

An Infrastructure Resilience Improvements Assessments Framework

Alexander V. Outkin, Robert F. Jeffers

Sandia National Laboratories

MORS 86th Symposium

Monterrey, CA

June 19, 2018

Based on and extends SAND2016-8927 C developed with Nathan Bixler and others.

Overview

- RDEIM and Input-Output Modeling
- Scenario Definition
- Impacts Assessment
- Resilience Investments
Microgrids Placement

RDEIM Overview

- Employs Input-Output methodology, based on inter-industry commodity flows
- Uses geographic extent of disruption to estimate GDP losses
 - By industry
 - By county
- Uses Net Total Requirements Multipliers
- Uses Bureau of Economic Analysis (BEA) and U.S. Census Bureau data
- Was originally based on Sandia's REAcct IO model
- Underwent significant improvements as a result of NRC-commissioned International Review Panel

RDEIM Overview (cont.)

- International External Peer Review completed in 2016. The model deemed representing the state of practice for nuclear accident estimation
- Operational model for nuclear accident modeling has been implemented in MACCS. In preparation for external release
- Operational model for general disruption estimation has been implemented in Excel and R
- Multiplier estimation implemented in R

RDEIM Fundamentals

- Estimates direct GDP reductions for each industry in the affected area
- Calculates indirect impacts on the national scale impacts using the Net Total Requirements Multipliers
- County-level data and results
- Arbitrary GIS partitions of affected area supported
- Partially automated for ad-hoc disruption areas
- Computes rapidly

Input-Output Methodology

- Represents flow of products between sectors of economy based on actual transactional data
- Linear, allows fast computation, analytically tractable
- Generally uses linear, fixed-proportion production functions
- Effects of local changes to the regional or national levels estimated using multipliers derived from the Regional Input-Output Modeling System (RIMS II)

Input-Output History

- Developed starting in 1930s by V. Leontief (Harvard, NBER)
- Represents aggregated transactions in economy
- Used extensively for estimating consequences of accidents and disasters, such as earthquakes and hurricanes
- Used for economic planning, on local, regional, and national levels

Input-Output Prevalence and Uses

- Incorporated into national accounting of many developed countries (USA, UK, EU, Japan...)
- Data are readily available
- Employed by:

DHS, FEMA, Census Bureau, DOE, DoD, Federal Reserve, Bureau of Economic Analysis, Department of Labor, EPA, US Corps of Engineers, HPA (UK, COCO-2 – economic consequences model)

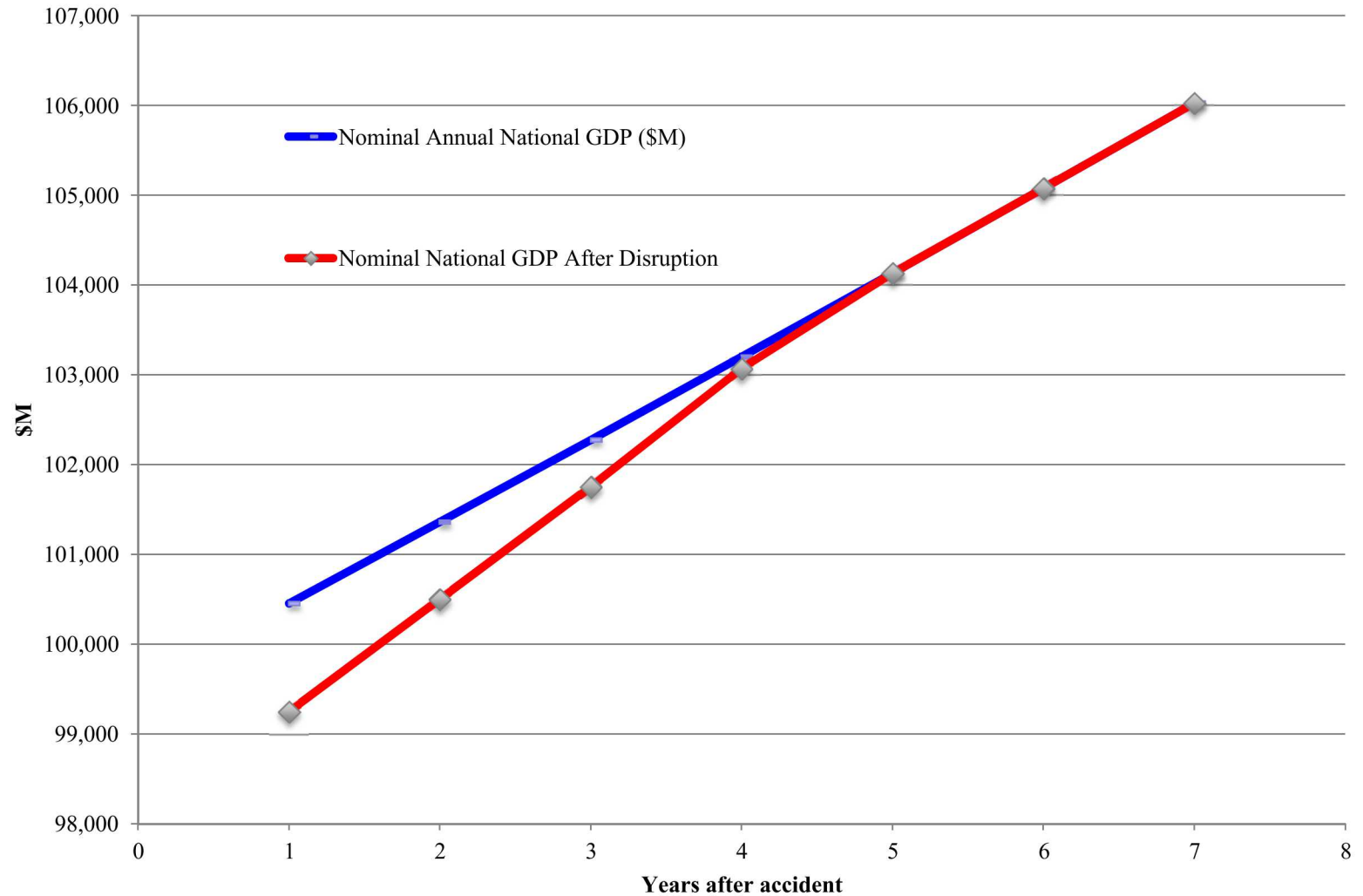
RDEIM Analysis

- Analysis includes:
 - Definition of the affected area
 - Restoration schedules by grid element
 - Calculation of GDP losses by industry for each county
 - Summation across all industries and counties and application of the Net Total Requirements Multipliers to calculate national impacts

RDEIM Data

- Sources: BEA, U.S. Census Bureau
 - US annual output
 - US annual value added
 - US employment
 - RIMS II Multipliers
 - County private industry employment
 - County government employment

Impact Estimation



Inputs to Long-Term Impacts

- Restoration schedule by grid element
- Duration of the national impacts
- Growth rate for future years' GDP
- Social discounting rate for future losses

Model Parameters

- GDP growth rate
 - How to estimate GDP in future years?
- Maximum duration of local impact
- Maximum duration of national impact
- Social discount rate
 - How much do we value future as compared to now?

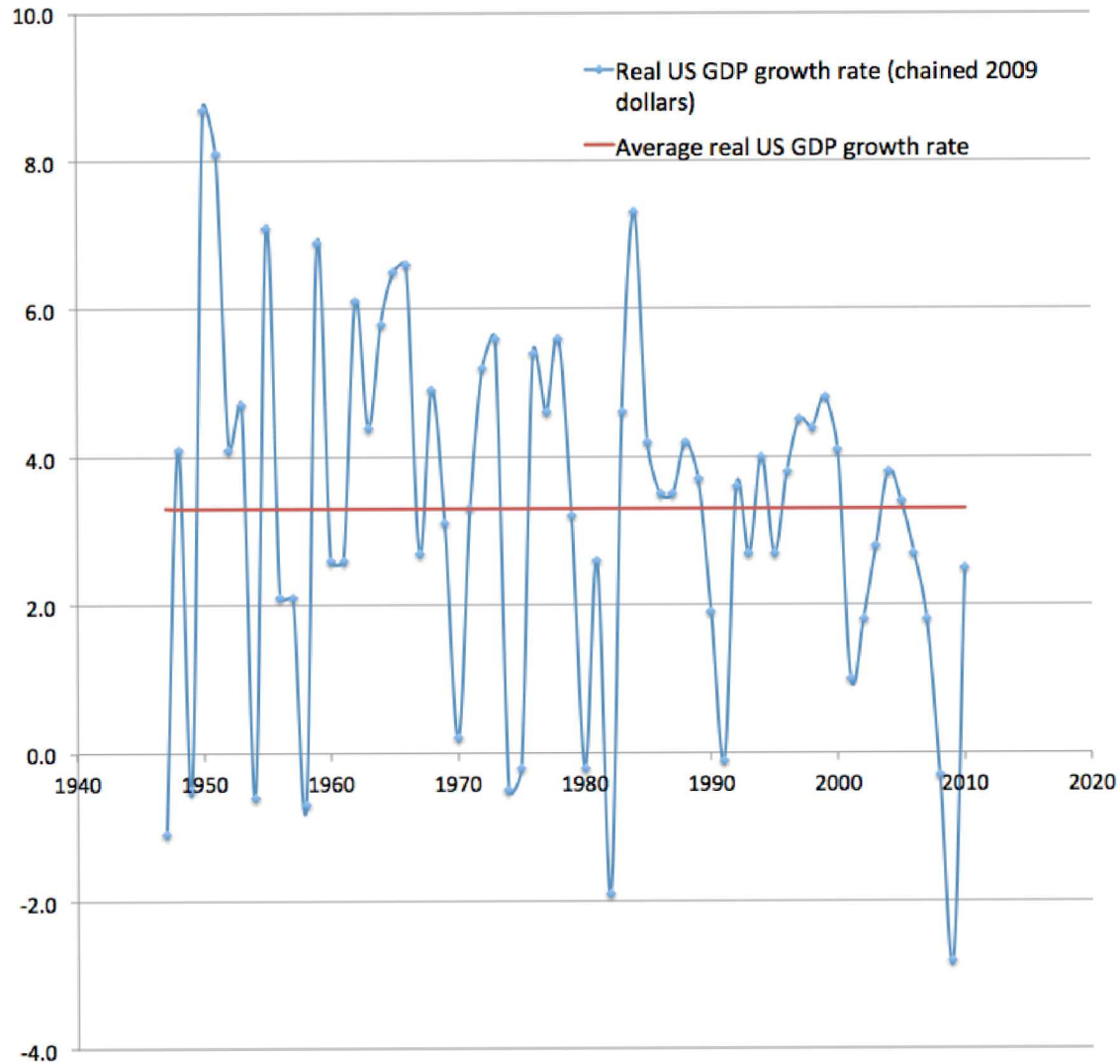
Parameter Values and Bounds

	Default value	Lower bound	Upper bound
Real GDP Growth Rates (%)	2.3	0	10
Social Discount Rate (%)	3	10	10
Max Duration Local Impact (yr)	10	1	30
Max. Duration of Nat. Impact (yr)	3	1	10

Sources:

- Historic data (US GDP growth rates (BEA), duration of recessions)
- Existing literature (social discount rate, loss calculation duration (COCO-2))
- Government policies and circulars (OMB Circular A-94)

Real GDP % Change over Time



Long-term Impacts Assumptions

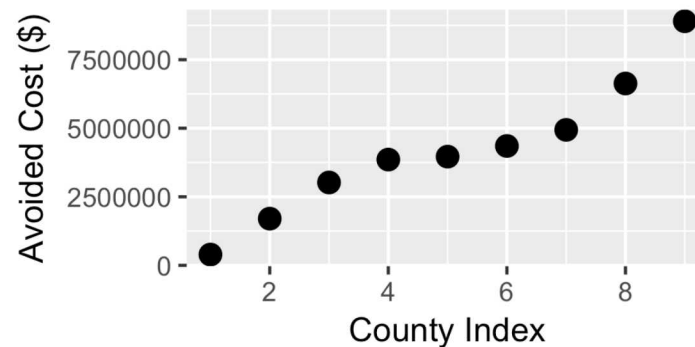
- Do not explicitly model adaptation
- Do not model long-term structural change
- Do not model downstream impacts

Impact Estimation Workflow

- Specify scenario parameters:
 - Restoration schedule by grid element
Can be industry-specific
 - National recovery rates. Can be industry-specific
- Retrieve annual GDP and employment data at the county and national levels
- Calculate local Net Total Requirements multipliers
- Calculate local and national direct losses
- Calculate local and national indirect and induced losses
- Aggregate the losses over time for the entire affected area taking into account the GDP growth rate and social discounting rate

Resilience Investments Evaluation Workflow

- Specify additional scenario parameters
 - Restoration schedule by grid element with investments
- Evaluate and compare possible investments



- Conduct cost-benefit analysis
 - GDP
 - Access to services, etc.

Notation

-
- V_i – annual value added for industry i
- ΔV_i – the direct value added change in industry i
- $\Delta V_{i,r}$ – the direct value added change in industry i in the grid element r .
- ΔV^D , ΔV^T , ΔV^{D+I} , ΔV^P – GDP (value added) losses, with indices D , T , DI , and P denoting the total, direct, direct plus indirect, and induced losses respectively.
- v_i – average value added per worker for industry i .
- Y_i – annual national gross output for industry i .
- E_i – national employment for industry i
- g – expected real *GDP* growth rate.
- ρ – social discount rate.
- t – Gregorian calendar time, expressed as a real number, in units of year
- t_0 – database year (starting time of base year).
- t_I – accident year (starting time of accident year).

Notation (cont.)

$m_i^{I,II}$ – the net total requirements multipliers of Type I or Type II.

$m_i^{I,II}$ – the final demand value added multipliers of Type I or Type II provided by the BEA.

$s_r(t)$ – disruption function representing the state of grid element r .

$l_{i,r}$ – number of industry i affected employees in grid element r .

T_R – maximum duration of economic loss calculation for directly affected area.

T_N – maximum duration of economic loss calculation for indirectly affected area.

Direct GDP Losses by Industry and Grid Element

- Direct annualized GDP

$$v_{i,r}^D = e^{g(t_I - t_0)} v_{i,r} l_{i,r}$$

- Cumulative scenario losses

$$\Delta V_{i,r}^D(T) = e^{g(t_I - t_0)} v_{i,r} l_{i,r} \int_0^T s_r(t) e^{(g-\rho)t} dt, \text{ where}$$

$s_r(t)$ is the recovery schedule for region r . Can be made industry-specific without changes to framework.

Direct GDP Loss for Affected Area

Direct loss until time T: entire area, all industries:

$$\Delta V^D(T) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} S_r(T), \text{ where}$$

$$S_r(t) = \int_0^T s_r(t) e^{(g-\rho)t} dt$$

Analytic Expressions for step restoration $s_r = \begin{cases} 1, & t \leq T_r \\ 0, & t > T_r \end{cases}$

1) $g \neq \rho$
$$\Delta V^D(T) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} \frac{e^{(g-\rho)T_r} - 1}{g - \rho}$$

2) $g = \rho$
$$\Delta V^D(T) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} T_r$$

Note: T – arbitrary \Rightarrow impacts over time

Total Impacts

Similar to Direct. Includes multipliers and national recovery estimates

$$\Delta V^T(T) = e^{g(t_I - t_0)} \sum_I v_i m^H_i \sum_R l_{i,r} \int_0^T s_r(t) s_N(t) e^{(g-\rho)t} dt, \text{ where}$$

$$s_N = \begin{cases} 1 - \frac{t}{T_N}, & t \leq T_N \\ 0, & t > T_N \end{cases}$$

where S_N is national restoration schedule. Linear, can be generalized. Analytical expressions analogous to direct

Indirect and Induced

- Indirect

$$\Delta V^I(T) = e^{g(t_I - t_0)} \sum_I v_i \sum_R l_{i,r} \int_0^T s_r(t) (s_N(t) m_i^I - 1) e^{(g-\rho)t} dt$$

- Induced

$$\Delta V^P(T) = \Delta V^T(T) - \Delta V^D(T) - \Delta V^I(T)$$

- Analytical expressions analogous to direct

Net Total Requirements Multipliers

New multipliers developed:

1. Initial disruption presented as value added losses in impacted area => “national” multipliers should operate on local changes in value added
2. If all industries in the affected area are shut down at the same time => multipliers have to be adjusted for intra-affected region trade to avoid double counting

Restoration Actions and Impacts of Different Restoration Schedules

- Temporal nature of the model allows investigation of impacts of different restoration
Regional restoration schedule s_r can reflect electric power availability, flooding, inundation, and other
- RDEIM results for a set of restoration schedules can be used for optimizing s_r to achieve specific objectives, such as local or national loss minimization, priority restoration for specific areas, industries, or facilities

Representing Resilience in RDEIM

- Different pre-disruption investment options, such as micro-grid placement would result in different post-disruption restoration schedules s_r . This allows prioritizing investments to achieve specific objectives: loss minimization, electric power availability maximization, etc.
- Different pre-disruption investments (shelters near productive facilities, other “in-vacuation” options) would affect the workforce availability $l_{i,r}$ and allow working towards loss minimization, and objectives

Specific Future Extensions to RDEIM

- Enable zip- or Census tract-level data
- Reflect commuting patterns and pre-disruption investments in Different pre-disruption investment options in workforce availability, $l_{i,r}$
- Enable optimization against different local restoration schedules s_r . Represent pre-disruption investments

Simple Notional Example

Affected Areas

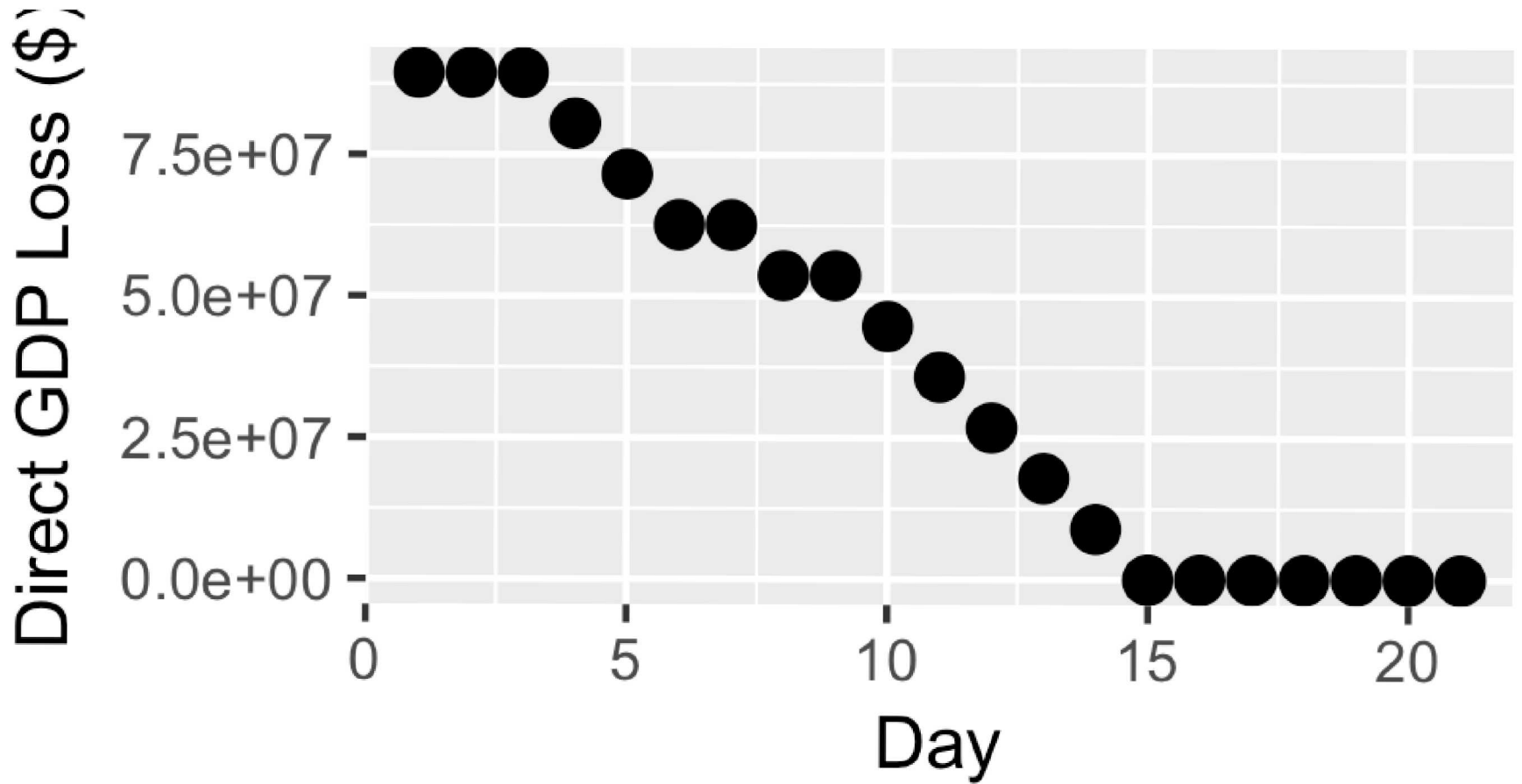
GEO.id	GEO.id2	Name
0500000US72127	72127	San Juan Municipio, Puerto Rico
0500000US72021	72021	Bayamón Municipio, Puerto Rico
0500000US72061	72061	Guaynabo Municipio, Puerto Rico
0500000US72033	72033	Cataño Municipio, Puerto Rico
0500000US72029	72029	Canóvanas Municipio, Puerto Rico
0500000US72135	72135	Toa Alta Municipio, Puerto Rico
0500000US72137	72137	Toa Baja Municipio, Puerto Rico
0500000US72031	72031	Carolina Municipio, Puerto Rico
0500000US72139	72139	Trujillo Alto Municipio, Puerto Rico

Simple Notional Example

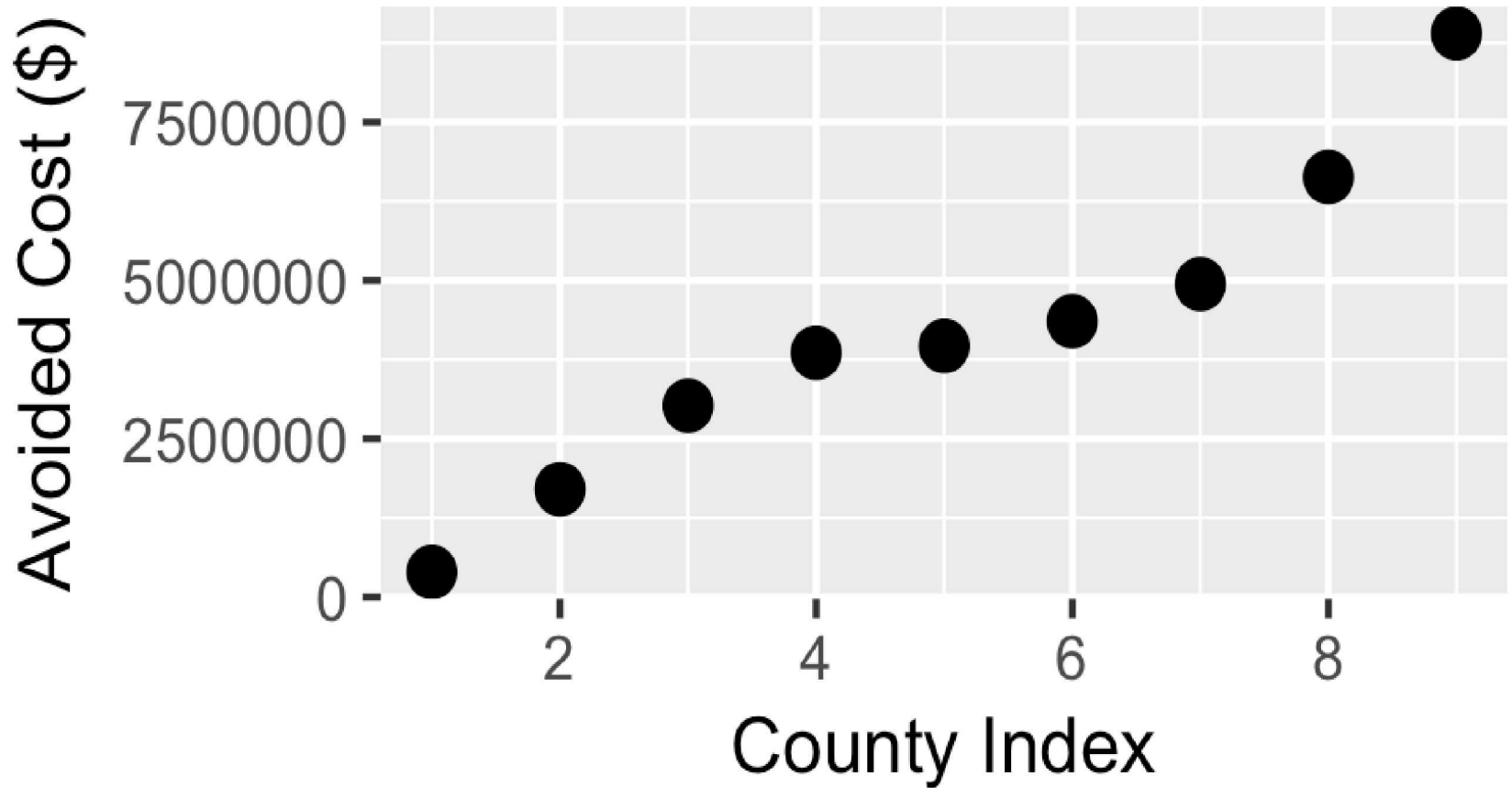
Industries

RDEIM_INDUSTY_ID	INDUSTRY_NAME
	Total
3	Agriculture forestry fishing and hunting
6	Mining
10	Utilities
11	Construction
12	Manufacturing
34	Wholesale trade
35	Retail trade
36	Transportation and warehousing
45	Information
51	Finance and insurance
56	Real estate and rental leasing
60	Professional scientific and technical services
64	Management of companies and enterprises
65	Administrative and waste management services
69	Educational services
70	Health care and social assistance
75	Arts entertainment and recreation
78	Accommodation and food services
81	Other services except government
83	Federal Civilian
85	State and Local Government

Daily GDP Loss



Avoided Loss vs. Location (County)



Resilience Evaluation Approach

Summary - Data

- Define affected area (a set of counties)
- Define spatial aggregation level (county)
- Define different resilience-enhancement options ($\Pi = \{p_1, p_2, \dots, p_k\}$)
- Generate disruption scenarios $(s_{i,r}^p, l_{i,r}^p)$ for different resilience-enhancement options
- Obtain and generate multiplier and value-added data

Resilience Evaluation Approach

Summary - Analysis

- Estimate value-added losses, affected customers, and other disruption outcomes for
$$\Pi = \{p_1, p_2, \dots, p_k\}$$
- Compare different options according disruption outcomes
 - Multi-objective. It is up to decision-makers to decide on tradeoffs
- Communicate the findings to the decision-makers to allow for their feedback and tradeoffs analysis associated with different options.

Summary

- Temporal model. Impacts estimated over time
- National and local scales
- Effects of recovery and restoration represented
- Avoided losses calculated for different resilience-enhancing investments
- Investments optimization
 - loss minimization vs. investment costs
 - restoration schedules given specific damage

Thank you!
