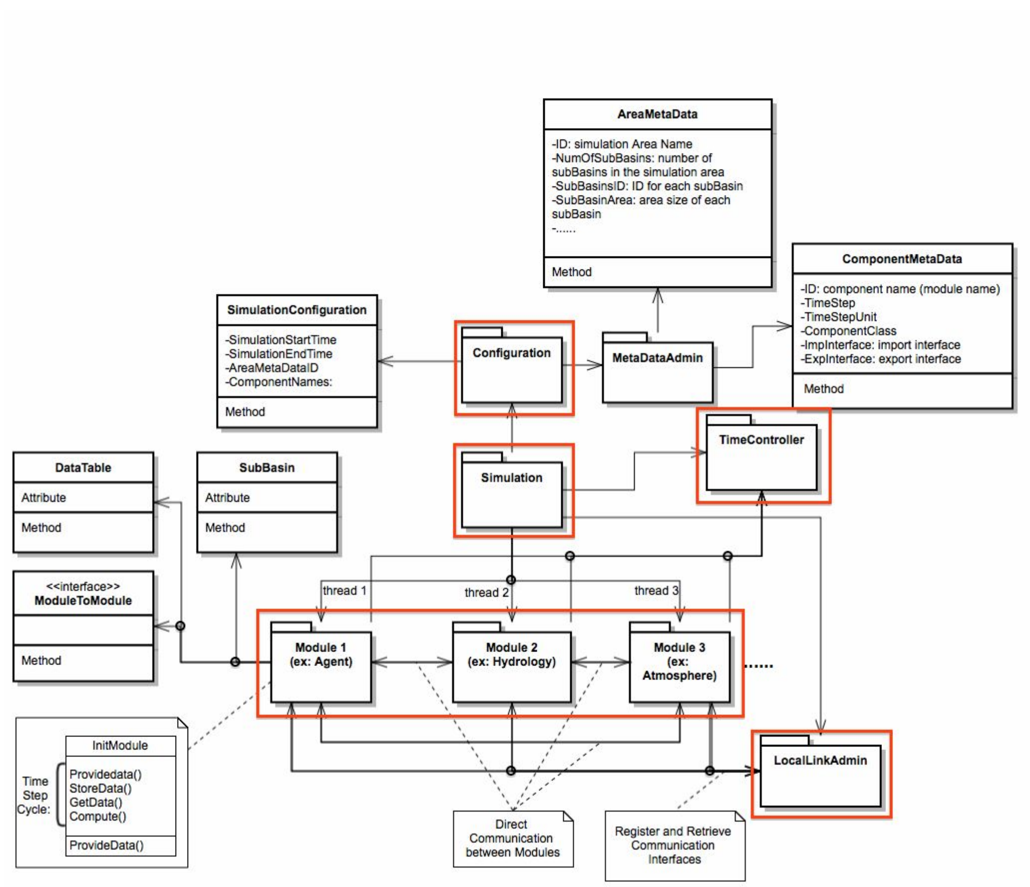

Figure 2: The WACCShed Platform (V1.0) – Principal Software Components

(ii) a set of DataTables (to store run-time module parameter values); and (iii) a set of interfaces for communication among different modules.

- *LocalLinkAdmin:* This component functions as a database for registering and retrieving the interfaces of all of the modules.

- *TimeController:* This component coordinates communication among different modules, and ensures that data exchanges among different modules are consistent.

- *Simulation:* This component is the Main class for instantiating each of the other four components. It also coordinates the interactions among the four other components, and it makes sure the simulation is fault safe; that is, it will abort the simulation if any simulation failure occurs.

Key capabilities of the WACCShed Platform (V1.0) are as follows:

- The platform can be easily modified and extended in accordance with user requirements.
- The platform has a simple well-designed TimeController to handle time coordination among different modules.
- The platform permits the modules to be flexibly implemented.
- The platform can be run on a cluster of computers, given appropriate extensions of a small number of Java classes.

3. WACCShed Base-Case Application: Overview

3.1. Base-Case Human Decision-Making and Watershed Environment

As depicted in Fig. 3, the base-case application represents an agricultural watershed that consists of upstream farmland suitable for growing corn and a downstream city. The upstream farmland is owned by a Farmer seeking to survive and prosper over time through appropriate annual allocations of her land among alternative uses. The city is overseen by a City Manager tasked with maintaining city social services and mitigating city flood damage through appropriate annual allocations of the city budget.

The decision-making of the Farmer and City Manager are complicated by three sources of uncertainty. First, both face *behavioral uncertainty* regarding the decisions to be selected by the other agent, and also by themselves when faced with equally preferred options (resolved by random "coin flips"). Second, both face *weather uncertainty* in the form of stochastic annual precipitation patterns. Third, the Farmer faces *economic uncertainty* in the form of stochastic annual planting costs and corn-market prices.

An additional complicating factor is that the financial and physical environments vary over time. As will be clarified in Sections 4.2 and 4.3, the Farmer's money holdings at the start of the initial year are set exogenously. However, the Farmer's money holdings at the start of each subsequent year are then determined endogenously by her interim receipts and expenditures. Also, levee quality at the start of the initial year is set exogenously. However, levee quality at the start of each subsequent year is then determined

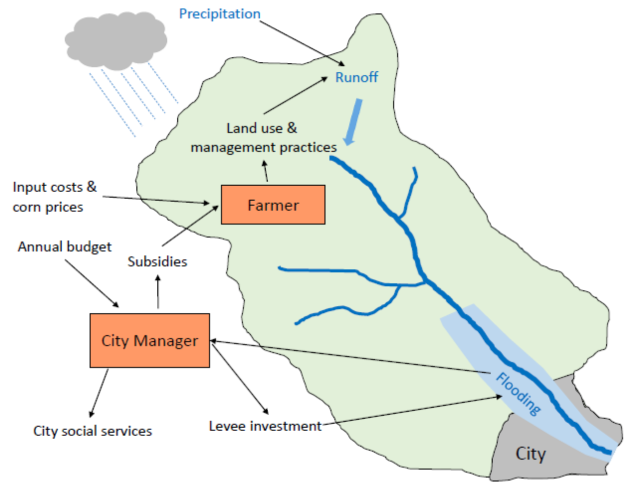

Figure 3: Base-case application of the WACCShed Platform

endogenously as a function of the City Manager's annual levee investment expenditures and a levee depreciation rate.

3.2. Base-Case Hydrology Module

The hydrology module for the WACCShed base-case application is a simplified implementation of the U.S. Army Corps of Engineers Hydrologic Modeling System (HEC-HMS). HEC-HMS is well tested and widely applied within the hydrology and engineering communities (Feldman, 2000; Scharffenberg, 2013). For example, it is used by the City of Ames, Iowa, to support flood prediction and response (Schmieg et al., 2011).

The WACCShed hydrology module permits simulation of single or multiple watershed sub-basins. For the base-case application, the module includes the entire Squaw Creek watershed (17 sub-basins) in accordance with the configuration and parameterization of the Ames model (Schmieg et al., 2011). The module includes functions to compute runoff from sub-basin areas, convert the runoff to sub-basin outflow, and route the sub-basin outflow to the watershed outlet. However, since it is primarily designed for the simulation of peak flow rates, a constant baseflow is assumed for simplicity. Runoff and river routing processes, as well as discharge output, are computed on a time-step identical to the time-step used for rainfall input data. Currently the module is capable of simulating either on a 30-minute or a 1-hour time-step.

The required input for the hydrology module is precipitation, and the output is discharge at the watershed outlet. The module is currently designed to use point-scale rainfall data (e.g., rain gauge data). The point-scale values are processed using the Thiessen Polygon gauge weighting technique to compute an average precipitation for each sub-basin. The Thiessen weights must be computed outside the module and specified prior to running the module.

Runoff for each sub-basin is computed using the sub-basin average precipitation and the curve number method. The curve number is an empirical value that describes the water runoff potential of a specified land area based on attributes such as vegetation cover and soil type.

4. Timeline of Activities for the Base-Case Application

4.1. Timeline of Activities: Overview

Activities in the base-case watershed are divided into periods ("years") during which a particular succession of events and decisions takes place. This section provides the timeline for these activities, first in summary verbal form, and then in more detailed analytic form.

A nomenclature table listing symbols and definitions for key base-case variables is provided in Appendix A. Technical details regarding the forms of the harvest productivity function and the city flood-damage function are relegated to Appendix B and Appendix C. Since the decision modes used by the Farmer and City Manager to make their land and budget allocation decisions are behavioral treatment factors, a detailed discussion of these modes is postponed until Section 5.4.

4.2. General Timeline of Annual Events and Decisions

In February the City Manager allocates the annual city budget among three portions to enhance city social welfare subject to feasibility constraints. City social welfare is expressed as a weighted combination of city social services and the mitigation of city flood damage. The first budget portion is for city social-service expenditures. The second budget portion is for subsidy support for retention land as a city flood-damage mitigation measure. The third budget portion is for investment in levee maintenance and improvements, another city flood-damage mitigation measure. The City Manager then sets the subsidy rate for retention land for the current year. In making these decisions, the City Manager takes into account their likely effect on the Farmer's subsequent land-allocation decisions.

In March, given the retention-land subsidy rate and a realization for input planting costs, the Farmer allocates her farmland among cropland, retention land, and fallow land in pursuit of consumption and savings goals subject to feasibility constraints. The Farmer immediately receives a subsidy payment from the City Manager for her retention-land portion. The Farmer then uses her resulting money holdings to purchase the inputs needed to plant her cropland with corn.

In October the City Manager observes the flood damage that has occurred in the city. This damage depends on the peak rate of water discharged into the city as well as on the city's levee quality. The peak discharge rate depends on the Farmer's land use and on the precipitation pattern realized during the *growing season*, i.e., May 1 through October 15. The city's levee quality depends on the levee investment undertaken by the City Manager in February for repairs and improvements, the quality of the levee at the start of the year, and the levee depreciation rate.

During October through December the Farmer harvests her corn crop, sells corn at the currently realized market price, and retains (and/or buys) corn for her own consumption. The size of the Farmer's corn crop depends on the amount of her cropland and on the precipitation pattern during the growing season.

At the end of December the Farmer and City Manager take stock of all that has happened during the past year. In particular, they consider the realizations for stochastic events (input costs, precipitation pattern, corn price), as well as the land and budget allocation decisions they each have taken. The Farmer considers how these events and decisions have affected the net benefits she has obtained from corn consumption as well as the amount of savings she has been able to put aside for future use. The City Manager considers how these events and decisions have affected city social welfare. Both the Farmer and the City Manager then use these considerations to inform their decision processes for the following year.

4.3. Detailed Timeline of Annual Events and Decisions

The analysis of the base-case watershed takes place over successive simulated years $t = 1, 2, \ldots$. As depicted in Table 1, each year t is divided into seasonal subperiods $t_1, \ldots, t_7$ during which various events and decisions are realized. Subperiod t_k denotes the time interval $[t{:}k,\ t{:}(k+1))$, with $t{:}1 = t$ and $t{:}8 = t+1$. Thus, year t covers the time interval $[t{:}1,\ t{:}8) = [t, t+1)$.

Table 1: Base-Case Timeline for Year-t Events and Decisions

Jan	Feb	March	April-Sept	Oct	Nov	Dec
t_1	t_2	t_3	t_4	t_5	t_6	t_7

For simplicity, it is assumed for the base case that the Farmer and City Manager are able to observe each event and decision as it occurs. The specific events and decisions occurring during each successive subperiod t_k for a general year t will now be more carefully explained.

January (subperiod $\mathbf{t_1}$): An input cost per acre is realized.

At the beginning of subperiod $t_1 = [t{:}1,t{:}2)$ the Farmer and City Manager are in information states $I^F_{t:1}$ and $I^{CM}_{t:1}$. These information states incorporate all currently observable aspects of their decision environments, including all maintained structural aspects, all event realizations observed prior to time $t{:}1$, and all decisions taken prior to time $t{:}1$. In particular, $I^F_{t:1}$ includes the Farmer's time-$t{:}1$ money holdings $M_{t:1}$, $I^{CM}_{t:1}$ includes the year-t city budget $B_{t:1}$, and both information sets include a planting density (seeds/acre) for cropland.[1] An input cost per acre is then realized, as follows:

$$
\begin{aligned}
\text{InputCost}_{t:1} &= \text{Input cost (\$/acre)} \\
&= \text{Per-acre cost of seed and chemicals} \\
&\quad\ \text{needed to plant cropland}
\end{aligned}
\tag{1}
$$

February (subperiod $\mathbf{t_2}$): City Manager allocates city budget.

At the beginning of subperiod $t_2 = [t{:}2,t{:}3)$ the City Manager allocates the city budget $B_{t:1}$ into a city social service expenditure portion, a subsidy portion, and a levee investment portion. This budget allocation is determined

[1] In the current study, the planting density is assumed to be constant over time. The decisions of the Farmer and City Manager during year t depend on their time-$t{:}1$ information states, but this dependence is suppressed below for ease of notation.

by the values set for two percentages, $s_{t:2}$ and $\ell_{t:2}$, as follows:

$$\begin{aligned}
&\text{RetSub}^{poss}(s_{t:2}) = s_{t:2} \cdot B_{t:1} \\
&\qquad\qquad = \text{Dollars set aside for retention-land subsidy spending} && (2)\\
&\tau_{t:2} = \tau(s_{t:2}) = [\text{RetSub}^{poss}(s_{t:2})]/[r^{max}A^F] \\
&\qquad\qquad = \text{Retention-land subsidy rate (\$/acre) set for year } t && (3)\\
&\text{LevInv}(\ell_{t:2}) = \ell_{t:2} \cdot B_{t:1} \\
&\qquad\qquad = \text{Dollars set aside for levee repair and improvement} && (4)\\
&\text{SocServ}^{poss}(s_{t:2}, \ell_{t:2}) = B_{t:1} - \text{RetSub}^{poss}(s_{t:2}) - \text{LevInv}(\ell_{t:2}) \\
&\qquad\qquad = \text{Dollars set aside for city social service spending} && (5)
\end{aligned}$$

In (3), A^F denotes the total amount of farmland in the watershed, and r^{max} is a watershed policy parameter that determines the maximum portion of A^F that the Farmer is allowed to allocate as retention land.

The City Manager's budget allocation in turn determines levee quality for year t, as follows:

$$\begin{aligned}
LQ_{t:2} = LQ(\ell_{t:2}) &= [1-\delta]LQ_{(t-1):2} + g\text{LevInv}(\ell_{t:2}) \\
&= \text{Levee quality for year } t && (6)
\end{aligned}$$

In (6), g (ft/\$) maps dollars of levee investment into levee quality (height), δ is a depreciation rate, and the levee quality $LQ_{(t-1):2}$ determined at time $(t-1)$:2 for year $t-1$ is known to the City Manager from inclusion in his information set $I^{CM}_{t:1}$.

March (subperiod t_3): The Farmer allocates her farmland.

At the beginning of subperiod $t_3 = [t{:}3, t{:}4)$ the Farmer allocates her farmland A^F among cropland, retention land, and fallow land. This allocation is determined by the values set for two percentages, $c_{t:3}$ and $r_{t:3}$, as follows:

$$\begin{aligned}
&A^{crop}(c_{t:3}) = c_{t:3}A^F = \text{Farmer's cropland for year } t && (7)\\
&A^{ret}(r_{t:3}) = r_{t:3}A^F = \text{Farmer's retention land for year } t && (8)\\
&A^{fal}(c_{t:3}, r_{t:3}) = A^F - A^{crop}(c_{t:3}) - A^{ret}(r_{t:3}) \\
&\qquad\qquad = \text{Farmer's fallow land for year } t && (9)
\end{aligned}$$

This land allocation determines additional outcomes at time t:3, as follows:

$$\begin{aligned} \text{RetSub}^{act}(\tau_{t:2} r_{t:3}) &= \tau_{t:2} r_{t:3} A^F \\ &= \text{F's actual retention-land subsidy receipts (\$) for year } t \quad (10) \\ \text{SocServ}^{act}(\tau_{t:2} r_{t:3}, \ell_{t:2}) &= B_{t:1} - \text{RetSub}^{act}(\tau_{t:2} r_{t:3}) - \text{LevInv}(\ell_{t:2}) \\ &= \text{CM's actual city social service spending (\$) for year } t \quad (11) \end{aligned}$$

The Farmer's money holdings at time t:3 are thus given by

$$M_{t:3}(\tau_{t:2} r_{t:3}) \ = \ M_{t:1} + \text{RetSub}^{act}(\tau_{t:2} r_{t:3}) \ \geq \ 0 \qquad (12)$$

The Farmer does not want to waste resources by designating more farmland as cropland than she can afford to plant. Since the planting density (seeds/acre) is a known constant over time, and a realization $\text{InputCost}_{t:1}$ (\$/acre) for year-t input costs has already been observed at time t:1, the Farmer can ensure non-wastage of cropland by imposing the following additional constraint on her choice of the percentages $(c_{t:3}, r_{t:3})$ at time t:3:

$$\begin{aligned} \text{InputCost}_{t:1} \cdot c_{t:3} A^F &= \text{InputCost}_{t:1} \cdot A^{crop}(c_{t:3}) \\ &\leq M_{t:3}(\tau_{t:2} r_{t:3}) \qquad (13) \end{aligned}$$

For later purposes, note that condition (13) together with the requirement $c_{t:3} \leq 1$ impose the following upper bound on $c_{t:3}$:

$$c_{t:3} \ \leq \ c^{max}(\tau_{t:2} r_{t:3}) \ \equiv \ \min\{1, \frac{M_{t:3}(\tau_{t:2} r_{t:3})}{\text{InputCost}_{t:1} \cdot A^F}\} \qquad (14)$$

April-September (subperiod t_4): The Farmer buys inputs, plants her corn crop, and tends her cropland.

At the beginning of subperiod $t_4 = [t{:}4, t{:}5)$ the Farmer uses her money holdings $M_{t:3}(\tau_{t:2} r_{t:3})$ to purchase all inputs needed to plant $A^{crop}(c_{t:3})$. The Farmer's money holdings at time t:4, after all input purchases have been made, are given by

$$M_{t:4}(c_{t:3}, \tau_{t:2} r_{t:3}) \ = \ M_{t:3}(\tau_{t:2} r_{t:3}) - \text{InputCost}_{t:1} A^{crop}(c_{t:3}) \ \geq \ 0 \qquad (15)$$

October (subperiod $\mathbf{t_5}$): A precipitation pattern is realized, which determines city social welfare and the Farmer's corn crop.

A precipitation pattern $\text{Precip}_{t:5}$ is realized during subperiod $t_5 = [t{:}5, t{:}6)$, based on the rainfall occurring during the year-t growing season. This precipitation pattern determines the following outcomes:

$$H_{t:5} = H(\text{Precip}_{t:5}) = \text{Harvest productivity (bushels/acre) for year } t \quad (16)$$

$$\text{CCrop}_{t:5}(c_{t:3}) = H_{t:5} \cdot A^{crop}(c_{t:3}) = \text{Corn crop (bushels) for year } t \quad (17)$$

$$\begin{aligned} Q_{p,t:5}(c_{t:3}, r_{t:3}) &= Q_p\big(\text{Precip}_{t:5}, A^{crop}(c_{t:3}), A^{ret}(r_{t:3}), A^{fal}(c_{t:3}, r_{t:3})\big) \\ &= \text{ Peak water discharge rate into the city during } t_1\text{-}t_4 \quad (18) \end{aligned}$$

$$\begin{aligned} FD_{t:5}(\ell_{t:2}, c_{t:3}, r_{t:3}) &= FD\big(LQ(\ell_{t:2}), Q_{p,t:5}(c_{t:3}, r_{t:3}),\big) \\ &= \text{ City flood damage (\$) during year } t \quad (19) \end{aligned}$$

$$\begin{aligned} &CSW_{t:5}(\tau_{t:2}, \ell_{t:2}, c_{t:3}, r_{t:3}) \\ &\quad = CSW\big(\text{SocServ}^{act}(\tau_{t:2} r_{t:3}, \ell_{t:2}), FD_{t:5}(\ell_{t:2}, c_{t:3}, r_{t:3})\big) \\ &\quad = \text{City social welfare (\$) for year } t \quad (20) \end{aligned}$$

Detailed specifications for the harvest productivity function (16) and the flood-damage function (19) are provided in Appendix B and Appendix C. The precise form of the city social welfare function (20) is given below in Section 5.4; see (31).

November (subperiod $\mathbf{t_6}$): A corn price is realized.

At the beginning of subperiod $t_6 = [t{:}6, t{:}7)$ a corn price, $\text{CPrice}_{t:6}$ (\$/bushel), is realized in the corn market. This corn price in turn determines

$$\begin{aligned} \text{Value}^{crop}_{t:6}(c_{t:3}) &= \text{CPrice}_{t:6}\text{CCrop}_{t:5}(c_{t:3}) \\ &= \text{Market value (\$) of the Farmer's corn crop} \quad (21) \end{aligned}$$

December (subperiod $\mathbf{t_7}$): Farmer welfare is determined, and the Farmer and City Manager update their information states.

At the beginning of subperiod $t_7 = [t{:}7, t{:}8)$, the Farmer's possible money holdings if she sells all of her crop are given by

$$M_{t:7}^{poss}(c_{t:3}, \tau_{t:2} r_{t:3}) = M_{t:4}(c_{t:3}, \tau_{t:2} r_{t:3}) + \text{Value}_{t:6}^{crop}(c_{t:3}) \tag{22}$$

The Farmer sells corn in the corn market at price $\text{CPrice}_{t:6}$ and retains (and/or buys) corn in amount $\text{Cons}_{t:7}^F$ to consume for herself. This determines her year-t welfare, measured by the utility (benefit) she obtains from the consumption of $\text{Cons}_{t:7}^F$. This consumption is determined as follows:

- If the Farmer is unable to attain at least her subsistence consumption level $\bar{C}^F$ (i.e., if $M_{t:7}^{poss}(c_{t:3}, \tau_{t:2} r_{t:3}) < \text{CPrice}_{t:6} \cdot \bar{C}^F$), then she consumes

$$\text{Cons}_{t:7}^F \;=\; \frac{M_{t:7}^{poss}(c_{t:3}, \tau_{t:2} r_{t:3})}{\text{CPrice}_{t:6}} \;<\; \bar{C}^F \tag{23}$$

  and dies at the end of subperiod t_7.

- If $M_{t:7}^{poss}(c_{t:3}, \tau_{t:2} r_{t:3}) \;\geq\; \text{CPrice}_{t:6} \cdot \bar{C}^F$, then the Farmer selects a consumption level $\text{Cons}_{t:7}^F$ and a savings level $S_{t:7}^F$ subject to the following budget, survival, and nonnegativity constraints:

$$M_{t:7}^{poss}(c_{t:3}, \tau_{t:2} r_{t:3}) \;=\; S_{t:7}^F \;+\; \text{CPrice}_{t:6} \cdot \text{Cons}_{t:7}^F \tag{24}$$

$$\text{Cons}_{t:7}^F \;\geq\; \bar{C}^F \tag{25}$$

$$S_{t:7}^F \geq 0 \tag{26}$$

  Thus, the Farmer's money holdings for the start of year $t+1$ are

$$M_{(t+1):1} = S_{t:7}^F \tag{27}$$

At the end of subperiod t_7, the Farmer (if alive) forms her updated information state $I_{(t+1):1}^F$. This updated information state consists of her previous information state $I_{t:1}^F$, a record of the events and decisions she observed during year t, and her money holdings (27) for the start of year $t+1$.

At the end of subperiod t_7 the City Manager forms his updated information state $I_{(t+1):1}^{CM}$. This updated information state consists of his previous information state $I_{t:1}^{CM}$, a record of the events and decisions he observed during year t, plus the city budget $B_{(t+1):1}$ for year $t+1$.

5. Sensitivity Design for the Base-Case Application

5.1. Sensitivity Design Overview

The sensitivity design for the base-case application focuses on welfare alignment. Sensitivity studies are conducted to determine how Farmer and City Manager welfare outcomes change in response to systematic variations in four treatment factors.

The first treatment factor, called the *Behavioral Treatment*, determines the decision modes used by the Farmer and the City Manager to determine their annual land and budget allocations. The second treatment factor, called the *Farmer's risk tolerance*, is a parameter D appearing in the function used to determine the Farmer's utility (benefit) from consumption. As clarified below, the setting for D affects the Farmer's tolerance for consuming at her subsistence level $\bar{C}^F$, where any unexpected downward fluctuation in consumption would be disastrous for her survival. The third treatment factor is a scaling parameter θ^0 that determines the initial magnitude of the *Farmer's savings target* (money holdings) for the end of her planning period. The fourth treatment factor, called *Levee Quality Effectiveness (LQE)*, measures the extent to which the City Manager's levee investments are effective in mitigating city flood damage.

Apart from these four treatment factors, all parameters and structural aspects of the base-case watershed are maintained at fixed settings for all of the sensitivity findings reported in this study.

5.2. Base-Case Settings for Maintained Parameter Values

The base-case settings for the maintained parameter values characterizing the harvest productivity function $H(\text{Precip})$ and the flood damage function $FD(LQ, Q_p)$ are given in Appendix B and Appendix C, respectively. The base-case settings for other maintained parameter values are given in Table 2.

5.3. Base-Case Settings for Environmental Scenarios

The annual weather (precipitation pattern) and economic conditions (costs and prices) are key environmental events driving the dynamics of the base-case watershed. For simplicity, these annual events are assumed to be governed by independent stationary probability distributions known to the Farmer and the City Manager.

The independent stationary probability distributions for the annual corn-production input cost, precipitation pattern, and corn price for the base-case application are specified below.

Table 2: Base-Case Settings for Other Maintained Parameter Values

Symbol	Base-Case Setting	Description
LRun	20 years	Length of each simulation run
NScenarios	31	Number of scenarios tested for each treatment
A^F	4,000 acres	Farmland owned and managed by F
A^W	444 acres	City land area managed by CM
$B_{t:1}$	$1,000,000	City budget at time t:1 for each year t
$\bar{C}^F$	125 bushels	F's subsistence corn-consumption for each year t
CN^{crop}	78	Curve number for cropland with mature crop
CN^{fal}	70	Curve number for fallow land
CN^{ret}	10	Curve number for retention land
δ	0.02	Levee quality depreciation rate for each year t
g	10^{-5} ft/$	Parameter in levee quality update function
$LQ_{0:2}$	3 ft	Initial levee quality (height)
$M_{1:1}$	$4,000,000	F's initial money holdings
ψ	1.0	City social welfare function parameter
r^{max}	0.25	F's max permitted retention land %, a policy variable

1. Three possible realizations for annual corn-production input costs estimated for 1997-2013 based on 2005-2013 data for seed and chemical costs, assuming corn-following-corn (ISU, 2015a):

   Low Input Cost: $604.20/acre (25% probability)

   Moderate Input Cost: $698.00/acre (50% probability)

   High Input Cost: $815.50/acre (25% probability)

2. Three possible realizations for annual precipitation (rainfall depth in inches), based on 1997-2013 data for Ames, Iowa (IEM, 2015):

   Low Precipitation (1999 data) (25% probability)

   Moderate Precipitation (2007 data) (50% probability)

   High Precipitation (2005 data) (25% probability)

3. Three possible realizations for the annual corn price, based on 1997-2013 data (ISU, 2015b):

   Low Corn Price: $3.66/bushel (25% probability)

   Moderate Corn Price: $4.40/bushel (50% probability)

   High Corn Price: $5.68/bushel (25% probability)

Making use of these independent stationary probability distributions for annual events, an ensemble $\mathcal{S}$ consisting of 31 potential environmental scenarios s, each covering 20 simulated years, was constructed for use in all reported computational experiments. Each scenario s takes the form

$$\text{scenario } s \;=\; \big((x_1^s, y_1^s, z_1^s),\; (x_2^s, y_2^s, z_2^s), \ldots, (x_{20}^s, y_{20}^s, z_{20}^s)\big) \tag{28}$$

where

$$\begin{aligned} x_j^s &= \text{input cost (low, mod, or high) in year } j \text{ under scenario } s \\ y_j^s &= \text{precipitation (low, mod, or high) in year } j \text{ under scenario } s \\ z_j^s &= \text{corn price (low, mod, or high) in year } j \text{ under scenario } s \end{aligned}$$

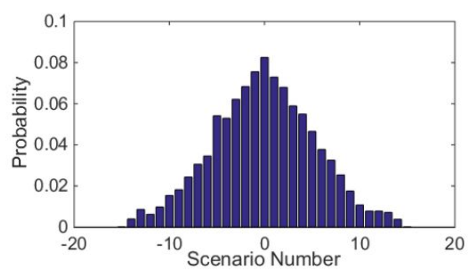

Figure 4: Probability distribution for the base-case environmental scenarios

As detailed in Appendix D, the 31 scenarios in the ensemble $\mathcal{S}$ have unique scenario numbers ranging from -15 to +15, assigned in accordance with their Hamming-measure distance from a *normal scenario* 0. The normal scenario 0 is characterized by moderate input costs, moderate precipitation, and moderate corn prices in each of the 20 simulated years. Scenarios with negative scenario numbers tend to deviate from scenario 0 on the low side, and scenarios with positive scenario numbers tend to deviate from scenario 0 on the high side. The bell-shaped probability distribution function calculated for these 31 scenarios is depicted in Fig. 4.

5.4. Behavioral Treatments

As detailed in Section 4.3, at time $t{:}3$ during each year t the Farmer allocates her farmland among cropland, retention land, and fallow land. This land allocation is determined by the values set for the cropland and retention-land percentages $(c_{t:3}, r_{t:3})$, which must lie in the following decision domain:

$$\text{DD}^F(r^{max}) = \{(c,r) \mid \ 0 \leq c,\ 0 \leq r \leq r^{max},\ c + r \leq 1\} \tag{29}$$

In (29), r^{max} in $[0,1]$ denotes the maximum percentage of farmland that the Farmer is permitted to set aside as retention land, interpreted as a watershed policy parameter.

Also, at time t:2 during each year t the City Manager allocates his city budget among city social-service expenditures, subsidy payments to retention land, and levee investment, taking into account the potential effects of the subsidy rate on subsequent Farmer decisions. This budget allocation is determined by the values set for the subsidy and levee investment percentages $(s_{t:2}, \ell_{t:2})$, which must lie in the following decision domain:

$$\text{DD}^{CM} = \{(s,\ell) \mid 0 \leq s,\ 0 \leq \ell,\ s + \ell \leq 1\} \tag{30}$$

Two decision modes are considered for the Farmer: F-OFF (myopic decision-maker) and F-ON (welfare optimizer). Also, two decision modes are considered for the City Manager: CM-OFF (myopic decision-maker) and CM-ON (welfare optimizer). For each decision mode, random "coin flips" are used to resolve indifference among available decision options.

More precisely, as detailed in Appendix E and Appendix F, the following four behavioral treatments are tested:

Behavioral Treatment 1: (F-OFF, CM-ON)

- The Farmer at time t:3 during each year t selects a land allocation from $\text{DD}^F(r^{max})$ that maximizes her expected money holdings at the start of time t:7, taking as given the year-t retention-land subsidy rate determined by the City Manager at time t:2. The Farmer at time t:7 then consumes as much as possible, subject to feasibility constraints and a year-t savings-target constraint.

- The City Manager at time t:2 during each year t selects a budget allocation from DD^{CM} that maximizes expected *city social welfare (CSW)* for year t subject to feasibility constraints, taking into account how the resulting year-t retention-land subsidy rate will affect the Farmer's land allocation at time t:3. Actual CSW for year t, determined at time t:5, is a weighted average of city social services ($) and city flood-damage mitigation ($) given by

$$\mathrm{CSW}_{t:5} \ = \ \mathrm{SocServ}^{act}_{t:3} \ + \ \psi \cdot \left[FD^{max} - FD_{t:5}\right] \tag{31}$$

In (31), ψ is a trade-off parameter, FD^{max} denotes maximum avoidable city flood damage,[2] $FD_{t:5}$ denotes actual city flood damage, and $[FD^{max} - FD_{t:5}]$ measures avoided city flood damage.

Behavioral Treatment 2: (F-ON, CM-ON)

- The Farmer at time t:3 during each year t determines an information-contingent plan for her year-t land allocation and consumption decisions by maximizing her year-t expected *utility-of-consumption (UOC)* subject to feasibility constraints, a savings-target constraint, and the retention-land subsidy rate determined by the City Manager at time t:2. Letting $\mathrm{Cons}^F_{t:7}$ denote the Farmer's corn consumption at time t:7, the UOC she attains from this corn consumption is measured by

  $$\mathrm{UOC}_{t:7} \ = \ u(\mathrm{Cons}^F_{t:7}) \ = \ \ln(\mathrm{Cons}^F_{t:7} - \bar{C}^F + D) \ \ , \tag{32}$$

  where the parameter D satisfies $D > \bar{C}^F$.[3]

- The City Manager behaves the same as in Behavioral Treatment 1.

Behavioral Treatment 3: (F-OFF, CM-OFF)

- The Farmer behaves the same as in Behavioral Treatment 1.

- The City Manager at time t:2 during each year t selects budget-allocation percentages equal to their time-t:2 *expected values* under Behavioral Treatment 1.

Behavioral Treatment 4: (F-ON, CM-OFF)

- The Farmer behaves the same as in Behavioral Treatment 2.

- The City Manager at time t:2 during each year t selects budget-allocation percentages equal to their time-t:2 *expected values* under Behavioral Treatment 2.

[2] As seen in Appendix C, FD^{max} is a parameter in the city flood damage function.
[3] This restriction on D ensures (32) is well-defined even when $\mathrm{Cons}^F_{t:7} = 0$.

5.5. Farmer Risk Tolerance Treatments

As seen in Section 5.4, the UOC attained by the Farmer from consumption of a corn amount $\mathrm{Cons}^F_{t:7}$ in any year t is given by (32). The parameter D appearing in (32), in bushel units, is required to be greater than the Farmer's subsistence consumption level $\bar{C}^F$=125.

By straightforward differentiation operations, it can be shown that

$$\frac{1}{D} \;=\; \frac{-u''(\bar{C}^F)}{u'(\bar{C}^F)} \tag{33}$$

Under F-ON treatments, the ratio $1/D$ in (33) measures the Farmer's *risk aversion*[4] at her subsistence consumption level $\bar{C}^F$, which implies that D measures the Farmer's *risk tolerance* at $\bar{C}^F$. Subsistence consumption is risky because any small downward fluctuation results in disaster (death) for the Farmer, hence zero consumption.

For the base-case application, the risk-tolerance parameter D is systematically varied as a treatment factor across computational experiments. Results for two different D settings are reported in this study, as follows:

Low Risk Tolerance: $D \;=\; 125.0001$ bushels

High Risk Tolerance: $D \;=\; 126$ bushels

Note that D determines the UOC value that the Farmer assigns to zero consumption (death). Specifically, given $\bar{C}^F$=125 bushels, it follows that

$$u(0) \;=\; \ln(-125 + D) \approx \begin{cases} -9 & \text{if } D = 125.0001 \text{ bushels} \\ 0 & \text{if } D = 126 \text{ bushels} \end{cases} \tag{34}$$

Under F-OFF treatments, the Farmer is only concerned with maximizing her yearly expected consumption; she does not consider the dispersion (variance)

[4]For the purposes of this study, *risk* is defined to be possibility that adverse outcomes occur that differ from expected outcomes. The ratio $-u''(C)/u'(C)$, referred to as the Arrow-Pratt Measure of Risk Aversion (APMRA) (Arrow, 1965; Pratt, 1964), is a standard metric used by economists to measure the risk aversion of a consumer with a UOC function $u(C)$. The APMRA provides a normalized measure of the curvature of u relative to the case of a linear UOC function whose curvature is zero. Given a consumer who maximizes expected UOC, the higher this consumer's APMRA, the more this consumer will be concerned about the possibility of adverse consumption outcomes that deviate from expected consumption outcomes.

of her possible UOC outcomes. Under F-ON treatments, however, the Farmer maximizes her yearly expected UOC; hence, the greater the curvature of her UOC function (i.e., the smaller the setting for D), the more the Farmer will take this dispersion into account.

5.6. Farmer Savings-Target Treatments

As noted in Section 5.4, under each behavioral treatment the Farmer at time t:3 during each year t determines her land allocation and consumption decisions subject to a savings target for her end-of-year money holdings. This savings target takes the form

$$S^F(\theta^0) = \theta^0 \cdot E\big[\text{CPrice}\big] \cdot \bar{C}^F \tag{35}$$

In (35), θ^0 is a unit-free non-negative scalar that affects the magnitude of the Farmer's savings target, $E[\text{CPrice}]$ is the stationary expectation for the annual corn price, and $\bar{C}^F$ is the Farmer's annual subsistence need for corn.

For the base-case application, the savings-target parameter θ^0 is systematically varied as a treatment factor across computational experiments. Results for three different θ^0 settings are reported in this study, as follows:

Low Savings Target:	θ^0	$=$	100
Moderate Savings Target:	θ^0	$=$	5,000
High Savings Target:	θ^0	$=$	20,000

As detailed in Appendix E, these are *initial* settings in the following sense: If a θ^0 setting results in a savings target (35) that would prevent the Farmer from consuming at least her subsistence consumption $\bar{C}^F$, the Farmer incrementally decreases this setting until either she can attain $\bar{C}^F$ or θ^0=0.

5.7. Levee Quality Effectiveness Treatments

As detailed in Appendix C, the flood damage function $FD(LQ, Q_p)$ determines city flood damage as a function of city levee quality LQ and the peak water discharge rate Q_p into the city. Among the parameters charactering this function are a_1 and a_{99}, which determine the effectiveness of the levee quality LQ in mitigating city flood damage.

For the base-case application, a common value – referred to as Levee Quality Effectiveness (LQE) – is set for these two parameters; i.e., LQE = $a_1 = a_{99}$. This LQE value is then systematically varied as a treatment factor across computational experiments. Results for two different LQE settings are reported in this study, as follows:

Low Levee Quality Effectiveness: LQE = 51.5 cfs/ft

High Levee Quality Effectiveness: LQE = 98.2 cfs/ft

6. Dynamic Feedback Effects in the Base-Case Application

As a prelude to the detailed presentation of welfare sensitivity results in Section 7, this section provides a more careful discussion of the dynamic coupled feedback effects underlying these welfare results. These feedback effects arise from strategic decision-making taking place within physical production and hydrological processes.

As detailed in Section 4.3, city social welfare (CSW) in each year t is a function (31) of city social services and city flood-damage mitigation in year t. City social welfare fluctuates from one year to the next in response to changes in factors affecting either welfare component. These factors include farmland allocation, budget allocation, precipitation, and levee quality depreciation. Farmland allocation affects potential city flood damage, since different types of land cover affect precipitation runoff. The budget allocation trades off city social services against increased city flood protection. Finally, precipitation and levee quality depreciation affect the potential for city flood damage.

Also, the welfare obtained by the Farmer in each year t is determined by the utility-of-consumption (UOC) she gains from corn consumption in year t, as measured by (32). The Farmer's UOC fluctuates from one year to the next in response to changes in factors affecting consumption possibilities. These factors include farmland allocation, retention-land subsidy rates, input costs, precipitation, and corn prices. Farmland allocation affects the Farmer's potential sources of income (crop sales versus subsidy payments). Subsidy rates determine income per acre of retention land. Input costs, precipitation, and corn prices affect potential net earnings from crop sales.

Environmental uncertainty is another factor that complicates the underlying dynamics. As detailed in Section 5.3, input costs, precipitation, and corn prices are modeled as stochastic processes. Possible realizations for these stochastic processes are modeled as an ensemble of 31 possible scenarios with associated probabilities. As seen in Fig. 4, this distribution reaches its peak at scenario 0, referred to as the normal scenario, which is characterized by moderate input costs, moderate precipitation, and moderate corn prices. However, as indicated in Table 3, the Farmer and City Manager do *not* necessarily achieve higher welfare outcomes under the normal scenario.

Table 3: *Ceteris Paribus* Effects of Random Events on the Farmer and City Manager

Parameter	Low	High	Rationale
Input Costs	+ for F − for CM	− for F + for CM	Low input costs encourage more cropland and less retention land
Precipitation	− for F + for CM	− for F − for CM	Dry/wet land is bad for crops but dry lessens city flood risk
Corn Price	? for F ? for CM	? for F ? for CM	F gains/loses from low corn price if F is a corn buyer/seller

In particular, low input costs and moderate precipitation are favorable for the Farmer's corn harvest, and hence for Farmer welfare. However, the extent to which either low or high corn prices are favorable for Farmer welfare depends on the extent to which the Farmer ends up buying or selling corn in the corn market to secure her desired consumption and savings levels.

On the other hand, low input costs tend to be unfavorable for city social welfare because they encourage the Farmer to allocate more of her land to cropland and less to retention land. Low precipitation tends to be favorable for city social welfare since it reduces the threat of city flooding. However, high input costs and/or low corn prices can also be favorable for city social welfare if the Farmer reacts by allocating more of her land to retention land rather than cropland, since retention land lessens the threat of city flooding.

An example will now be given to illustrate the complicated interplay of these effects over 20 simulated years. Simulated time series outcomes will be compared when the Farmer's decision mode is changed from F-OFF to F-ON, given a fixed decision mode CM-ON for the City Manager and fixed values (High, Mod, Low) for the remaining treatment factors (D, θ^0, LQE).

The environmental scenario selected for this illustration is $s = -1$ in Fig. 4. The component values for this scenario are plotted in Fig. 5. In earlier years, input costs vary between low and moderate, precipitation varies between low and moderate, and corn prices generally vary between moderate and high; these years are relatively favorable for farming. In later years, input costs vary between moderate and high, precipitation tends to vary between moderate and high, and corn prices tend to vary between moderate and low;

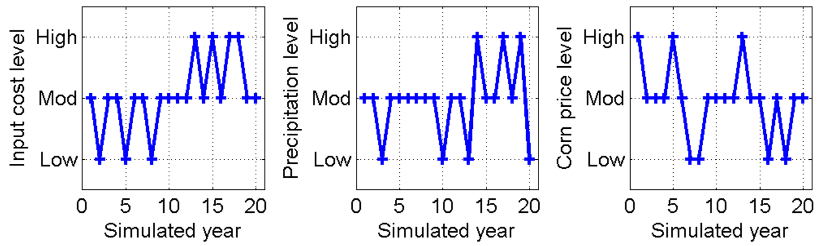

Figure 5: Illustrative environmental scenario $s = -1$ for input costs, precipitation, and corn prices over 20 simulated years

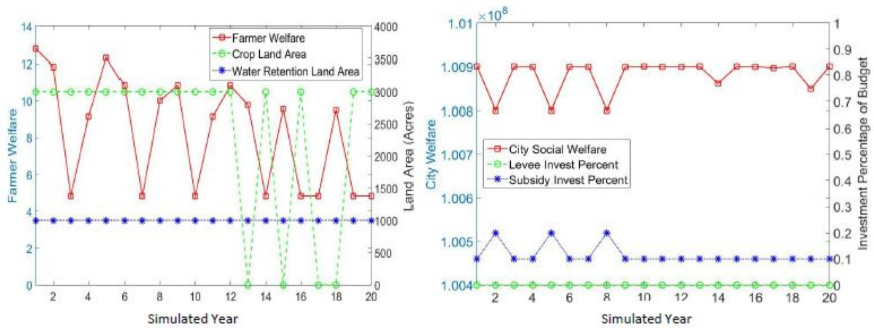

Figure 6: Illustrative time-series outcomes for the Farmer and City Manager over 20 simulated years, given scenario $s = -1$, (D, θ^0, LQE) = (High, Mod, Low), and F-OFF

these years are less favorable for farming.

Given these settings, Fig. 6 plots outcomes for the Farmer and City Manager when the Farmer uses the F-OFF decision mode. Throughout all 20 years, the F-OFF Farmer persistently allocates 1000 of her 4000 acres of farmland to retention land, the maximum allowable portion (r^{max}=0.25). During the first thirteen years, the F-OFF Farmer devotes her remaining 3000 acres to cropland. During the final seven years, however, the F-OFF Farmer alternates the allocation of these 3000 acres between cropland and fallow land. What explains these land allocation decisions?

As detailed in Appendix E.2, at time t:3 during each year t the F-OFF Farmer determines the allocation of her farmland among cropland, retention-land, and fallow land by comparing the per-acre expected net earnings from each option. The F-OFF Farmer calculates these expected net earnings taking as given the input cost realized at time t:1 and the retention-land subsidy rate set by the City Manager at time t:2. From Figs. Fig. 5 and 6, it is seen that the F-OFF Farmer's land allocation decisions are driven by these two conditioning factors.

Specifically, given LQE=Low, levee investment is not an effective use of city budget monies for city flood-damage mitigation. Consequently, the City Manager sets levee investment to zero each year, and he sets the subsidy rate for retention land at the lowest possible level that ensures the F-OFF Farmer allocates the maximum allowed portion of her land (1000 acres) to retention land. In the early years favorable to farming, the subsidy rate has to be raised in years 2, 5, and 8 to counter low input cost realizations that increase the relative profitability of cropland. In other years, however, a lower subsidy rate suffices to ensure that the F-OFF Farmer allocates 1000 acres to retention land.

The F-OFF Farmer's remaining allocation decision is between cropland and fallow land. The F-OFF Farmer's cropland allocation at time t:3 during each year t exhibits a strong negative correlation with the input cost realized at time t:1. In years 13, 15, and 17 the high input costs induce the F-OFF Farmer to devote her remaining 3000 acres to fallow land; in all other years the low to moderate input costs induce the F-OFF Farmer to devote her remaining 3000 acres to cropland.

The precipitation pattern and corn price realized during subperiods t_5 and t_6 do not affect the F-OFF Farmer's land allocation decision at time t:3. However, the precipitation pattern affects the F-OFF Farmer's harvest productivity (bushels/acre) determined during subperiod t_5 and the corn price affects the F-OFF Farmer's net earnings per acre of cropland, determined at time t:7, as well as her ability to buy corn (if necessary) to ensure subsistence consumption at time t:7. Consequently, fluctuations in precipitation and corn prices from one year to the next tend to cause fluctuations in the F-OFF Farmer's welfare from one year to the next.

The City Manager's subsidy-rate increases in years 2, 5, and 8 result in drops in city social welfare, since less budget monies are available for city social services. Additional drops in city social welfare occur in years 14 and 19 due to a combination of factors leading to higher city flood damage in these years: namely, high precipitation, and large cropland allocations (3000 acres) with corresponding increases in runoff risk. Since levee investment is zero during these years, the ongoing depreciation in levee quality results in a larger drop in city social welfare in year 19 than in year 14.

Consider, instead, the Farmer and City Manager outcomes plotted in Figure 7 for the case in which the Farmer uses the F-ON decision mode.

A budget allocation of 10% for subsidy payments, resulting in a \$100/acre subsidy rate, is sufficient to ensure the F-ON Farmer persistently allocates 1000 of her 4000 acres of farmland to retention land, the maximum allowed portion. In years 2, 5, and 8 the low input costs induce the F-ON Farmer to allocate her remaining 3000 acres to cropland. In all other years the F-ON Farmer leaves these 3000 acres fallow because she perceives crop planting to be too risky. Despite having no income from crop sales, she is able to sustain her corn consumption above subsistence by using her steady stream of subsidy payments to purchase corn in the corn market.

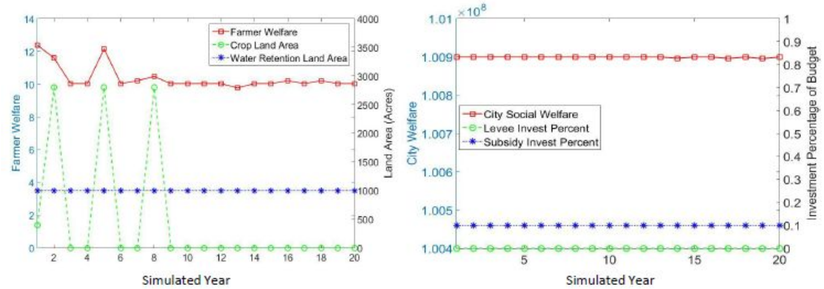

Figure 7: Illustrative time-series outcomes for the Farmer and City Manager over 20 simulated years, given scenario $s = -1$, (D, θ^0, LQE) = (High, Mod, Low), and F-ON

Comparing Fig. 6 for F-OFF with Fig. 7 for F-ON, it is seen that the more cautious behavior of the F-ON Farmer in the face of environmental risk results in higher and more stable Farmer welfare outcomes over time. The F-OFF and F-ON Farmers both allocate 1000 acres to retention land in each of the 20 years, thus benefiting from a steady stream of subsidy payments. However, based on expected net earnings assessments, the F-OFF Farmer allocates her remaining 3000 acres to cropland rather than fallow land in all but four of the 20 years, ignoring the risk of negative net earnings from cropland. In contrast, the risk-averse F-ON Farmer largely avoids this risk by choosing to leave her remaining 3000 acres fallow in all but three years.

Although the F-ON and F-OFF Farmers make different decisions regarding the allocation of their remaining 3000 acres between cropland and fallowland, this has essentially no affect on potential city flood damage because the cropland curve number (78) and the fallow land curve number (70) are similar. However, for the F-ON case, the City Manager does not need to raise the subsidy rate in years 2, 5, and 8 to ensure the Farmer maintains 1000 acres as retention land. This results in more stable city social welfare outcomes over time for the F-ON case relative to the F-OFF case.

7. Welfare Sensitivity Results for the Base-Case Application

7.1. Welfare Results: Introduction

This section reports welfare findings for our base-case sensitivity studies. As detailed in Section 5, four treatment factors are highlighted. The decision modes specified for the Farmer and City Manager, OFF or ON, determine how they select their yearly land and budget allocations. The Farmer's risk tolerance and savings-target scaling parameters D and θ^0 determine the degree of caution the Farmer displays as she attempts to both survive and prosper in her uncertain world. Finally, levee quality effectiveness (LQE) determines the extent to which the City Manager's levee investments are effective in mitigating city flood damage.

7.2. Welfare Results: Summary Report

Figures 8 and 9 report normalized welfare outcomes under a range of treatments, conditional on CM-ON and CM-OFF respectively. Each figure displays four result matrices, where each result matrix reports six normalized welfare outcomes for the Farmer and City Manager for six tested combinations of θ^0 and LQE, conditional on a particular setting D for the Farmer's risk tolerance and a particular setting F-OFF (two-stage decision mode) or F-ON (max yearly expected UOC) for the Farmer's decision mode.

In each of the eight result matrices displayed in Figs. 8 and 9, Farmer welfare is measured as *normalized farmer welfare (NFW)*, defined as follows:

$$NFW \;\equiv\; \frac{FW - FW^{min}}{FW^{max} - FW^{min}} \tag{36}$$

In (36), FW denotes the Farmer's expected total UOC calculated across the 31 possible environmental scenarios for 20 simulated years, and FW^{min} and FW^{max} denote the minimum and maximum values attained by FW across all 48 tested combinations of θ^0 and LQE in the eight result matrices.

Similarly, in each of the eight result matrices displayed in Figs. 8 and 9, the welfare of the city is measured as *normalized city welfare (NCW)*, defined as follows:

$$NCW \;\equiv\; \frac{CW - CW^{min}}{CW^{max} - CW^{min}} \tag{37}$$

F-OFF: Two-Stage Decision Mode

High Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 75.28 NFW = 82.58	NCW = 68.38 NFW = 81.85	NCW = 68.38 NFW = 0.55
LQE=High	NCW = 93.83 NFW = 23.25	NCW = 72.16 NFW = 71.74	NCW = 72.15 NFW = 0.41

Low Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 75.28 NFW = 64.60	NCW = 68.38 NFW = 81.81	NCW = 68.38 NFW = 0.40
LQE=High	NCW = 93.83 NFW = 23.15	NCW = 72.16 NFW = 71.68	NCW = 72.15 NFW = 0.27

F-ON: Max Yearly Expected UOC Decision Mode

High Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 74.55 NFW = 99.46	NCW = 74.33 NFW = 100.00	NCW = 93.61 NFW = 0.15
LQE=High	NCW = 100.00 NFW = 19.65	NCW = 75.64 NFW = 99.95	NCW = 98.59 NFW = 0.15

Low Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 74.55 NFW = 99.46	NCW = 74.33 NFW = 100.00	NCW = 93.61 NFW= 0.01
LQE=High	NCW = 100.00 NFW = 19.54	NCW = 75.64 NFW = 99.94	NCW = 98.59 NFW = 0.01

Figure 8: Normalized Farmer welfare (NFW) and normalized city welfare (NCW) for farmer decision modes F-OFF and F-ON under various (D, θ^0, LQE) settings, conditional on CM-ON

In (37), CW denotes expected total CSW calculated across the 31 possible environmental scenarios for 20 simulated years, and CW^{min} and CW^{max} denote the minimum and maximum values attained by CW across all 48 tested combinations of θ^0 and LQE in the eight result matrices.

The results reported in Fig. 8 for CM-ON show that, all else equal, NCW increases and NFW stays the same or decreases as LQE is increased from low to high. This occurs because the increase in LQE implies that a higher CSW outcome can be obtained for the same overall budget spending level, either by maintaining current spending portions, or by shifting monies away from levee investment and towards city social services and/or subsidy payments.

This same LQE sensitivity pattern is also observed in Fig. 9 for CM-OFF, with four exceptions. Given F-OFF, θ^0 either Mod or High, and D either Low or High, it is seen that NCW in fact *declines* from 68.38 to 0 as LQE is increased from Low to High.

These four exceptional cases occur because, given CM-OFF, the City Manager sets his subsidy and levee investment portions in each year t at their expected year-t values (across scenarios) for the corresponding CM-ON case. In some scenarios for some years, these portions are far lower than the portions set by the CM-ON City Manager based on input cost observations and calculated F-OFF Farmer responses to alternative subsidy rate settings. Faced with a low subsidy rate, the F-OFF Farmer with a moderate or high

F-OFF: Two-Stage Decision Mode

High Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 70.48 NFW = 81.04	NCW = 68.38 NFW = 82.26	NCW = 68.38 NFW = 0.44
LQE=High	NCW = 94.43 NFW= 23.25	NCW = 0.00 NFW = 78.93	NCW = 0.00 NFW = 0.15

Low Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 70.48 NFW = 63.07	NCW = 68.38 NFW = 82.22	NCW = 68.38 NFW = 0.30
LQE=High	NCW = 94.43 NFW = 23.15	NCW = 0.00 NFW = 78.89	NCW = 0.00 NFW = 0.00

F-ON: Max Yearly Expected UOC Decision Mode

High Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 74.33 NFW = 99.47	NCW = 74.29 NFW = 99.98	NCW = 93.60 NFW = 0.15
LQE=High	NCW = 99.98 NFW = 19.65	NCW = 75.62 NFW = 99.93	NCW = 98.59 NFW = 0.15

Low Farmer Risk Tolerance D

	θ^0=Low	θ^0=Mod	θ^0=High
LQE=Low	NCW = 74.33 NFW = 99.46	NCW = 74.29 NFW = 99.98	NCW = 93.60 NFW = 0.01
LQE=High	NCW = 99.98 NFW = 19.54	NCW = 75.62 NFW = 99.92	NCW = 98.59 NFW = 0.01

Figure 9: Normalized Farmer welfare (NFW) and normalized city welfare (NCW) for farmer decision modes F-OFF and F-ON under various (D, θ^0, LQE) settings, conditional on CM-OFF

savings target will tend to put all of her land into cropland because she has enough accumulated money holdings to afford the input costs. The combined effect of a large amount of cropland with low levee investment then results in relatively large city flood damage. This in turn results in a low NCW outcome relative to the corresponding CM-ON case. Indeed, NCW equals zero for these four exceptional cases, the lowest NCW value attained across all 48 tested treatments reported in Figs. 8 and 9.

The results reported in Figs. 8 and 9 show that Farmer and city welfare outcomes are *not* well aligned with regard to Farmer savings behavior. All else equal, NFW is at or very near its highest level when the Farmer's targeted savings level is set at a moderate level (θ^0=Mod). On the other hand, NCW tends to be highest when the Farmer saves too little (θ^0=Low); in this case the Farmer allocates at least some of her land to retention land in order to secure income for the purchase of inputs for crop production.

The only exceptions to the pattern of highest NCW occurring at θ^0=Low are for the treatments with LQE=Low and F-ON. In the latter treatments, regardless of the settings for other treatment factors, NCW is highest when θ^0=High.

The reason for this is as follows. Given LQE=Low (in contrast to High), retention land increases its effectiveness as a city flood-damage mitigation measure in comparison with levee investment. Given θ^0=High (in contrast to Low or Mod) the F-ON Farmer foresees that she will have to consume at her subsistence level $\bar{C}^F$, regardless of her land allocation. Consequently, she randomly allocates her farmland among cropland, retention land, and fallow land, regardless of the subsidy rate, which results on average in a relatively high portion of retention land. Moreover, perceiving the F-ON Farmer's lack of responsiveness to the subsidy rate, the CM-ON City Manager sets the subsidy rate to zero and devotes the entire city budget to other welfare-enhancing expenditures. The CM-OFF City Manager likewise sets a zero subsidy rate, which is the expected subsidy rate for the CM-ON case.

On the other hand, conditional on θ^0=Mod, Farmer and city welfare outcomes *are* well aligned with regard to the Farmer's decision mode. All else equal, both NFW and NCW increase if the Farmer's decision mode is changed from F-OFF to F-ON.

An interesting aspect of Fig. 8 for CM-ON and Fig. 9 for CM-OFF is that NFW and NCW display a high degree of insensitivity to the City Manager's decision mode. The only exceptions are the treatments, noted above, with F-OFF, θ^0 either Mod or High, LQE=High, and D either Low or High. For reasons noted above, in these treatments the CM-ON City Manager achieves much higher NCW than the CM-OFF City Manager.

A surprising aspect of Figs. 8 and 9 is that NFW and NCW are highly insensitive to the setting for the Farmer's risk tolerance D. *A priori*, we postulated that the Farmer's higher tolerance for risk under a higher value of D would lead to riskier decision-making. However, all else equal, a change from D=Low to D=High has essentially no effect on Farmer decisions. Rather, the only effect is a larger dispersion of UOC outcomes for D=Low resulting from the larger negative UOC value assigned to death for D=Low; see (34). The explanation for this insensitivity appears to be the relatively low probability of extreme scenarios in which the Farmer dies, as well as the relatively high setting ($\bar{C}^F$=125 bushels) for the Farmer's subsistence consumption.[5] Given this insensitivity, we hereafter only report results for D=High.

[5] The Farmer's logarithmic UOC function (32) is extremely flat as a function of D in a neighborhood of $\bar{C}^F$=125. For example, if the Farmer consumes $\bar{C}^F$=125 bushels in each of the 20 simulated years, her resulting total UOC summed over these 20 simulated years equals 96.6 for D=Low and 96.7 for D=High.

7.3. Detailed Welfare Results

7.3.1. Welfare Metrics

In this section the welfare of the Farmer is measured by total UOC attained over 20 simulated years, and the welfare of the city is measured by total CSW attained over 20 simulated years. Outcomes for total UOC and total CSW are reported in two forms: (i) in expected form, as a probability-weighted average across the 31 possible environmental scenarios, together with dispersion ranges; and (ii) differentiated by environmental scenario.

Regarding form (i), bar charts are used to report expected values and dispersion ranges for total UOC and total CSW under various treatments. The height of a bar indicates expected value, and the vertical line centered at each bar height depicts the dispersion range for the expected value, determined as plus or minus one standard deviation around the expected value.

Regarding form (ii), each scenario – identified by its scenario number – represents low, moderate, or high annual realizations over 20 simulated years for three environmental factors: namely, input cost, precipitation, and corn price. The scenarios are dispersed around the normal scenario 0 for which all factors take on moderate values. As cautioned in Section 7.1, however, welfare outcomes are not systematically related to scenario numbers; for example, welfare outcomes do not necessarily peak at the normal scenario 0. Detailed discussions are provided below for the welfare patterns displayed across scenarios.

Finally, in interpreting the reported results below, which are conditioned on high Farmer risk tolerance D=126 bushels and a subsistence consumption level $\bar{C}^F$=125 bushels, it is useful to recall two points derivable from (32) and (34). First, if the Farmer consumes at her subsistence level $\bar{C}^F$ in each of the 20 simulated years, then the total UOC she attains is 96.7. Second, at zero consumption (death), the UOC of the Farmer is $u(0) = 0$.

7.3.2. Detailed Welfare Results: CM-ON

Figures 10 and 11 provide an alternative visualization of the expected welfare outcomes reported in Fig. 8 for D=High and CM-ON. As previously noted, all else equal, expected welfare for both the Farmer and the City Manager tend to be higher for F-ON than for F-OFF.

A new aspect of Figs. 10 and 11 is the reporting of dispersion ranges. An immediate observation here is that the dispersion of welfare outcomes tends to be larger (and in some cases substantially larger) for the F-OFF

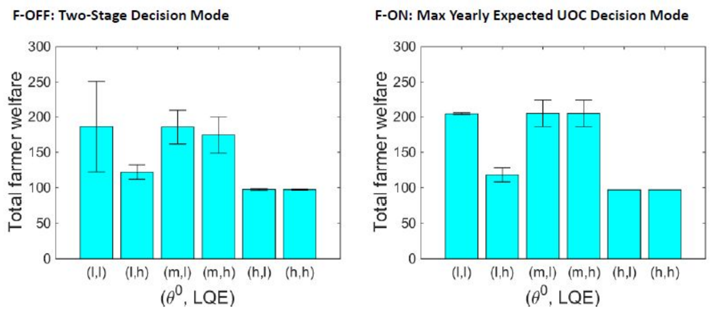

Figure 10: Expected total UOC (with dispersion ranges) for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, given D=High and CM-ON.

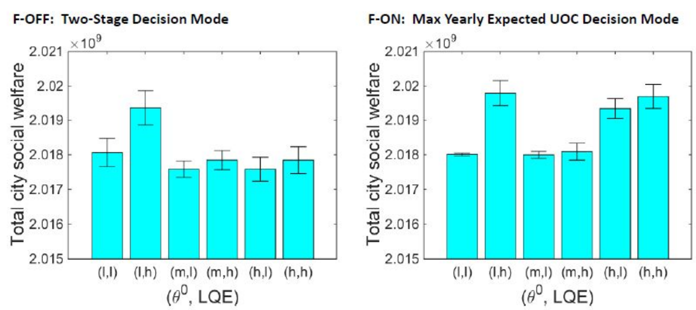

Figure 11: Expected total CSW (with dispersion ranges) for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, given D=High and CM-ON.

treatments relative to the F-ON treatments. The dispersion ranges reflect the extent to which welfare outcomes fluctuate across scenarios. To provide a better understanding of these dispersion ranges, Figures 12 and 13 report welfare outcomes for the same set of treatments depicted in Figs. 10 and 11, only now differentiated by environmental scenario.

Two striking aspects of Figs. 12 and 13 are: (i) larger fluctuations across scenarios for the F-OFF treatments relative to the F-ON treatments; and (ii) the high degree of welfare misalignment for the F-ON treatments. To understand these findings, it is essential to examine carefully the underlying dynamic interactions between the Farmer and the City Manager.

Consider, first, the F-ON treatments with θ^0=High, denoted by upward-pointing triangles. For each treatment, welfare outcomes for both the Farmer and the City Manager tend to be relatively stable across scenarios; yet total UOC tends to be relatively *low* whereas total CSW tends to be relatively

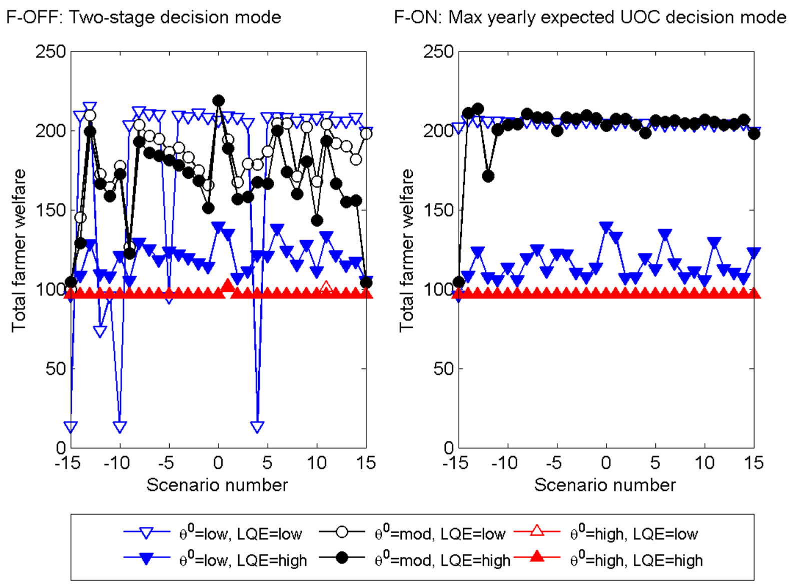

Figure 12: Total UOC for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, by scenario, conditional on D=High and CM-ON.

high. What explains these findings?

The F-ON Farmer's high savings target forces her to consume at her subsistence level each year, hence her total UOC is at the subsistence level 96.7 across scenarios. The F-ON Farmer is able to foresee this result, hence she understands that her UOC will not be affected by her land allocation. She therefore chooses her land allocation randomly, resulting in a retention-land allocation of 500 acres (half the maximum allowed portion) on average. Perceiving the F-ON Farmer's lack of responsiveness to the subsidy rate, the CM-ON City Manager sets the subsidy rate to zero and devotes the entire city budget to city social services and levee investment. Thus, total CSW tends to be relatively high and stable across scenarios, with a higher total CSW resulting for LQE=High (upward-pointing solid triangles) than for LQE=Low (upward-pointing open triangles).

Next consider the F-ON treatments with (θ^0,LQE)=(Low,High), denoted by downward-pointing solid triangles. Total UOC tends to be relatively *low* across scenarios, fluctuating within a small range above subsistence, while

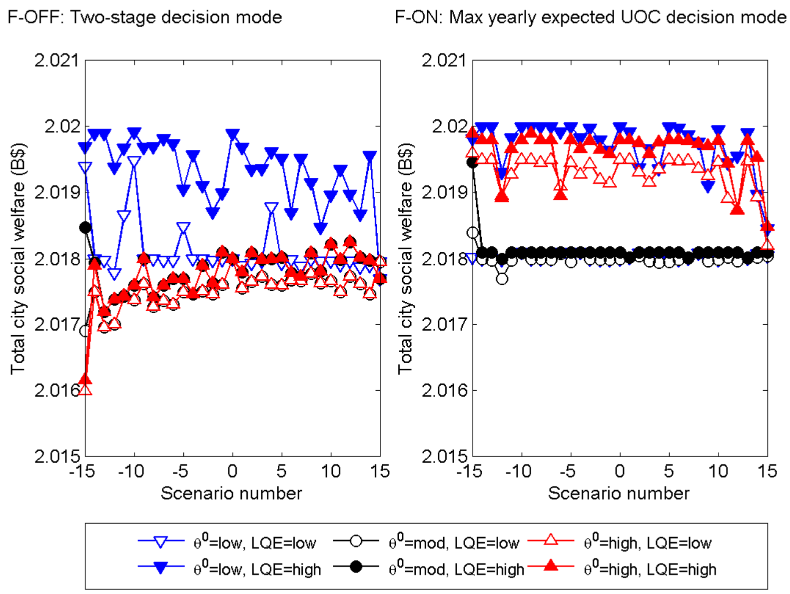

Figure 13: Total CSW for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, by scenario, conditional on D=High and CM-ON

total CSW tends to be relatively *high* across scenarios. What explains these results?

Under these settings the F-ON Farmer has a low savings target and consumes most of her money holdings at time t:7 during each year t, which in turn results in low savings from one year to the next. The CM-ON City Manager foresees that the F-ON Farmer will have to depend on subsidy payments if she wants to allocate any sizable portion of her farmland to cropland. In particular, he foresees that a subsidy rate set very close to zero will suffice to induce the F-ON Farmer to allocate the maximum allowed portion of her farmland to retention land. Moreover, since LQE=High, levee investment is an effective alternative flood-damage mitigation option to subsidy payments, which provides another incentive to the City Manager to offer a subsidy rate that is very close to zero. In consequence, subsidy payments are very small, and the F-ON Farmer typically allocates fewer than 100 of her farmland acres to cropland due to lack of income for the payment of input costs. Although her exposure to crop production risks is small, her UOC in good farming years is also small. On the other hand, CSW tends to be relatively high.

For the remaining F-ON treatments, denoted by circles and downward-pointing open triangles, either θ^0=Mod or (θ^0,LQE) = (Low,Low). The F-ON Farmer is therefore able to purchase inputs for crop production either through her own savings (θ^0=Mod) or through subsidy payments for retention land (LQE=Low). The F-ON Farmer diversifies her land between cropland and retention land, and this diversification tends to result in high total UOC outcomes across scenarios. On the other hand, total CSW tends to be relatively *low* across scenarios because the City Manager has to devote more of the city budget to subsidy payments and/or to levee investment to ensure city flood-damage mitigation.

Now consider, instead, the F-OFF treatments reported in Figs. 12 and 13. Welfare outcomes for some treatments exhibit relatively large fluctuations across scenarios, and the degree of welfare alignment is mixed. What explains these findings?

For the F-OFF treatments with (θ^0,LQE)=(Low,High), which are denoted by downward-pointing solid triangles, total UOC tends to be relatively *low* across scenarios whereas total CSW tends to be relatively *high* across scenarios. The explanation for this welfare misalignment is similar to the explanation for the F-ON case. Given her low savings from one year to the next, the F-OFF Farmer is forced to augment her savings with income from subsidy payments if she wishes to purchase the inputs required to plant even modest amounts of cropland. Also, since LQE=High, levee investment is an effective flood-mitigation alternative to retention-land subsidy payments. The City Manager thus foresees each year that he can achieve a relatively high CSW by setting a relatively low retention-land subsidy rate. As a result, total UOC fluctuates within a small range above subsistence across scenarios while total CSW tends to be relatively high across scenarios.

For the F-OFF treatments with either θ^0=Mod or (θ^0,LQE) = (Low,Low), denoted by circles and downward-pointing open triangles, total UOC tends to be relatively *high* across scenarios whereas total CSW tends to be relatively *low* across scenarios. The explanation for this welfare misalignment is again similar to the explanation for the corresponding F-ON treatments. On the other hand, total UOC and total CSW both exhibit much greater dispersion across scenarios in these F-OFF treatments than in the corresponding F-ON treatments. As in the corresponding F-ON treatments, the F-OFF Farmer is able to purchase inputs for crop production either through her own savings (θ^0=Mod) or through subsidy payments for retention land

(LQE=Low). However, in comparison with the F-ON Farmer, the F-OFF Farmer on average tends to allocate five times more of her land to cropland because she ignores the production risks arising from uncertain precipitation and corn prices. Consequently, although the F-OFF Farmer does better than the F-ON Farmer in good crop years, she does worse than the F-ON Farmer in bad crop years and is more likely to die before the end of the 20 years. If the Farmer dies, all of her land reverts to fallow land with a relatively high curve number (runoff potential).

Finally, consider the F-OFF treatments with θ^0=High, denoted by upward-pointing triangles. Total UOC and total CSW both tend to be relatively *low* across scenarios for these treatments. The essential reason for this welfare alignment is that the F-OFF Farmer is myopic; she does not foresee that her high savings target will require her to consume at her subsistence level regardless of her land allocation, and she does not take into account the risks associated with crop production. Thus, in comparison with the corresponding F-ON treatments, the F-OFF Farmer tends to allocate more farmland to cropland and less to retention land, even though the City Manager sets a higher subsidy rate for retention land. This larger cropland allocation (with higher runoff potential), together with higher subsidy payments, reduces total CSW in comparison with the corresponding F-ON treatments.

7.3.3. Detailed Welfare Results: CM-OFF

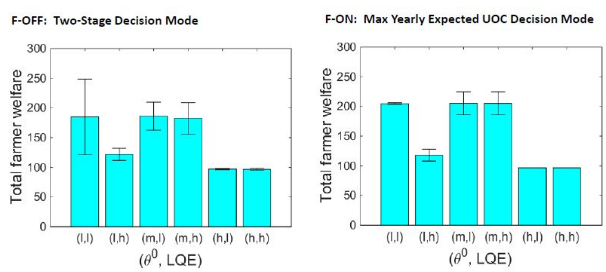

Figure 14: Expected total UOC (with dispersion ranges) for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, given D=High and CM-OFF.

Figures 14 and 15 provide an alternative visualization of the expected welfare outcomes reported in Fig. 9 for D=High and CM-OFF. As for the CM-ON case, all else equal, expected welfare for both the Farmer and the City Manager tend to be higher for F-ON than for F-OFF; and the dispersion of welfare outcomes tends to be larger (and in some cases substantially larger)

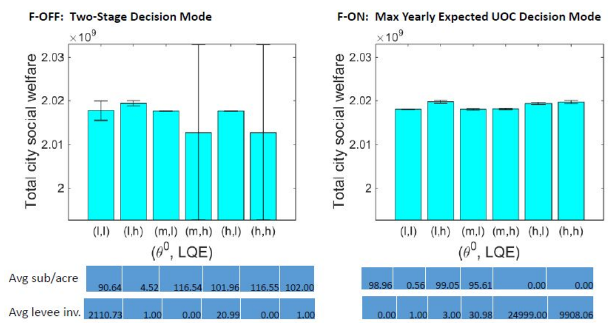

Figure 15: Expected total CSW (with dispersion ranges) for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, given D=High and CM-OFF, with corresponding average City Manager subsidy rates ($/acre) and levee investments ($)

for the F-OFF treatments relative to the F-ON treatments. To provide a better understanding of these findings, Figures 16 and 17 report welfare outcomes for the same set of treatments depicted in Figs. 14 and 15, only now differentiated by environmental scenario.

Comparing the scenario-conditioned results in Figs. 16 and 17 for CM-OFF with the scenario-conditioned results in Figs. 12 and 13 for CM-ON, only one significant difference is seen. Given F-OFF, the total CSW that results under treatments (θ^0,LQE) = (Mod,High) and (θ^0,LQE) = (High,High) is far more volatile for CM-OFF than for CM-ON.

What explains this difference? As seen in Section 7.2, the two indicated treatments are precisely the treatments for which NCW=0, the lowest NCW level attained across all tested treatments. These NCW=0 outcomes occur because the CM-OFF City Manager sets his annual budgeted portions for subsidy payments and levee investment at their expected optimal annual levels, ignoring actual conditions.

Specifically, these expected optimal annual levels are calculated as the probability-weighted averages of the scenario-conditioned optimal annual levels determined in the CM-ON case. Consequently, in each year t these expected optimal levels do not take into account the actual input cost for year t or the way in which the F-OFF Farmer will respond to this actual input cost in choosing her year-t land allocation.

For scenario realizations that are close to normal, the resulting differences in total CSW outcomes for the CM-OFF and CM-ON treatments are not substantial. However, for more extreme scenario realizations, the city can sustain a relatively large amount of flood damage in the CM-OFF case

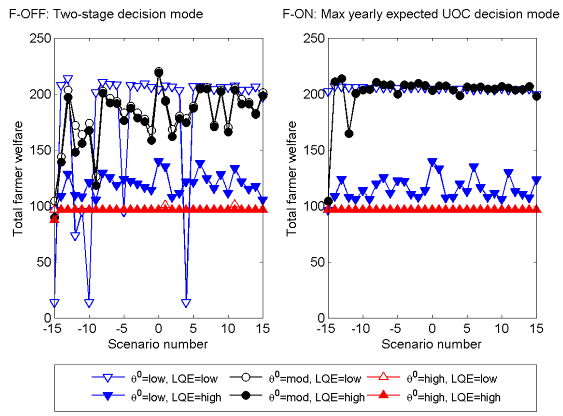

Figure 16: Total UOC for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, by scenario, given D=High and CM-OFF.

because the CM-OFF City Manager has not taken proper precautions to protect against flood damage.

This is precisely what happens in treatments (θ^0,LQE) = (Mod,High) and (θ^0,LQE) = (High,High). The CM-ON City Manager sets his annual subsidy and levee investment portions at levels that are substantially higher than the portions set by the CM-OFF City Manager in these same treatments. This occurs because the CM-ON City Manager knows that an F-OFF Farmer does not consider crop production risks. Thus, an F-OFF Farmer with a moderate or high savings target, hence with plenty of money holdings on hand for the purchase of inputs for crop planting, will tend to allocate a large portion of her farmland to cropland (with high runoff potential). To protect against this, the CM-ON City Manager allocates a relatively large portion of the annual city budget to retention-land subsidy payments and to levee investment.

The CM-OFF City Manager does not take these precautions; he allocates relatively small portions of the annual city budget to subsidy payments and levee investment in these two treatments. The combined effects of a large amount of cropland with low levee investment then results in a relatively large amount of city flood damage in environmental scenarios with moderate to high precipitation.

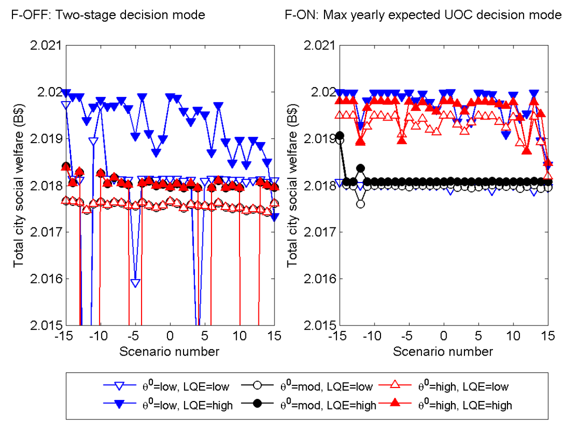

Figure 17: Total CSW for farmer decision modes F-OFF and F-ON under various (θ^0, LQE) settings, by scenario, given D=High and CM-OFF.

8. Conclusion

This study reports on the development the WACCShed Platform, an agent-based framework that permits watersheds to be studied as open-ended dynamic CNH systems. A key feature of the platform is its ability to model strategic decision-making among interacting human participants seeking to survive and prosper within a watershed environment constrained by institutional arrangements and physical processes. A relatively simple watershed application is presented to illustrate how the platform can be used to determine the effects of these human interactions on private and social welfare outcomes over time.

The flexible modular architecture of the WACCShed Platform makes it particularly well suited for Iterative Participatory Modeling (IPM). The IPM approach envisions multidisciplinary researchers and stakeholders engaging together in the ongoing study of a real-world system of mutual interest for the purpose of discovering more effective governance tools. This ongoing study involves a repeated looping through four stages: field study and data analysis; role-playing games; agent-based model design and implementation; and intensive computational experiments (Barreteau et al., 2012; Daniell, 2012; Giuliani and Castelletti, 2013). As depicted in Fig. 1, the WACCShed Platform is currently being used as an initial modeling platform for an IPM process whose purpose is improved local governance for the Squaw Creek watershed in central Iowa.

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Appendix A. Nomenclature for Base-Case Variables

Table A.4 provides a list of symbols and abbreviated definitions for the key variables and functional forms appearing in the modeling of the base-case watershed. A variable is classified as exogenous (Exog) if its value is an external input to the base-case watershed model and endogenous (Endog) if its value is determined within the base-case watershed model.

Table A.4: Nomenclature for Key Base-Case Variables and Functions

Symbol	Variable Type	**Units**	**Description**
A^F	Exog	acres	Farmland owned and managed by F
$A^{crop}_{t:3}$	Endog	acres	Cropland selected by F at t:3
$A^{ret}_{t:3}$	Endog	acres	Retention land selected by F at t:3
$A^{fal}_{t:3}$	Endog	acres	Fallow land selected by F at t:3
A^W	Exog	acres	City land area managed by CM
$B_{t:1}$	Exog	\$	City budget at time t:1 for year t
$c_{t:3}$	Endog	%	F's cropland allocation at t:3
$\bar{C}^F$	Exog	bushels	F's subsistence corn-consumption for each year t
$\text{CCrop}_{t:5}$	Endog	bushels	F's corn crop realized at t:5
CM	Exog	dm agent	City Manager residing in urban watershed area
$\text{Cons}^F_{t:7}$	Endog	bushels	F's actual corn consumption at t:7
$\text{CPrice}_{t:6}$	Exog	\$/bushel	Corn price realized at t:6
$\text{CSW}_{t:5}$	Endog	\$	City social welfare for year t, determined at t:5
D	Exog	bushels	Parameter in F's utility-of-consumption (UOC) function
δ	Exog	%	Levee quality depreciation rate for each year t
F	Exog	dm agent	Farmer residing in rural watershed area
FD^{max}	Exog	\$	Maximum avoidable flood damage for the city
$FD_{t:5}$	Endog	\$	City flood damage realized during subperiod t_5
g	Exog	ft/\$	Parameter in levee quality update function
$H_{t:5}$	Endog	bushels/acre	Harvest productivity realized during subperiod t_5
$I^{CM}_{1:1}$	Exog	info	CM's initial information state at time 1:1
$I^F_{1:1}$	Exog	info	F's initial information state at time 1:1
$I^{CM}_{t:k}$	Endog	info	CM's information state at time $t{:}k \neq 1{:}1$
$I^F_{t:k}$	Endog	info	F's information state at time $t{:}k \neq 1{:}1$
$\text{InputCost}_{t:1}$	Exog	\$/acre	Per-acre corn planting input cost realized at t:1
$\ell_{t:2}$	Endog	%	CM's budget allocation for levee investment at t:2
$\text{LevInv}_{t:2}$	Endog	\$	CM's levee investment at t:2
$LQ_{0:2}$	Exog	height in feet	Levee quality for year 0 determined at 0:2
$LQ_{t:2}$	Endog	height in feet	Levee quality for year t determined at t:2
$M_{1:1}$	Exog	\$	F's initial money holdings at time 1:1
$M_{t:k}$	Endog	\$	F's money holdings at time $t{:}k \neq 1{:}1$
$M^{poss}_{t:7}$	Endog	\$	F's money holdings at t:7 if she sells her total crop
$\text{Precip}_{t:5}$	Exog	rainfall	Precipitation pattern realized during subperiod t_5
ψ	Exog	unit-free scalar	Parameter in city social welfare function
$Q_{p,t:5}$	Endog	cfs	Peak water discharge rate into city during subperiods t_1-t_5
r^{max}	Exog	%	Upper bound on F's r decisions, a policy variable
$r_{t:3}$	Endog	%	F's retention-land allocation decision at t:3
$\text{RetSub}^{poss}_{t:2}$	Endog	\$	CM's planned subsidy payment expenditures at t:2
$\text{RetSub}^{act}_{t:3}$	Endog	\$	CM's actual subsidy payment expenditures at t:3
s	Exog	scenario	Environmental conditions (weather & market)
$s_{t:2}$	Endog	%	CM's budget allocation for subsidy payments at t:2
$S^F_{t:3}(\theta)$	Endog	\$	F's savings target at t:3 (function of θ)
$S^F_{t:7}$	Endog	\$	F's actual savings level determined at t:7
$\text{SocServ}^{poss}_{t:2}$	Endog	\$	CM's planned social service expenditures at t:2
$\text{SocServe}^{act}_{t:3}$	Endog	\$	CM's actual social service expenditures at t:3
t	Exog	year identifier	$t = 1, 2, \ldots,$ with year $t \equiv$ time interval $[t, t+1)$
$t{:}k$	Exog	time point	$k = 1, \ldots 8,$ with $t{:}1 \equiv t$ and $t{:}8 \equiv t+1$
t_k	Exog	subperiod	$t_k \;\equiv\; [t{:}k,\, t{:}k+1),\; k = 1, \ldots, 7$
$\tau_{t:2}$	Endog	\$/acre	Retention-land subsidy rate set by CM at t:2
θ^0	Exog	unit-free scalar	Initially given value for θ
$\text{UOC}_{t:7}$	Endog	utils	F's utility-of-consumption for year t, determined at t:7
$\text{Value}^{crop}_{t:6}$	Endog	\$	Market value of F's corn crop at t:6

Appendix B. Base-Case Harvest Productivity Function

In the base-case application, the planting density (seeds/acre) is assumed to be constant over time, and the harvest productivity (bushels/acre) realized at the end of the growing season (May 1 - October 15) during each year t is assumed to be determined as a function solely of the precipitation pattern $\text{Precip}_{t:5}$ realized during this growing season:

$$H_{t:5} \;=\; H(\text{Precip}_{t:5}) \tag{B.1}$$

The precise manner in which the harvest productivity function (B.1) is specified will now be explained. This specification is not an empirically-derived expression. Rather, it is a general qualitative depiction of key relationships.

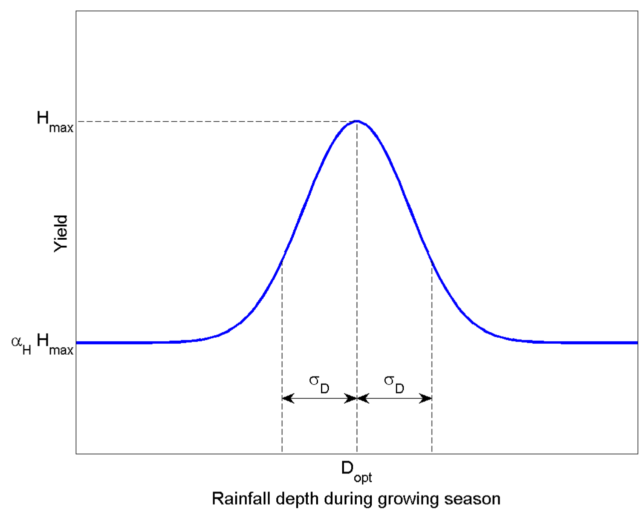

Figure B.18: Base-case specification for the harvest productivity function H, conditional on a constant planting density (seeds/acre)

The precipitation pattern $\text{Precip}_{t:5}$ realized during the year-t growing season is proxied by rainfall depth D_t, i.e., by the total accumulated rainfall during this growing season, measured in inches. As depicted in Fig. B.18, harvest productivity attains its maximum value H^{max} for a certain optimal amount of rainfall, D^{opt}. Below this optimal amount, harvest productivity is reduced because the crops need more water. Above this optimal amount, harvest productivity is reduced because the soil is too wet. For either low rainfall or high rainfall, harvest productivity is a fraction α_H of H^{max}.

More precisely, the base-case harvest productivity function (B.1) takes the following Gaussian form:

$$H_{t:5} \;=\; H^{max} \cdot \left[\alpha_H + (1-\alpha_H)\exp\Big(-\frac{(D_t - D^{opt})^2}{\sigma_D^2}\Big)\right] \tag{B.2}$$

The parameter σ_D in (B.2) controls the width of the bell curve. The following specific parameter values are maintained for (B.2):[6]

- $\alpha_H = 0.8$
- $D^{opt} = 26.72$ inches
- $H^{max} = 168$ bushels/acre
- $\sigma_D = 5$ inches

Appendix C. Base-Case Flood Damage Function

In the base-case application, flood damage $FD_{t:5}$ to the city at time t:5 during each year t is determined as a function of the city's levee quality $LQ_{t:2}$ and the peak water discharge rate $Q_{p,t:5}$ into the city during the year-t:

$$FD_{t:5} \;=\; FD(LQ_{t:2}, Q_{p,t:5}) \tag{C.1}$$

The precise manner in which the flood damage function (C.1) is specified will now be explained. This specification is not an empirically-derived expression. Rather, it is a general qualitative depiction of key relationships.

As illustrated in Fig. C.19, for any given levee quality, flood damage FD is assumed to be small until the water discharge rate Q reaches a point where the water flow begins to overtop the levee. As Q increases further, flood damage increases sharply. However, for large Q, the entire city is flooded and flood damage approaches the *maximum avoidable flood damage*, FD^{max}.

More precisely, for any given levee quality LQ, the base-case flood damage function (C.1) is specified as a logistic function:

$$FD(LQ, Q_{p,t:5}) = \frac{FD^{max}}{1 + \exp\big(-\frac{Q_{p,t:5} - Q_h(LQ)}{\Delta Q(LQ)}\big)} \tag{C.2}$$

[6]The setting for H^{max} is the Northwest Iowa district average corn yield from 2005-2014, as reported in AGDM (2015, Table 1).

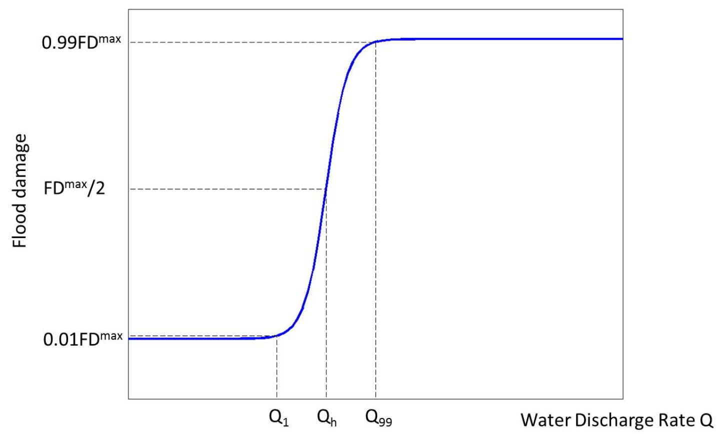

Figure C.19: Base-case specification for the flood damage function FD, conditional on a given levee quality

where

$$Q_h(LQ) = \frac{Q_1(LQ) + Q_{99}(LQ)}{2} \tag{C.3}$$

and

$$\Delta Q(LQ) = \frac{Q_{99}(LQ) - Q_1(LQ)}{9.2} \tag{C.4}$$

and Q_1 and Q_{99} are the the discharges at which the flood damage is 1% and 99%, respectively, of the maximum value. The discharge rates $Q_1(LQ)$ and $Q_{99}(LQ)$ are assumed to increase linearly with levee quality:

$$Q_1(LQ) = Q_{1n} + a_1 LQ \tag{C.5}$$

$$Q_{99}(LQ) = Q_{99n} + a_{99} LQ \tag{C.6}$$

where Q_{1n} and Q_{99n} are the values of Q_1 and Q_{99} for no levee and a_1 and a_{99} are coefficients.

The following specific parameter values are maintained for the base-case flood damage function (C.2):

- The base-case value for FD^{max} is a fixed proportion of the City Manager's base-case annual city budget $B = \$1M$:

$$\text{FD}^{max} \;=\; 100 \cdot B \tag{C.7}$$

- The peak water discharge rates Q_p for different types of years:

$$\begin{array}{ll} \text{Low Precipitation year:} & Q_p = 369.8 \text{ cfs} \\ \text{Moderate Precipitation Year:} & Q_p = 451.8 \text{ cfs} \\ \text{High Precipitation year:} & Q_p = 756.7 \text{ cfs} \end{array}$$

- The ordinates in the linear affine relationships (C.5) and (C.6):

$$\begin{aligned} Q_{1n} &= 369.8 \text{ cfs} \\ Q_{99n} &= 756.7 \text{ cfs} \end{aligned}$$

As detailed in Section 5.7, in the base-case application a common "levee quality effectiveness" (LQE) value is set for the parameters a_1 and a_{99} in (C.5) and (C.6). This LQE value is then systematically varied as a treatment factor across computational experiments.

Appendix D. Base-Case Scenario Construction for Random Events

As explained in Section 5.3, in the base-case application the annual input costs, weather (precipitation pattern), and corn price for the base-case watershed are assumed to be governed by independent stationary probability distributions. Based on these distributions for annual environmental conditions, an ensemble $\mathcal{S}$ consisting of 31 possible environmental scenarios s was constructed for the base-case watershed using the following eight steps.

1. Three Java pseudo random number generators initialized with 5000 distinct seeds were used to generate three groups of 5000 sequences of length 20 for input costs x, precipitation y, and corn price z, respectively, in accordance with the independent stationary probability distributions specified in Section 5.3.
2. The sequences from these three groups were then matched (in their order of generation) to form 5000 scenarios $\hat{s}$, each 20 simulated years in length, as illustrated below:

$$\hat{s} \;=\; \big((x_1^{\hat{s}}, y_1^{\hat{s}}, z_1^{\hat{s}}),\; (x_2^{\hat{s}}, y_2^{\hat{s}}, z_2^{\hat{s}}), \ldots, (x_{20}^{\hat{s}}, y_{20}^{\hat{s}}, z_{20}^{\hat{s}})\big) \qquad \text{(D.1)}$$

3. Without loss of generality, the numerical x, y, and z values in each scenario $\hat{s}$ were then replaced by indicator values equal to 0 for a low value, 1 for a moderate value, and 2 for a high value.

4. The resulting collection $\hat{\mathcal{S}}$ of 5000 scenarios $\hat{s}$ was then enlarged to 5003 scenarios by the addition of (i) the *extreme-low scenario* s^{low} consisting of all 0 values; (ii) the *normal scenario* s^{norm} consisting of all 1 values; and (iii) the *extreme-high scenario* s^{high} consisting of all 2 values. Let this augmented scenario set be denoted by $\hat{\mathcal{S}}^A$.
5. The distance $d(\hat{s}, s^{norm})$ of each scenario $\hat{s}$ in $\hat{\mathcal{S}}^A$ from the normal scenario s^{norm} was then calculated using a Hamming signed-distance measure that calculates the accumulated differences in successive scenario values. For example, given two-year scenarios

$$\hat{s} = ((0,1,1),(2,1,0)) \quad \text{and} \quad s^{norm} = ((1,1,1),(1,1,1)) \tag{D.2}$$

one has

$$\begin{aligned} d(\hat{s}, s^{norm}) &= (0-1)+(1-1)+(1-1)+(2-1)+(1-1)+(0-1) \\ &= -1. \end{aligned} \tag{D.3}$$

6. Each scenario $\hat{s}$ in $\hat{\mathcal{S}}^A$ was then assigned to one and only one of the following 31 scenario clusters S_d in accordance with its signed distance $d = d(\hat{s}, s^{norm})$:

$$\begin{aligned} &-60,\ [-59,-15],\ [-14,-13],\ -12,\ -11,\ -10, \ldots\ldots, -1 \\ &\qquad 0,\ 1, \ldots\ldots, 10,\ 11,\ 12,\ [13,14],\ [15,59],\ 60 \end{aligned} \tag{D.4}$$

7. For each scenario cluster S_d, a single representative scenario s_d was then selected from among those scenarios in S_d having the highest assigned probability. The resulting set $\mathcal{S}$ of 31 selected scenarios s_d was then taken to be the scenario ensemble for the base-case application.
8. The original probability assigned to each s_d in $\mathcal{S}$ was then re-normalized by setting this probability equal to the number of scenarios in cluster S_d, divided by 5003, so that the summation of the re-normalized probabilities attached to the 31 scenarios in $\mathcal{S}$ exactly equaled 1.0.
9. Each of the 31 scenarios s_d in $\mathcal{S}$ was then assigned a *scenario number* equal to its signed distance from the normal scenario s^{norm}. Note that the scenario number for s^{norm} is 0.

The resulting probability distribution for the 31 environmental scenarios in $\mathcal{S}$ is depicted in Fig. 4.

Appendix E. Farmer's Base-Case Decision Modes

Appendix E.1. The Farmer's Intertemporal Welfare Maximization Problem

For the base-case application, the ultimate intertemporal objective of the Farmer at time $t{:}3$ is assumed to be the selection of an information-contingent plan for her land allocation decisions $\{c_{y:3}, r_{y:3}\}$ and consumption decisions $\{\text{Cons}^F_{y:7}\}$ over all future years $y \geq t$ to maximize her expected intertemporal utility-of-consumption (UOC), measured by

$$E[\sum_{y=t}^{\infty} \beta^{y-t}\text{UOC}_{y:7} \mid I^F_{t:3}] \tag{E.1}$$

In (E.2), β is a positive time-preference discount factor, and $\text{UOC}_{y:7}$ takes the form

$$\text{UOC}_{y:7} \;=\; u(\text{Cons}^F_{y:7}) \;=\; \ln(\text{Cons}^F_{y:7} - \bar{C}^F + D) \tag{E.2}$$

where: ln denotes the natural logarithm function; $\text{Cons}^F_{y:7}$ denotes the Farmer's corn consumption determined at time $y{:}7$ for year y; $\bar{C}^F$ denotes the Farmer's positive annual corn-consumption subsistence needs; and D is a risk tolerance parameter whose value is constrained to satisfy $D > \bar{C}^F$.[7]

The farmer's land allocation and consumption decisions at time $y{:}3$ in each year $y \geq t$ must be compatible with the following survival, budget, and feasibility constraints:

$$\text{Cons}^F_{y:7} \;\geq\; \bar{C}^F \tag{E.3}$$

$$\text{CPrice}_{y:6} \cdot \text{Cons}^F_{y:7} \;\leq\; M^{poss}_{y:7} \tag{E.4}$$

$$0 \leq c_{y:3} \tag{E.5}$$

$$0 \leq r_{y:3} \leq r^{max} \tag{E.6}$$

$$c_{y:3} + r_{y:3} \leq 1 \tag{E.7}$$

From the vantage point of time $t{:}3$, the Farmer's possible money holdings $M^{poss}_{y:7}$ at the future time $y{:}7$ depend either directly or indirectly on all of the

[7] The restriction $D > \bar{C}^F > 0$ ensures that (E.2) is well defined even if $C^F_{y:7}$=0 (F dies) or $C^F_{y:7}$=$\bar{C}^F$ in some year y.

event and decision realizations occurring between t:3 and y:7. This can be deduced from the relationships set out in Section 4.3, as follows:

$$\begin{aligned}
M_{y:7}^{poss} &= M_{y:4} + \mathrm{Value}_{y:6}^{crop} \\
&= M_{y:4} + \mathrm{CPrice}_{y:6} \cdot \mathrm{CCrop}_{y:5} \\
&= M_{y:4} + \mathrm{CPrice}_{y:6} \cdot H_{y:5} \cdot A_{y:3}^{crop} \\
&= M_{y:4} + \mathrm{CPrice}_{y:6} \cdot H_{y:5} \cdot c_{y:3} \cdot A^F
\end{aligned} \tag{E.8}$$

Moreover, the Farmer's money holdings $M_{y:4}$ at time y:4, given by

$$\begin{aligned}
M_{y:4} &= M_{y:3} - \mathrm{InputCost}_{y:1} \cdot A_{y:3}^{crop} \\
&= M_{y:3} - \mathrm{InputCost}_{y:1} \cdot c_{y:3} \cdot A^F \\
&= M_{y:1} + \mathrm{RetSub}_{y:3}^{act} - \mathrm{InputCost}_{y:1} \cdot c_{y:3} \cdot A^F \\
&= M_{y:1} + \tau_{y:2} \cdot A_{y:3}^{ret} - \mathrm{InputCost}_{y:1} \cdot c_{y:3} \cdot A^F \\
&= M_{y:1} + \frac{s_{y:2} \cdot B_{y:1}}{r^{max} A^F} \cdot A_{y:3}^{ret} - \mathrm{InputCost}_{y:1} \cdot c_{y:3} \cdot A^F \\
&= M_{y:1} + \frac{s_{y:2} \cdot B_{y:1}}{r^{max} A^F} \cdot r_{y:3} \cdot A^F - \mathrm{InputCost}_{y:1} \cdot c_{y:3} \cdot A^F \,,
\end{aligned} \tag{E.9}$$

must be non-negative in sign. Finally, the Farmer's money holdings $M_{y:1}$ at the start of year y must be expressed as a function of event and decision realizations occurring between t:3 and the end of year $y - 1$ and must also be nonnegative in sign.

In principle, the Farmer's expected UOC maximization problem outlined above can be solved as a stochastic dynamic programming (DP) problem. The key conceptual construct underlying stochastic DP for a decision-maker dm is the *value function* $V_t(I)$, defined to be the optimum expected total reward that can be obtained by the dm, starting at time t in state I.

Suppose a dm is currently in state I at some current time t. Suppose the dm implements a decision d, experiences a random event ω, obtains an immediate reward $R_t(I, d, \omega)$, and transits to a new state $I' = X_t(I, d, \omega)$. Then the best that the dm can do, starting from time $t + 1$, is $V_{t+1}(I')$. Consequently, letting $E[\cdot]$ denote expectation with respect to the random event ω, the best the dm can do, starting in state I at time t, is

$$V_t(I) = \max_d E\left[R_t(I, d, \omega) + \beta V_{t+1}(X_t(I, d, \omega))\right] \tag{E.10}$$

Finally, let Π^* denote the *optimal policy function* giving the optimal decision d^* in (E.10) as a function $d^* = \Pi^*(t, I)$ of the current time t and state I. Then (E.10) can equivalently be written as

$$V_t(I) = E\left[R_t(I, \Pi^*(t, I)) + \beta V_{t+1}(X_t(I, \Pi^*(t, I)), \omega)\right] \tag{E.11}$$

The recursive relationships (E.10) and (E.11) provide simple illustrations of Richard Bellman's celebrated *principle of optimality* for stochastic DP problems; see (Powell, 2011, 2014).

On the other hand, it is impractical to expect the Farmer to be able to solve a constrained expected intertemporal UOC maximization problem of this form for each successive year t. It requires too much information about the probability distributions for future input costs, corn prices, and precipitation patterns, too much information about future city budgets and subsidy portion selections $\{B_{y:1}, s_{y:2}\}_{y \geq t}$, and too much computational time.

Consequently, in this study we instead investigate two alternative decision modes that the Farmer could implement to obtain an approximate solution for this problem. These two decision modes, F-OFF and F-ON, are described in detail in Appendix E.2 and Appendix E.3, respectively.

Appendix E.2. F-OFF Decision Mode: Myopic Two-Stage Decision Process

As detailed in Section 4.3, at time t:3 during each year t the Farmer allocates her farmland A^F into three portions by choice of the percentages $(c_{t:3}, r_{t:3})$. One portion, $c_{t:3}A^F$, is for cropland, a second portion, $r_{t:3}A^F$, is for retention land, and the remaining portion, $[1 - c_{t:3} - r_{t:3}]A^F$, is left fallow. At the subsequent time t:7 the Farmer divides her money holdings $M_{t:7}(c_{t:3}, \tau_{t:2}r_{t:3})$ between consumption $\text{Cons}^F_{t:7}$ and savings $S^F_{t:7}$.

The F-OFF decision mode for the Farmer is summarized as follows. During each year t the Farmer determines her year-t land allocation and subsequent consumption and savings portions by solving two successive myopic decision problems, as follows:

- At time t:3, conditional on information state $I^F_{t:3}$, the Farmer chooses a feasible land allocation (c, r) to maximize her expected possible money holdings at time t:7, denoted by $E[M^{poss}_{t:7}(c, \tau_{t:2}r) \mid I^F_{t:3}]$.

- At time t:7, conditional on information state $I^F_{t:7}$, the Farmer chooses a consumption level $\text{Cons}^F_{t:7}$ to maximize her year-t UOC subject to a savings-target constraint and a subsistence constraint.

A detailed derivation of the if-then decision rules that solve these two successive decision problems will now be given.

Using the notation from Section 4.3, the Farmer's first-stage decision problem at time $t{:}3$ takes the following form:

$$\max_{c,r} E\big[M^{poss}_{t:7}(c, \tau_{t:2}r) \mid I^F_{t:3}\big] \tag{E.12}$$

subject to the feasibility conditions

$$0 \ \leq \ c \ \leq \ c^{max}(\tau_{t:2}r) \tag{E.13}$$
$$0 \ \leq \ r \leq r^{max} \tag{E.14}$$
$$c + r \ \leq \ 1 \tag{E.15}$$

where, as in (14),

$$c^{max}(\tau_{t:2}r) \ = \ \min\{1, \frac{M_{t:3}(\tau_{t:2}r)}{\text{InputCost}_{t:1} \cdot A^F}\} \tag{E.16}$$

and, as derived in Appendix E.1,

$$\begin{aligned} M^{poss}_{t:7}(c, \tau_{t:2}r) \ &= \ M_{t:1} + \tau_{t:2}rA^F \\ &+ \ \big[\text{CPrice}_{t:6}H(\text{Precip}_{t:5}) - \text{InputCost}_{t:1}\big]A^{crop}_{t:3}(c) \end{aligned} \tag{E.17}$$

As detailed in Section 4.3, the Farmer's information state $I^F_{t:3}$ at time $t{:}3$ includes: the information state $I^F_{t:1}$ (hence all structural parameters such as A^F); the Farmer's money holdings $M_{t:1}$ at time $t{:}1$; the realization $\text{InputCost}_{t:1}$ for input costs at time $t{:}1$; the City Manager's selection of a retention-land subsidy rate $\tau_{t:2}$ at time $t{:}2$; the stationary probability distributions governing corn price and harvest productivity; and the knowledge that these probability distributions are independent of each other. It follows that

$$\begin{aligned} E\big[M^{poss}_{t:7}(c, \tau_{t:2}r) \mid I_{t:3}\big] \ &= \ M_{t:1} + \tau_{t:2}rA^F \\ &+ \big[E\text{CPrice} \cdot EH(\text{Precip}) - \text{InputCost}_{t:1}\big]A^{crop}_{t:3}(c) \end{aligned} \tag{E.18}$$

We will now develop an if-then decision rule for the Farmer that solves this first-stage decision problem at time $t{:}3$. As noted above, and explained carefully in Section 5.3, all stochastic events for the base-case application are generated by independent stationary probability distributions that are known to the Farmer.

The net earnings obtained by the Farmer from the sale of her corn crop at time t:7, per acre of planted cropland, is given by

$$\text{NetEarn}_{t:7} \;=\; \text{CPrice}_{t:6} \cdot H(\text{Precip}_{t:5}) - \text{InputCost}_{t:1} \;\; (\$/\text{acre}) \qquad \text{(E.19)}$$

Given the ensemble of possible environmental scenarios specified in Appendix D, the net earnings (E.19) can be either positive or negative. At time t:3 the Farmer calculates her *expected* net earnings per acre of planted cropland, conditional on her observed per-acre input cost at time t:1, as

$$\begin{aligned} E_{t:3}\pi^{crop} \;&=\; E\left[\text{NetEarn}_{t:7} \mid I_{t:3}\right] \\ &=\; E\text{CPrice} \cdot EH(\text{Precip}) - \text{InputCost}_{t:1} \end{aligned} \qquad \text{(E.20)}$$

In addition, the Farmer knows that her net earnings per acre of retention land is given by the subsidy rate $\tau_{t:2}$ announced by the City Manager at time t:2, as determined in (3); i.e.,

$$E_{t:3}\pi^{ret} \;=\; \tau_{t:2} \qquad \text{(E.21)}$$

Finally, the Farmer knows that her net earnings per acre of fallow land is zero; i.e.,

$$E_{t:3}\pi^{fal} \;=\; 0 \qquad \text{(E.22)}$$

Also, as detailed in Appendix E.1, the Farmer's base-case UOC function (E.2) for each year t is specified to be a logarithmic (hence strictly concave) function of her consumption at time t:7. It follows from Jensen's inequality for strictly concave functions[8] that the Farmer is risk averse in the following sense: If at time t:3 the Farmer is offered a choice between a sure-thing option offering a consumption level C^* for sure at time t:7 and a random lottery that offers a non-degenerate random consumption level C at time t:7 whose expectation is C^*, the Farmer will strictly prefer the sure-thing option. That is, $u(C^*) = u(EC) > Eu(C)$. However, if the Farmer is offered two different sure-thing options of equal value, we assume below that the Farmer flips a fair coin to decide which option to accept.

Finally, consider the upper bound $c^{max}(\tau_{t:2}r)$ on $c_{t:3}$, given by (E.16). If $\tau_{t:2} = 0$, this upper bound is equal to $c^{max}(0)$ independently of r. Suppose

[8] Jensen's inequality, found in any standard real analysis textbook, can be roughly stated as follows: If $f(x)$ is a concave function of x, then $f(Ex) \geq Ef(x)$; and this inequality holds *strictly* if $f(x)$ is a *strictly* concave function of x.

$\tau_{t:2} > 0$. In this case $M_{t:3}(\tau_{t:2}r)$ is a linear, positive-valued, and strictly-increasing function of $r \geq 0$, and $c^{max}(\tau_{t:2}r)$ is a continuous non-decreasing function of r.

Claim: Given $\tau_{t:2} > 0$, there exists a *largest* value $r^L \in [0, r^{max}]$ that maximizes $c^{max}(\tau_{t:2}r)$ subject to $c^{max}(\tau_{t:2}r) + r \leq 1$.

Proof: Suppose $\tau_{t:2} > 0$. If $c^{max}(0) = 1$, then $r^L = 0$. If $c^{max}(0) < 1$, then, since $c^{max}(\tau_{t:2}r)$ is a continuous non-decreasing function of r, there must be a maximum range of r values of the form $[0, r^*]$ with $r^* \leq r^{max}$ for which $c^{max}(\tau_{t:2}r) + r \leq 1$. If $c^{max}(\tau_{t:2}r^{max}) + r^{max} > 1$, then r^* is the solution to $c^{max}(\tau_{t:2}r) + r = 1$. If $c^{max}(\tau_{t:2}r^{max}) + r^{max} \leq 1$, then $r^* = r^{max}$. By the Weierstrass Theorem (or direct simple analysis), there must exist some point in $[0, r^*]$ at which the continuous function $c^{max}(\tau_{t:2}r)$ attains a maximum over this interval. Since $c^{max}(\tau_{t:2}r)$ is non-decreasing in r, the largest value r^L in $[0, r^*]$ at which this maximum is attained is $r^L = r^*$. QED

Given the above points, the solution $(c_{t:3}, r_{t:3})$ for the Farmer's first-stage decision problem (E.12) at time t:3 is as follows:

Solution to the Farmer's First-Stage Decision Problem at Time t:3

Case 1: If $E_{t:3}\pi^{crop} > E_{t:3}\pi^{ret} > E_{t:3}\pi^{fal}$, plant the largest feasible portion of farmland as cropland, allocate the portion r^L to retention, and leave the remaining portion fallow; i.e., set

$$(c_{t:3}, r_{t:3}) = (c^{max}(\tau_{t:2}r^L), r^L) \tag{E.23}$$

Case 2: If $E_{t:3}\pi^{crop} > E_{t:3}\pi^{ret} = E_{t:3}\pi^{fal}$, plant the largest feasible portion of farmland as cropland and, with prob 1/2-1/2, allocate the remaining portion to retention or fallow land; i.e., with prob 1/2-1/2 set

$$\begin{aligned} (c_{t:3}, r_{t:3}) &= (c^{max}(0), \min\{1 - c^{max}(0), r^{max}\}) \\ \text{or } (c_{t:3}, r_{t:3}) &= (c^{max}(0), 0) \end{aligned} \tag{E.24}$$

Case 3: If $E_{t:3}\pi^{ret} > E_{t:3}\pi^{fal} \geq E_{t:3}\pi^{crop}$, allocate the largest feasible portion of farmland to retention and leave the remainder fallow; i.e., set

$$(c_{t:3}, r_{t:3}) = (0, r^{max}) \tag{E.25}$$

Case 4: If $E_{t:3}\pi^{ret} = E_{t:3}\pi^{fal} \ \geq \ E_{t:3}\pi^{crop}$, then with prob 1/2-1/2 allocate the largest feasible portion of farmland to retention and the remainder to fallow, or allocate all farmland to fallow; i.e., with prob 1/2-1/2 set

$$(c_{t:3}, r_{t:3}) = (0, r^{max}) \text{ or } (c_{t:3}, r_{t:3}) = (0, 0) \tag{E.26}$$

Case 5: If $E_{t:3}\pi^{ret} \ \geq \ E_{t:3}\pi^{crop} \ > \ E_{t:3}\pi^{fal}$, allocate the largest feasible portion of farmland to retention, allocate the largest feasible portion of the remainder to cropland, and leave the rest fallow; i.e., set

$$(c_{t:3}, r_{t:3}) = (\min\{c^{max}(\tau_{t:2}r^{max}), 1 - r^{max}\}, r^{max}) \tag{E.27}$$

Consider, now, the Farmer's second-stage decision problem at time t:7. The Farmer's savings target for her money holdings at the end of year t is assumed to take the following form:

$$S^F(\theta^0) = \theta^0 \cdot E\big[\text{CPrice}\big] \cdot \bar{C}^F \tag{E.28}$$

In (E.28), θ^0 is a risk-aversion factor whose value determines the scale of the Farmer's savings target, E[CPrice] is the stationary expectation for the annual corn price, and $\bar{C}^F$ is the Farmer's annual subsistence need for corn. The Farmer determines her corn consumption $\text{Cons}^F_{t:7}$ at time t:7 by implementing the following if-then decision rule:

Solution to the Farmer's Second-Stage Decision Problem at Time t:7

- If the Farmer's money holdings are insufficient to attain her subsistence consumption $\bar{C}^F$, that is, if $M^{poss}_{t:7}(c_{t:3}, \tau_{t:2}r_{t:3}) \ < \ \text{CPrice}_{t:6} \cdot \bar{C}^F$, then

$$\text{Cons}^F_{t:7} \ = \ \frac{M^{poss}_{t:7}(c_{t:3}, \tau_{t:2}r_{t:3})}{\text{CPrice}_{t:6}} \ < \ \bar{C}^F \tag{E.29}$$

  and the Farmer dies at the end of subperiod t_7.

- If the Farmer's money holdings are sufficient to attain $\bar{C}^F$ but not to attain her targeted savings $S^F(\theta^0)$, that is, if $\text{CPrice}_{t:6} \cdot \bar{C}^F \ \leq \ M^{poss}_{t:7}(c_{t:3}, \tau_{t:2}r_{t:3}) < S^F(\theta^0) + \text{CPrice}_{t:6} \cdot \bar{C}^F$, then

$$\text{Cons}^F_{t:7} = \bar{C}^F \text{ and } S^F_{t:7} = M^{poss}_{t:7}(c_{t:3}, \tau_{t:2}r_{t:3}) - \text{CPrice}_{t:6} \cdot \bar{C}^F \tag{E.30}$$

- If the Farmer's money holdings are sufficient to attain $\bar{C}^F$ and $S^F(\theta^0)$, that is, if $M^{poss}_{t:7}(c_{t:3}, \tau_{t:2}r_{t:3}) \ \geq \ S^F(\theta^0) + \text{CPrice}_{t:6} \cdot \bar{C}^F$, then

$$\text{Cons}^F_{t:7} \ = \ \frac{\big[M^{poss}_{t:7}(c_{t:3}, \tau_{t:2}r_{t:3}) - S^F(\theta^0)\big]}{\text{CPrice}_{t:6}} \ \text{ and } \ S^F_{t:7} = S^F(\theta^0) \tag{E.31}$$

Appendix E.3. F-ON Decision Mode: Yearly Expected UOC Maximization

As explained in Section 5.3 and Appendix D, all stochastic events for the base-case application are generated by independent stationary probability distributions that are known to the Farmer. In particular, then, the Farmer knows the true stationary expectation for the annual corn price.

The F-ON decision mode for the Farmer is summarized as follows. At each time $t{:}3$ during each successive year t, the Farmer selects her land allocation percentages $(c_{t:3}, r_{t:3})$ and her consumption and savings levels $\mathrm{Cons}^F_{t:7}$ and $\mathrm{Sav}^F_{t:7}$ to maximize her expected UOC for year t subject to budget constraints and an initially desired savings target for her end-of-year money holdings. As in Appendix E.3, the Farmer's initially desired savings target is assumed to take the form (E.28).

The F-ON decision mode for the Farmer will now be more carefully explained. Without loss of generality, attention will be focused on the Farmer's implementation of this decision mode at time 1:3 for year 1. The resulting problem formulation is easily generalized to apply to arbitrary successive years $t \geq 1$.

Suppose the Farmer at time 1:3 in year 1 is considering the selection of her land allocation, consumption, and savings decisions for year 1, denoted as follows:

$$d^F \ = \ \big(c_{1:3}, r_{1:3}, \mathrm{Cons}^F_{1:7}, S^F_{1:7}\big) \tag{E.32}$$

However, the Farmer realizes that, between her choice of land allocation percentages at time 1:3 and her choice of consumption and savings decisions at time 1:7, she will acquire additional information: namely, she will observe the realization of a precipitation pattern $\mathrm{Precip}_{1:5}$ during subperiod 1_5 and a corn price $\mathrm{CPrice}_{1:6}$ at time 1:6. Consequently, in order to make efficient use of her information, she should choose the decisions in (E.32) as functions of her available information.

The Farmer's information state $I^F_{1:3}$ at time 1:3 includes her information state $I^F_{1:1}$ at time 1:1, her input-cost observation $\mathrm{InputCost}_{1:1}$ at time 1:1, and the City Manager's subsidy percentage $s_{1:2}$ for year 1 as announced at time 1:2. That is,

$$I^F_{1:3} \ = \ \big\{I^F_{1:1}, \mathrm{InputCost}_{1:1}, s_{1:2}\big\} \tag{E.33}$$

The Farmer's information state $I^F_{1:1}$ at time 1:1 in turn includes all maintained structural aspects of the Farmer's decision environment, including the initially given level θ^0 for the scale factor θ determining her savings target (E.28) for the end of year 1.

At time 1:3 the Farmer selects her choices for $c_{1:3}$ and $r_{1:3}$ from her decision domain $\mathrm{DD}^F(r^{max})$ in (29) as functions $c(I^F_{1:3})$ and $r(I^F_{1:3})$ of the information set $I^F_{1:3}$. However, the Farmer also understands that her information set $I^F_{1:7}$ at time 1:7 will be larger than her information set $I^F_{1:3}$ at time 1:3, as follows:

$$I^F_{1:7} \;=\; \big\{I^F_{1:3}, \mathrm{Precip}_{1:5}, \mathrm{CPrice}_{1:6}\big\} \tag{E.34}$$

Consequently, to determine an optimal solution for her expected UOC maximization problem at time 1:3, the Farmer chooses a collection of information-contingent decision *functions* of the following form:

$$d^F(\boldsymbol{I}) \;=\; \big(c(I^F_{1:3}), r(I^F_{1:3}), \mathrm{Cons}^F(I_{1:7}), S^F(I_{1:7})\big) \tag{E.35}$$

The F-ON Farmer's expected UOC maximization problem at time 1:3 thus takes the following form:

$$\max\; E\left[u(\mathrm{Cons}^F_{1:7}) \mid I^F_{1:3}\right] \tag{E.36}$$

with respect to choice of d^F subject to the constraints

$$d^F \;=\; d^F(\boldsymbol{I}) \tag{E.37}$$
$$0 \le c_{1:3} \tag{E.38}$$
$$0 \le r_{1:3} \le r^{max} \tag{E.39}$$
$$c_{1:3} + r_{1:3} \le 1 \tag{E.40}$$
$$M_{1:3} \;=\; M_{1:1} + \tau_{1:2} \cdot r_{1:3} \cdot A^F \tag{E.41}$$
$$M_{1:4} \;=\; M_{1:3} - \mathrm{InputCost}_{1:1} \cdot c_{1:3} \cdot A^F \tag{E.42}$$
$$M_{1:4} \;\ge\; 0 \tag{E.43}$$
$$M^{poss}_{1:7} \;=\; M_{1:4} + \mathrm{CPrice}_{1:6} \cdot H_{1:5} \cdot c_{1:3} \cdot A^F \tag{E.44}$$
$$\mathrm{Cons}^F_{1:7} \;\ge\; \bar{C}^F \tag{E.45}$$
$$\mathrm{CPrice}_{1:6} \cdot \mathrm{Cons}^F_{1:7} \;=\; M^{poss}_{1:7} - S^F_{1:7} \tag{E.46}$$
$$S^F_{1:7} \;=\; \theta_{1:7} \cdot E\big[\mathrm{CPrice}\big] \cdot \bar{C}^F \tag{E.47}$$
$$\theta_{1:7} = \max_{0 \le \rho \le 1} \{\, \rho \cdot \theta^0 \mid \text{F's maximization problem has a solution}\} \tag{E.48}$$

Detailed explanations for constraints (E.38) through (E.47) are provided in Section 4.3. However, constraint (E.48) needs further explanation. Suppose the savings-target scaling factor θ is simply fixed at the initial value

θ^0, and the constraint (E.48) is omitted. Then the above expected UOC maximization problem will fail to have a solution if there exists an information state $I_{1:7}$ for which the Farmer is unable to achieve both her savings target and her subsistence consumption needs. Consequently, it is instead assumed that the F-ON Farmer is able to ratchet down the value of θ^0 towards zero in any feasible information state $I_{1:7}$ in which she is unable to secure her subsistence consumption needs at the initial scaling level θ^0. This information-contingent downward ratcheting is captured in constraint (E.48). A solution will still fail to exist if there exists at least one feasible information state $I_{1:7}$ for which the F-ON Farmer is unable to secure her subsistence consumption needs even if she ratchets her year-1 savings target all the way down to zero.

For analytical tractability, the F-ON Farmer's decision domain $\mathrm{DD}^F(r^{max})$ in (29) – represented by constraints (E.38) through (E.40) in the above expected UOC maximization problem – is approximated by a finite subset AD^F, constructed as follows. First, the upper limit r^{max} for the portion r of farmland that the F-ON Farmer can allocate to retention land, interpreted as a watershed policy parameter, is maintained at the fixed value 0.25. Second, the range of possible values for the F-ON Farmer's cropland portion c and retention land portion r are restricted to the following subsets:

$$c \in \mathcal{C} = \{0.0, 0.1, \ldots, 0.9, 1.0\} \tag{E.49}$$

$$r \in \mathcal{R}(r^{max}) = \{0.0, 0.2, \ldots, 0.8, 1.0\} \cdot r^{max} \tag{E.50}$$

Then AD^F is given by

$$\mathrm{AD}^F = \{(c, r) \mid \ c \in \mathcal{C}, r \in \mathcal{R}(r^{max}), \ c + r \leq 1\} \tag{E.51}$$

Finally, if the expected UOC maximization problem (E.36) for any year t has multiple possible solutions, the F-ON Farmer uses a random "coin flip" to select a particular solution.

Appendix F. CM-ON Base-Case Budget-Allocation Process

As explained in Section 4.3, at time t:2 in each year t the City Manager allocates the year-t city budget $B_{t:1}$ into three portions by choice of the percentages $(s_{t:2}, \ell_{t:2})$. One portion is for city social service expenditures, a second portion is for retention-land subsidies (a flood-damage mitigation measure), and a third portion is for levee investment (another flood-damage mitigation measure).

Under CM-ON treatments, described in Section 5.4, the City Manager is a welfare optimizer with successive one-year planning horizons. The objective of the City Manager at time t:2 in each year t is to select $(s_{t:2}, \ell_{t:2})$ to maximize expected city social welfare (CSW) for year t, subject to system constraints.[9]

Actual CSW for year t cannot be determined until time t:5, after city social-service expenditures and flood damage for year t have both been realized. This actual CSW is measured by

$$CSW_{t:5} \;=\; \text{SocServ}^{act}_{t:3} \;+\; \psi \cdot \left[FD^{max} - FD_{t:5}\right] \;, \tag{F.1}$$

where the trade-off weight ψ is strictly positive. The term FD^{max} in (F.1) denotes the maximum avoidable city flood damage in any given year, hence $[FD^{max} - FD_{t:5}]$ measures the amount of city flood damage avoided in year t. Actual CSW in year t is thus a weighted combination of year-t city social service expenditures and year-t city flood-damage mitigation.

At time t:2 the CM-ON City Manager does not know what the actual social-service expenditures and flood-damage mitigation will be at time t:5. However, given his objective, he will allocate the entire city budget to social services unless he sees some way in which the flood damage $\text{FD}_{t:5}$ can be mitigated by his choices of $s_{t:2}$ and $l_{t:2}$ at time t:2.

In actual fact, $\text{FD}_{t:5}$ does depend on the City Manager's choices for $s_{t:2}$ and $l_{t:2}$. This follows because flood damage is determined by the functional relationship (19), reproduced here for ease of reference:

$$FD_{t:5} = FD(LQ_{t:2}, Q_{p,t:5}) \tag{F.2}$$

where the peak water discharge rate Q_p is given by

$$Q_{p,t:5} = Q_p(\text{Precip}_{t:5}, A^{crop}_{t:3}, A^{ret}_{t:3}, A^{fal}_{t:3}) \tag{F.3}$$

Thus, $FD_{t:5}$ depends through $Q_{p,t:5}$ on the Farmer's land allocation decisions, which in turn depend on the City Manager's retention subsidy decision $s_{t:2}$;

[9]Levee investment at time t:2 is a physical capital investment that could yield a stream of returns over both current and future years in the form of increased flood-damage mitigation. Ideally, this full stream of returns should be taken into account in the specification of CSW. However, for the base-case application, it is assumed for simplicity that the CM-ON City Manager at each time t:2 only considers year-t returns to levee investment.

and $FD_{t:5}$ depends directly on the levee quality $LQ_{t:2}$, which in turn depends on the City Manager's levee investment decision $\ell_{t:2}$.

The CM-ON City Manager's information state $I^{CM}_{t:2}$ at time t:2 includes the input cost realized at time t:1, denoted by $\text{InputCost}_{t:1}$. In addition, however, it also includes all structural aspects of the CM's decision environment, including in particular the independent stationary probability distributions governing the realizations of the precipitation pattern $\text{Precip}_{t:5}$ and the corn price $\text{CPrice}_{t:6}$. Thus, the CM-ON City Manager at time t:2 is able to calculate the Farmer's *response functions* $r(I^F_{t:3})$ and $c(I^F_{t:3})$ for $c_{t:3}$ and $r_{t:3}$ at time t:3 as functions of the Farmer's time-t:3 information set[10]

$$I^F_{t:3} = \{I^F_{t:1}, \text{InputCost}_{t:1}, s_{t:2}\} \tag{F.4}$$

However, the CM-ON City Manager at time t:2 still does not know for sure the future flood damage level $FD_{t:5}$ as a function of his decisions $s_{t:2}$ and $\ell_{t:2}$ at time t:2 because $FD_{t:5}$ also depends (through $Q_{p,t:5}$) on the random event $\text{Precip}_{t:5}$. Thus, from the vantage point of t:2, year-t CSW is an $(s_{t:2}, \ell_{t:2})$-conditioned random variable of the form

$$CSW(s_{t:2},\ \ell_{t:2},\ c(I_{t:3}), r(I_{t:3}), \text{Precip}_{t:5}) \tag{F.5}$$

where the only aspect that is random as of time t:2 is the precise realization for $\text{Precip}_{t:5}$. Consequently, at time t:2 the CM-ON City Manager forms an *expectation* for year-t CSW, conditional on each of his possible choices for $(s_{t:2}, \ell_{t:2})$, where the expectation is taken with respect to the known probability distribution for $\text{Precip}_{t:5}$.

The CM-ON City Manager's expected CSW maximization problem at time t:2 thus takes the following form:

$$\max_{s_{t:2},\ell_{t:2}} E[CSW(s_{t:2}, \ell_{t:2}, c(I^F_{t:3}), r(I^F_{t:3}), \text{Precip}_{t:5}) \mid I^{CM}_{t:2}] \tag{F.6}$$

subject to the constraints

$$0 \ \leq \ s_{t:2} \tag{F.7}$$
$$0 \ \leq \ \ell_{t:2} \tag{F.8}$$
$$s_{t:2} + \ell_{t:2} \ \leq \ 1 \tag{F.9}$$

[10]In game theory terms, this makes the CM-ON City Manager a Stackelberg leader, able to determine the response of the Farmer-follower at time t:3 to each of his possible decisions $s_{t:2}$ at time t:2.

For analytical tractability, the City Manager's decision domain DD^{CM} in (30) – represented by constraints (F.7) through (F.9) above – is approximated by a finite subset AD^{CM}, constructed as follows. The range of possible values for the City Manager's subsidy portion s and levee investment portion ℓ are restricted to the following subsets:

$$s \in \mathcal{S} = \{0.0, 0.1, \ldots, 0.9, 1.0\} \tag{F.10}$$

$$\ell \in \mathcal{L} = \{0.0, 0.1, \ldots, 0.9, 1.0\} \tag{F.11}$$

Then AD^{CM} is given by

$$\mathrm{AD}^{CM} = \{(s, \ell) \mid \ s \in \mathcal{S}, \ell \in \mathcal{L}, \ s + \ell \leq 1\} \tag{F.12}$$

Finally, if the expected CSW maximization problem (F.6) for any year t has multiple possible solutions, the CM-ON City Manager uses a random "coin flip" to select a particular solution.