This presentation does not necessarily reflect the views of the United States Government, and is only the view of the author

Assessing and Communicating Resilience/Efficiency Tradeoffs in Complex Systems

Igor Linkov, PhD

Senior Science and Technology Manager (SSTM), US Army Engineer R&D Center;

Adjunct Professor, Carnegie Mellon University and University of Florida

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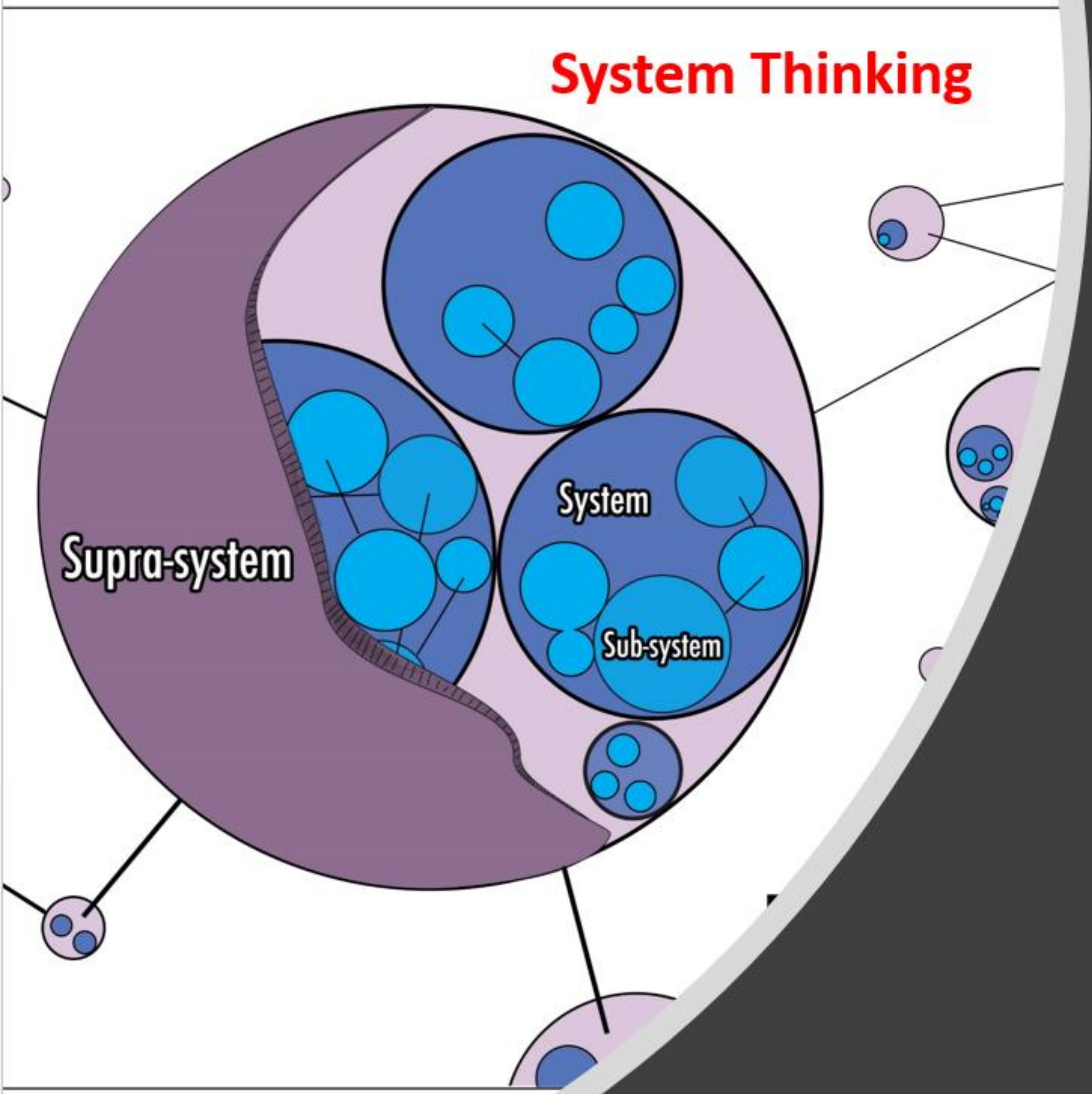
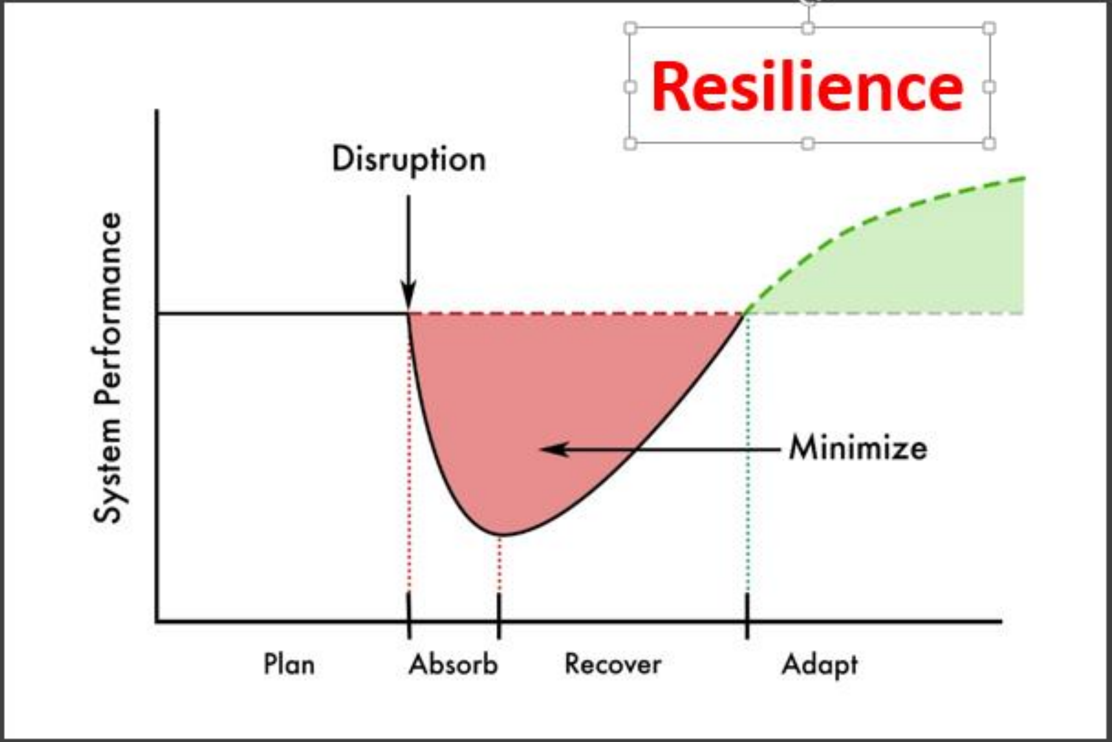
1 October 2022

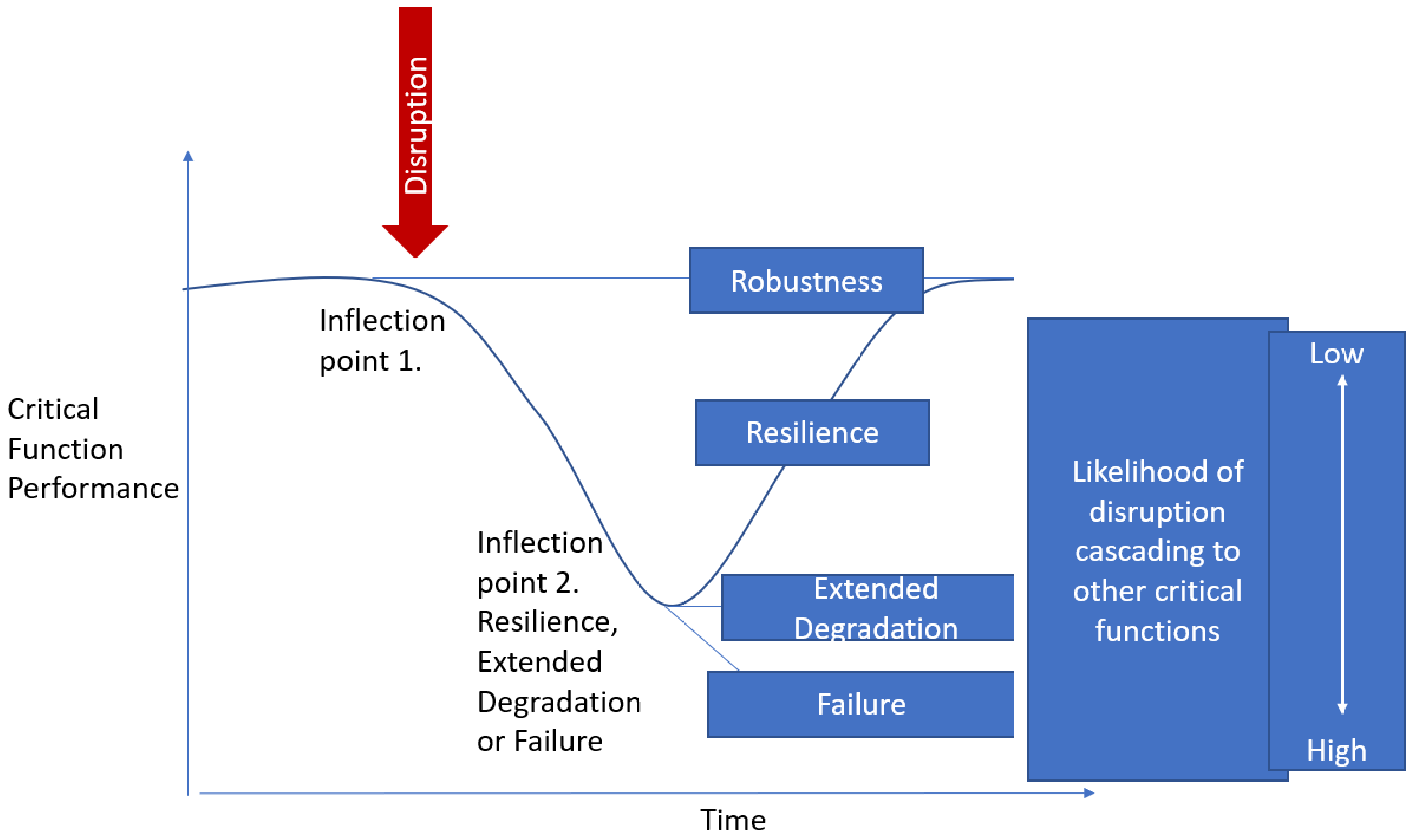


What Makes Complex Systems (Communities) Susceptible to Threat?



After Linkov and Trump, 2019

Crisis Management, Business Continuity and Resilience



After Galaitsi, Linkov et al, 2022

What Did the [real] Doctor Say?

Klasa et al. BMC Geriatrics (2021) 21:51
https://doi.org/10.1186/s12877-020-01965-2

BMC Geriatrics

REVIEW Open Access

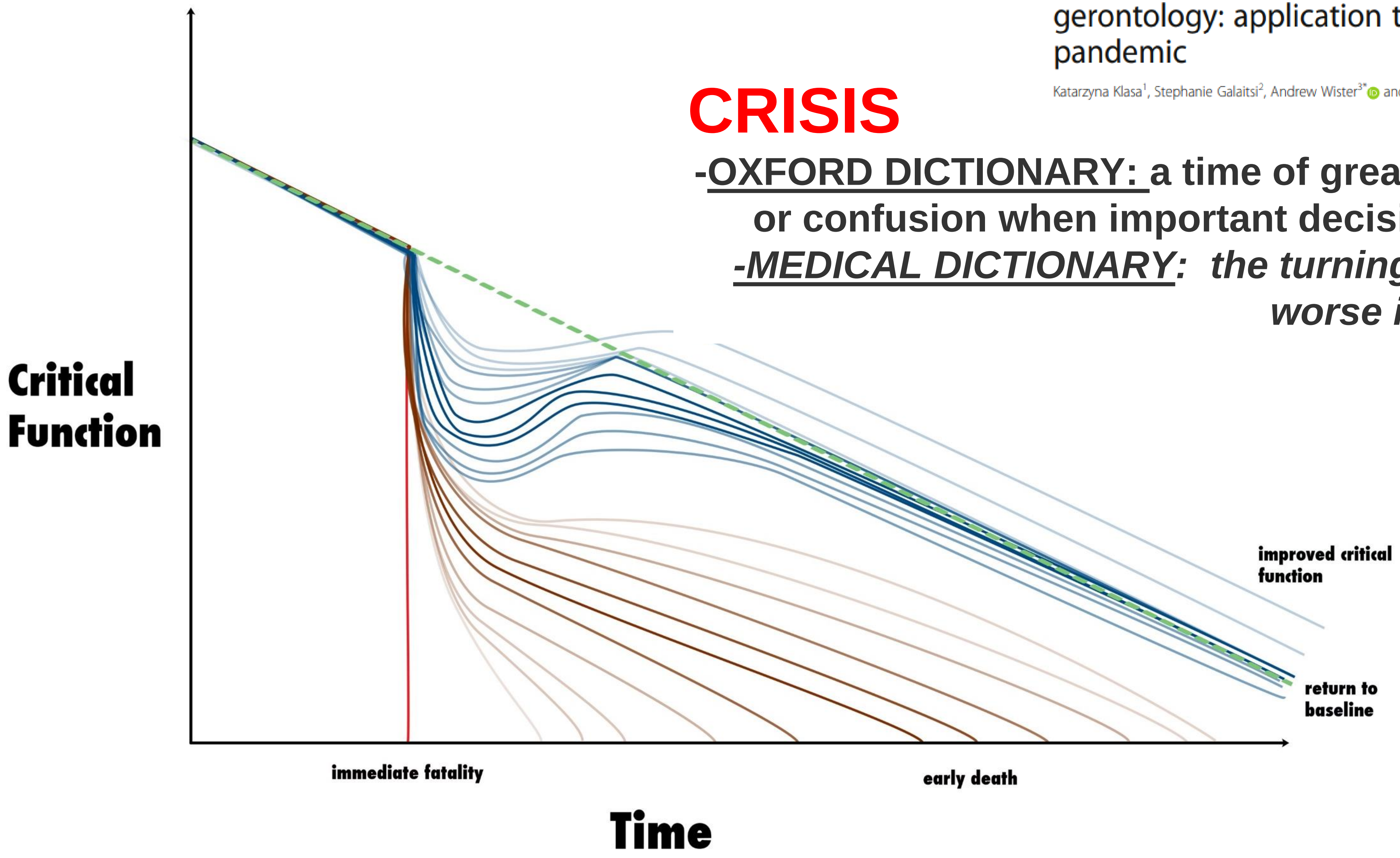
System models for resilience in gerontology: application to the COVID-19 pandemic

Katarzyna Klasa[1], Stephanie Galaitsi[2], Andrew Wister[3*] and Igor Linkov[2]

CRISIS

-OXFORD DICTIONARY: a time of great danger, difficulty, or confusion when important decisions must be made

-MEDICAL DICTIONARY: the turning point for better or worse in an acute disease



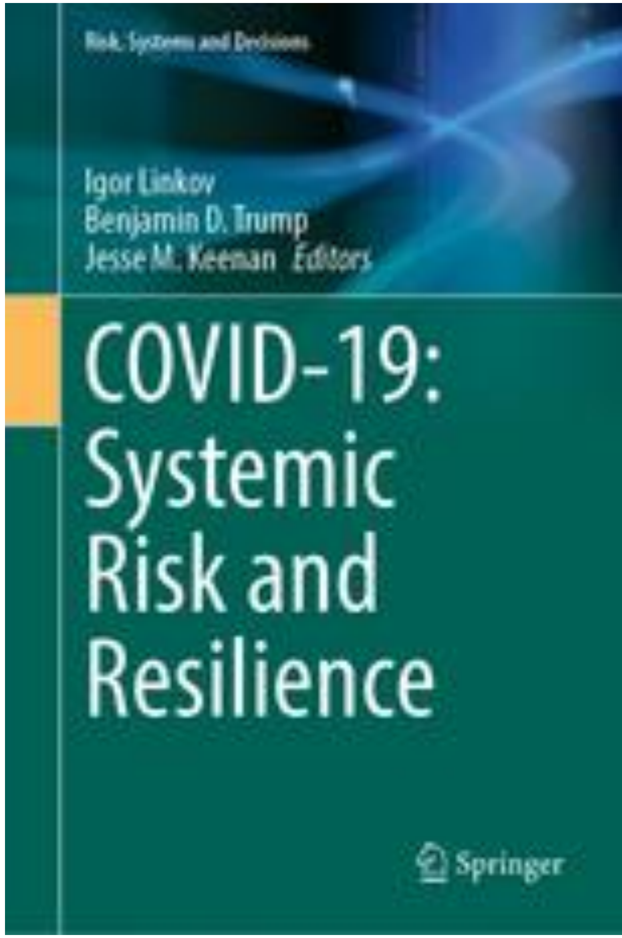
Outline: Science and Practice of Resilience

Uncertainty in Modeling: IAEA Model intercomparisons – significant uncertainty driven by judgment of modelers

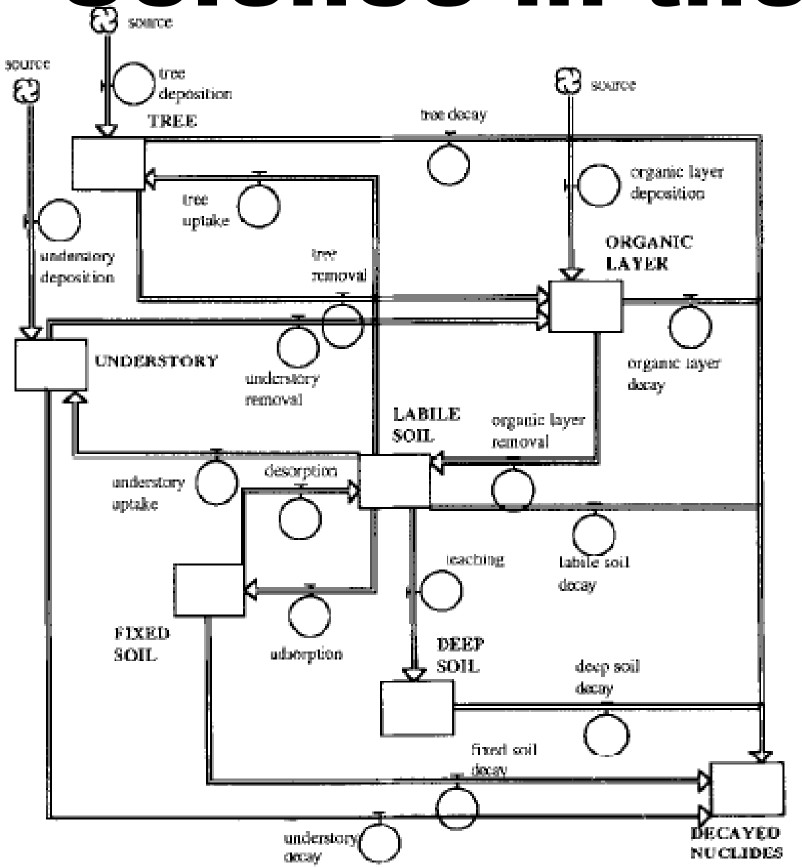
Science and Crisis: Historical perspectives (Venice), Decision Maker Needs in COVID - New England, Supply Chain Crisis in CA

Resilience Theory: Taxonomy, Measurements, Efficiency/Resilience, By Design and by Intervention

Conclusion: Scientists need to be honest to data, relevant to decisions, and timely in crises.



Science in the Time of Crises: Chernobyl



FORESTPATH (1993-1995)

ELSEVIER

Available online at www.sciencedirect.com

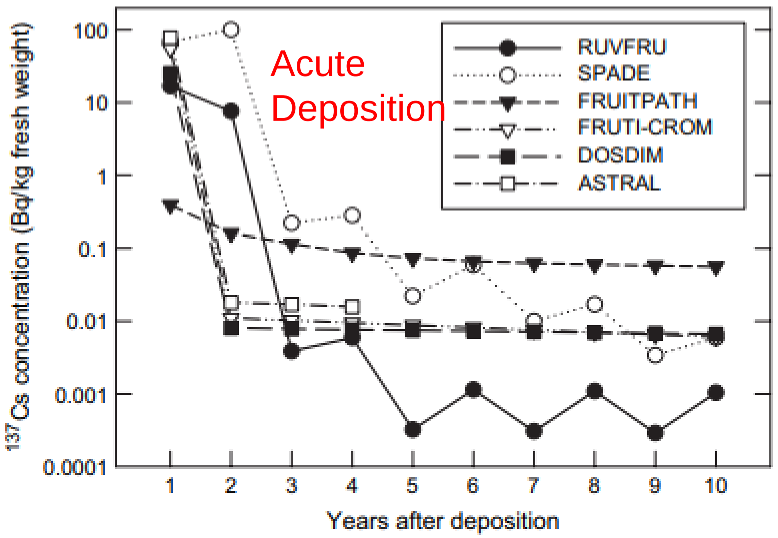
SCIENCE DIRECT

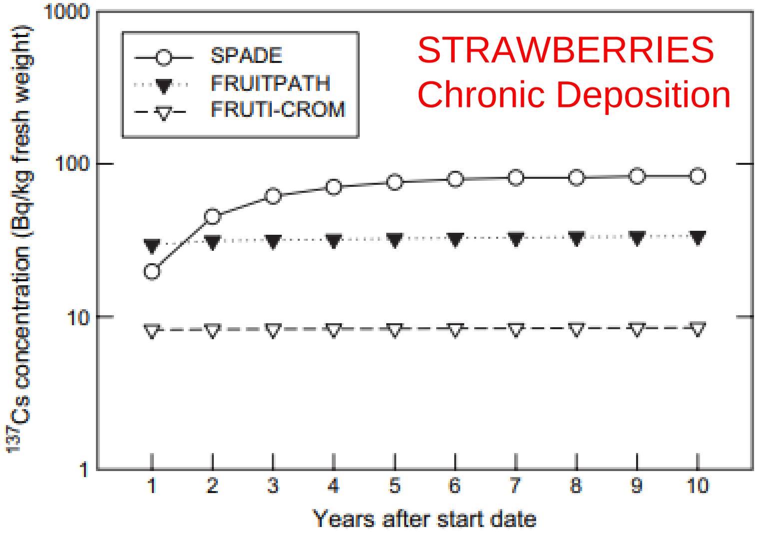
Journal of Environmental Radioactivity 84 (2005) 271–284

JOURNAL OF ENVIRONMENTAL RADIOACTIVITY

FRUITPATH (1995-2002)

280 F. Carini et al. / J. Environ. Radioactivity 84 (2005) 271–284





Forests in Japan (2012)

Environmental Science & Technology

Viewpoint

pubs.acs.org/est

Radioactive Contamination of Natural Ecosystems: Seeing the Wood Despite the Trees

Shoji Hashimoto,[*,†] Igor Linkov,[‡] George Shaw,[§] and Shinji Kaneko[†]

SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
ENVIRONMENTAL SCIENCES
BIOGEOCHEMISTRY
POLLUTION REMEDIATION

Predicted spatio-temporal dynamics of radiocesium deposited onto forests following the Fukushima nuclear accident

Shoji Hashimoto[1], Toshiya Matsuura[2], Kazuki Nanko[1], Igor Linkov[3], George Shaw[4] & Shinji Kaneko[1]

International Atomic Energy Agency Model Intercomparisons

- Multiple types of uncertainty strongly affect modeling results
  - parameter, model, scenario
- Understanding uncertainty is essential to:
  - Conduct analysis consistent with current regulatory guidance
  - Gain trust and confidence

Generally:

- Conclusions can be generalized to a wide range of models and situations.

Risk Analysis, Vol. 23, No. 6, 2003

Model Uncertainty and Choices Made by Modelers: Lessons Learned from the International Atomic Energy Agency Model Intercomparisons†

Igor Linkov[1]* and Dmitriy Burmistrov[2]

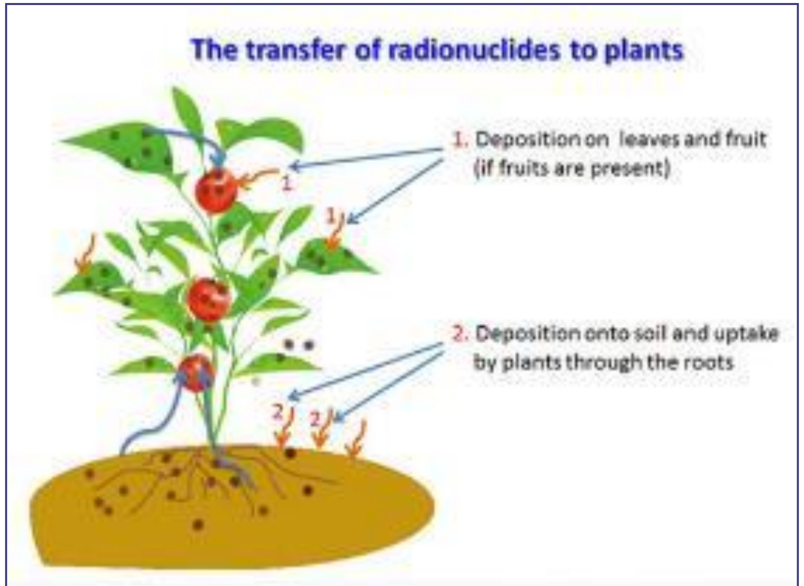
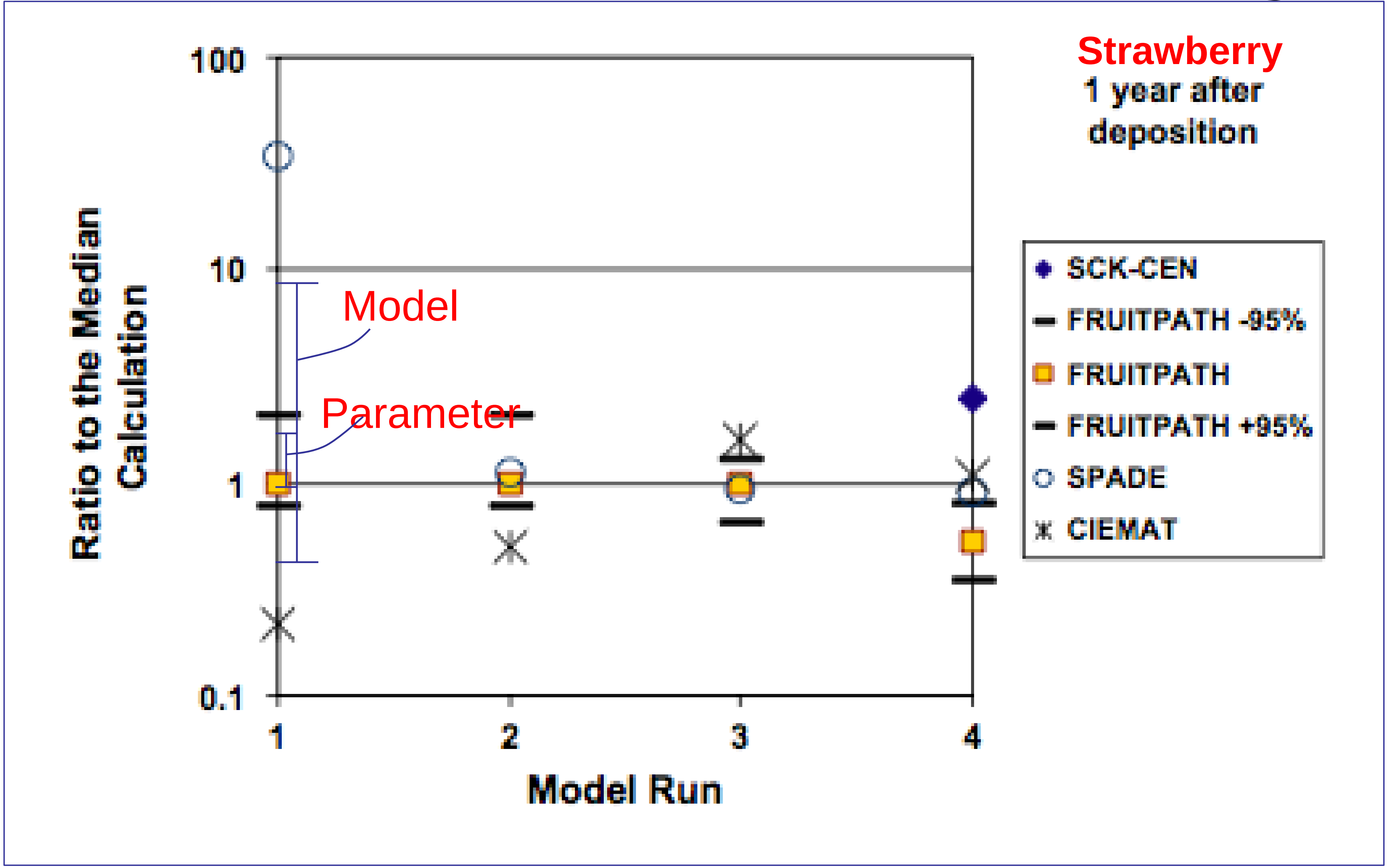
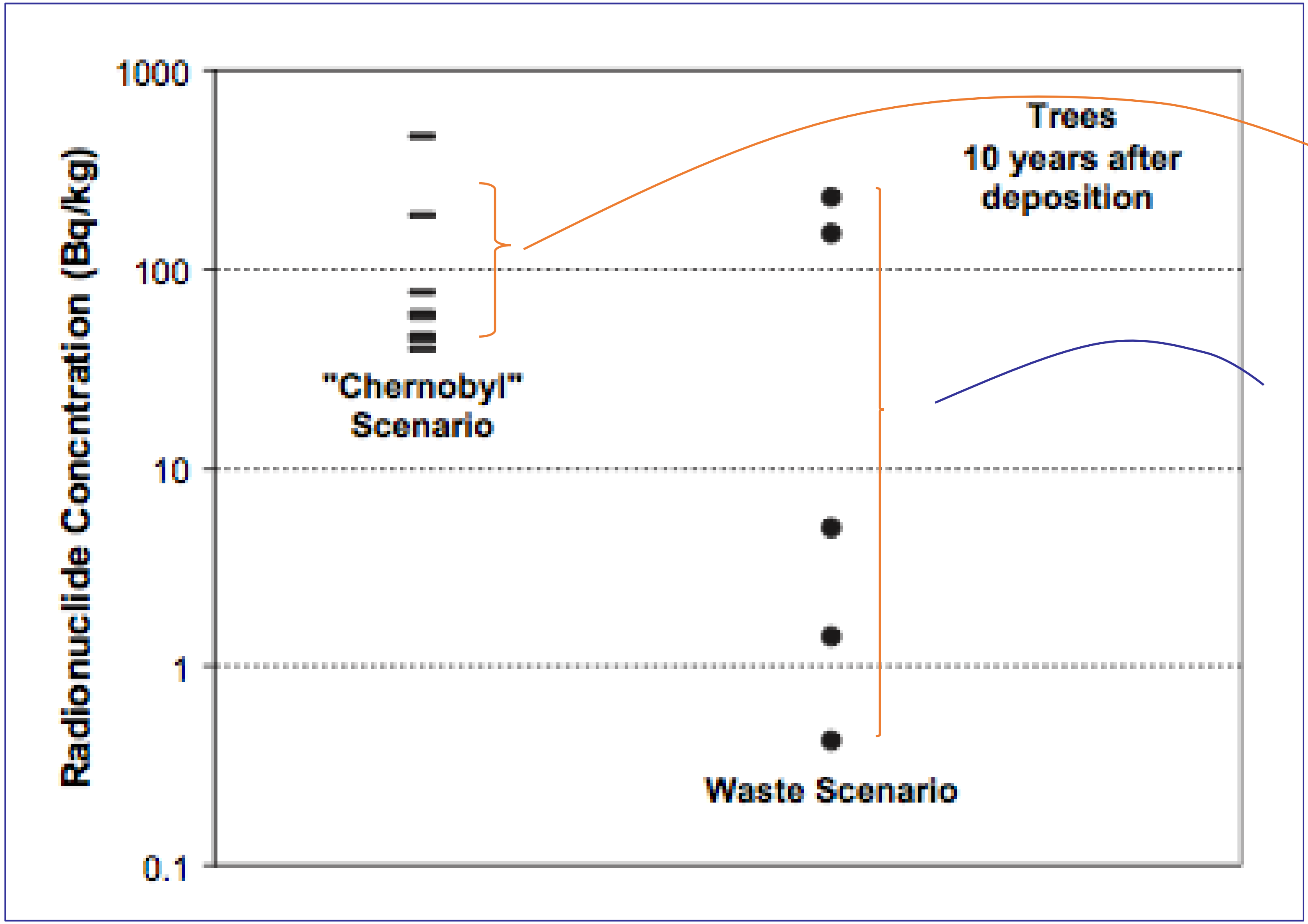


Figure 4: The transfer of radioactive material (radionuclides) to plants

Model vs. Parameter Uncertainty

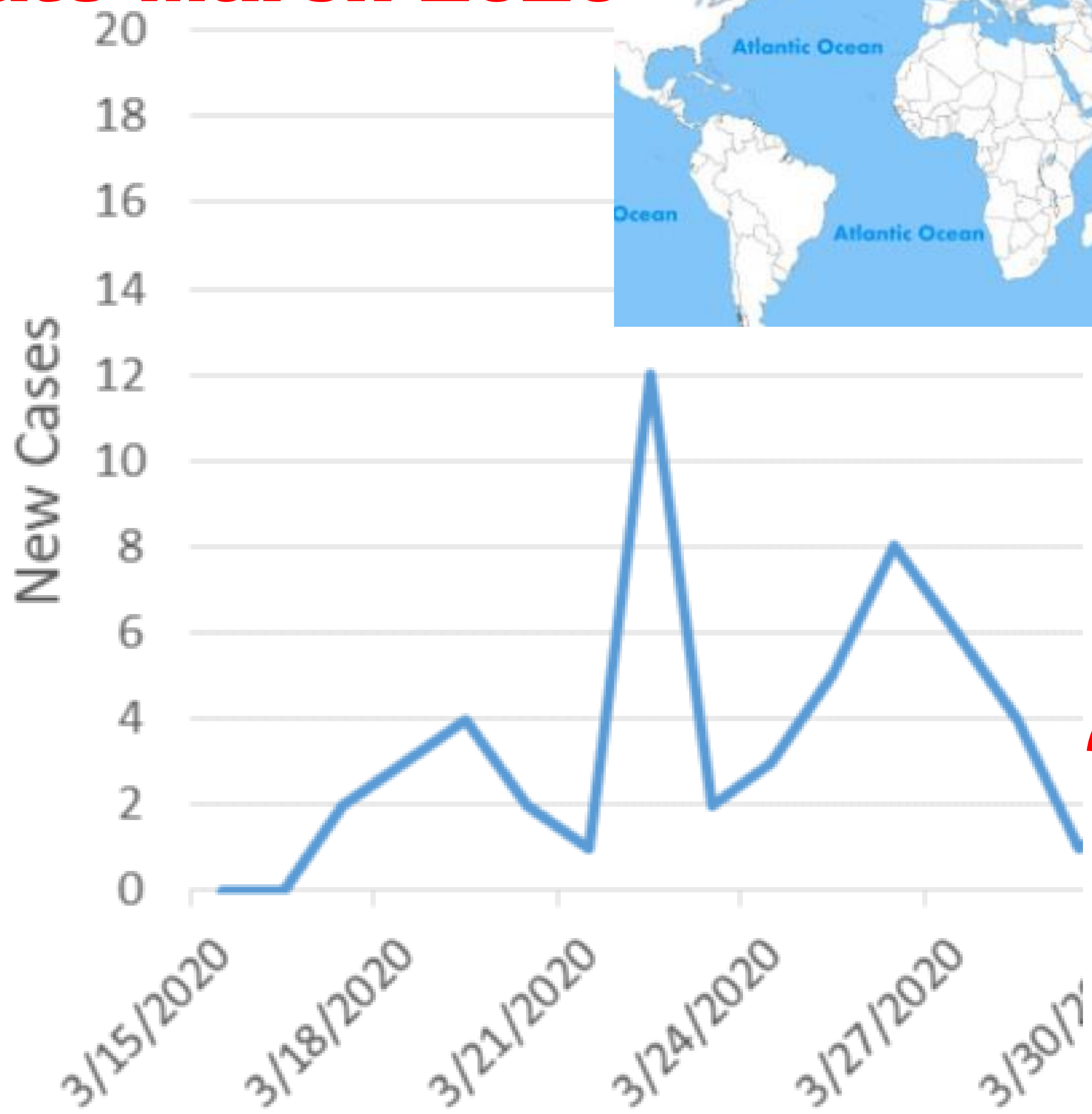


“Modeler” Uncertainty (Subjectivity)



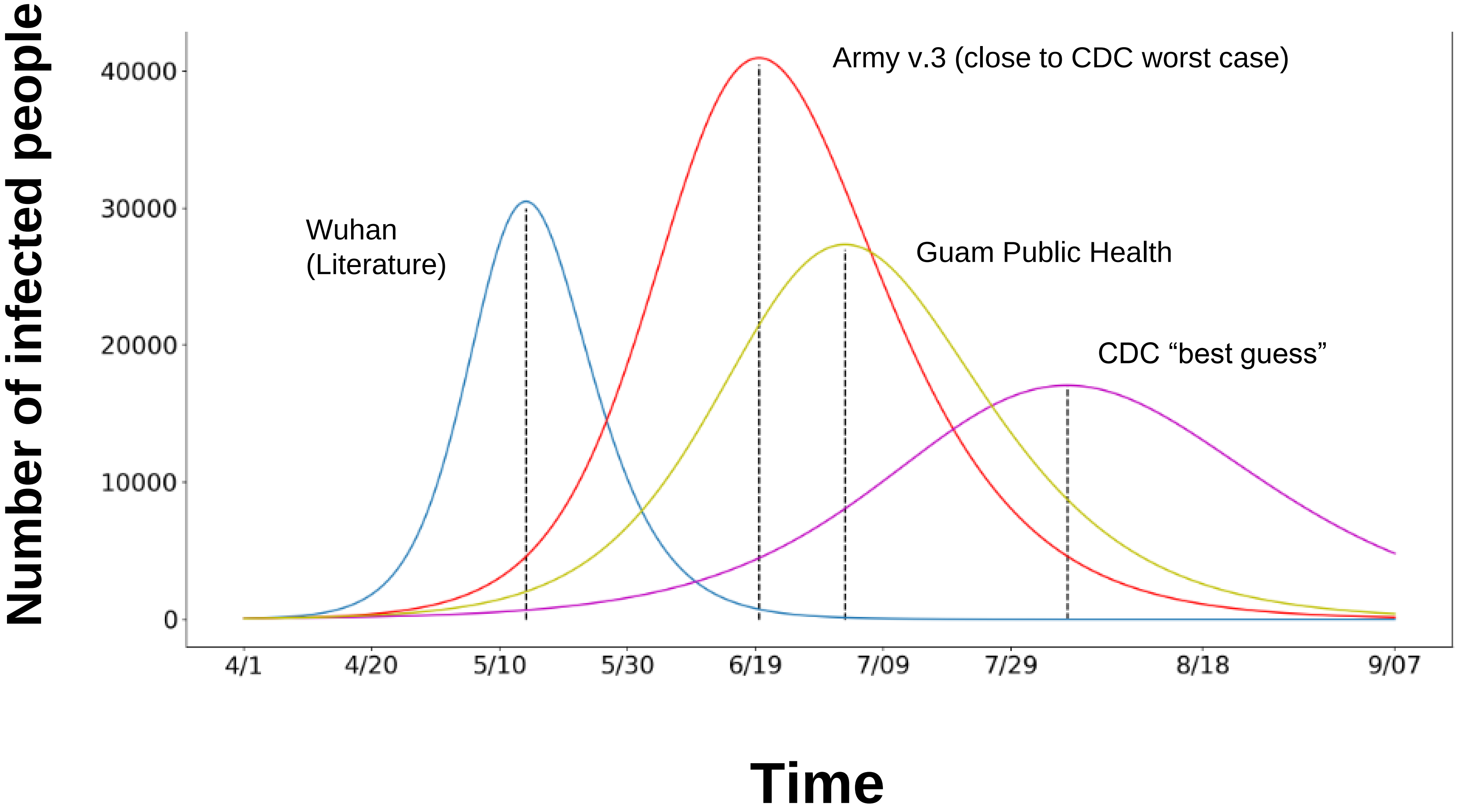
- **Familiar “Chernobyl” Scenario within 1 order of magnitude**
- **Unfamiliar Waste Scenario almost 3 orders of magnitude**

Guam, Late March 2020

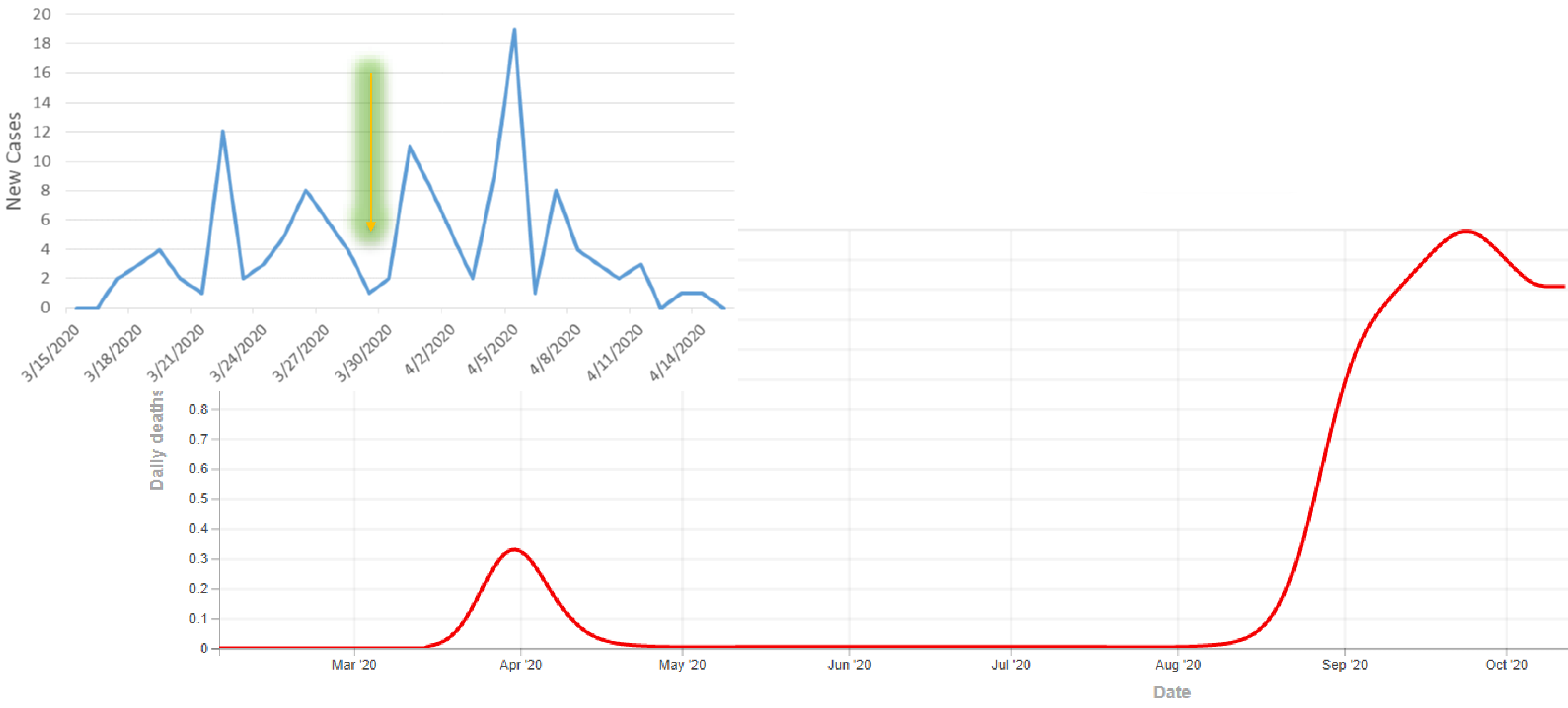


?

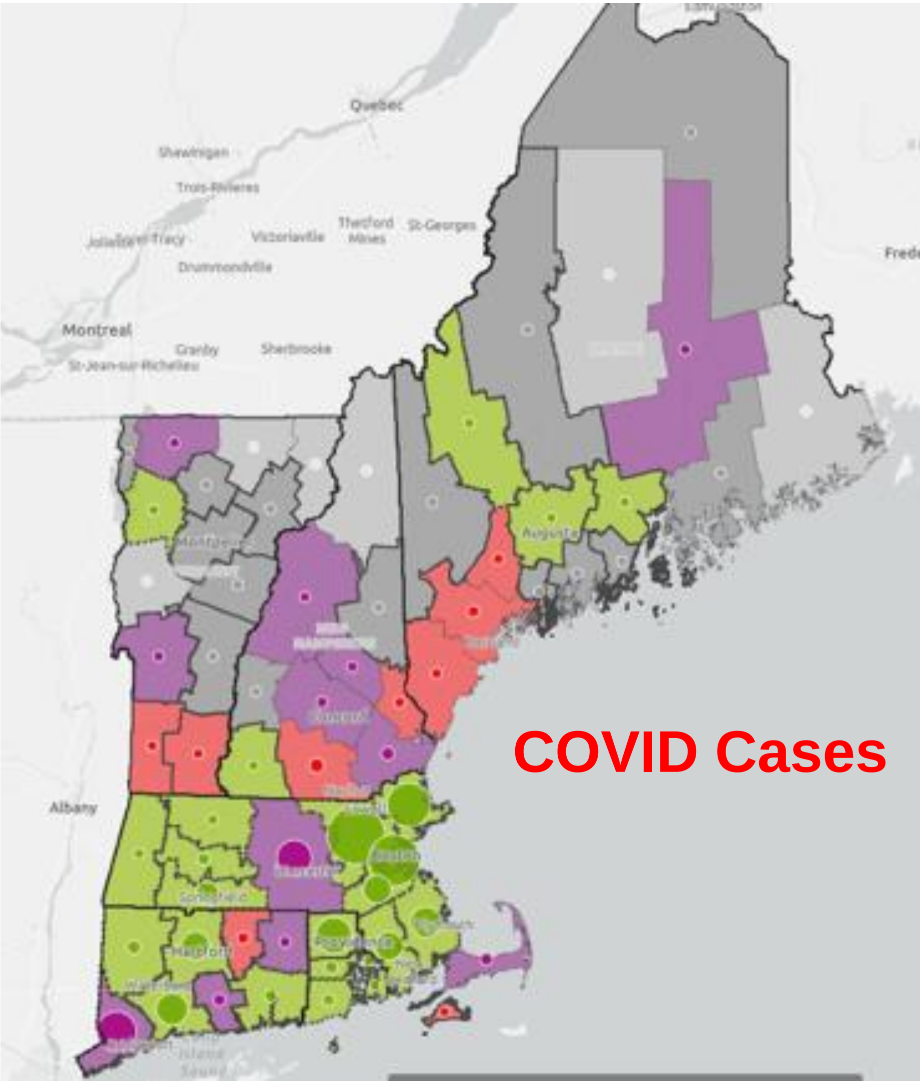
Comparison of different SEIR models



What Actually Happened in Guam?



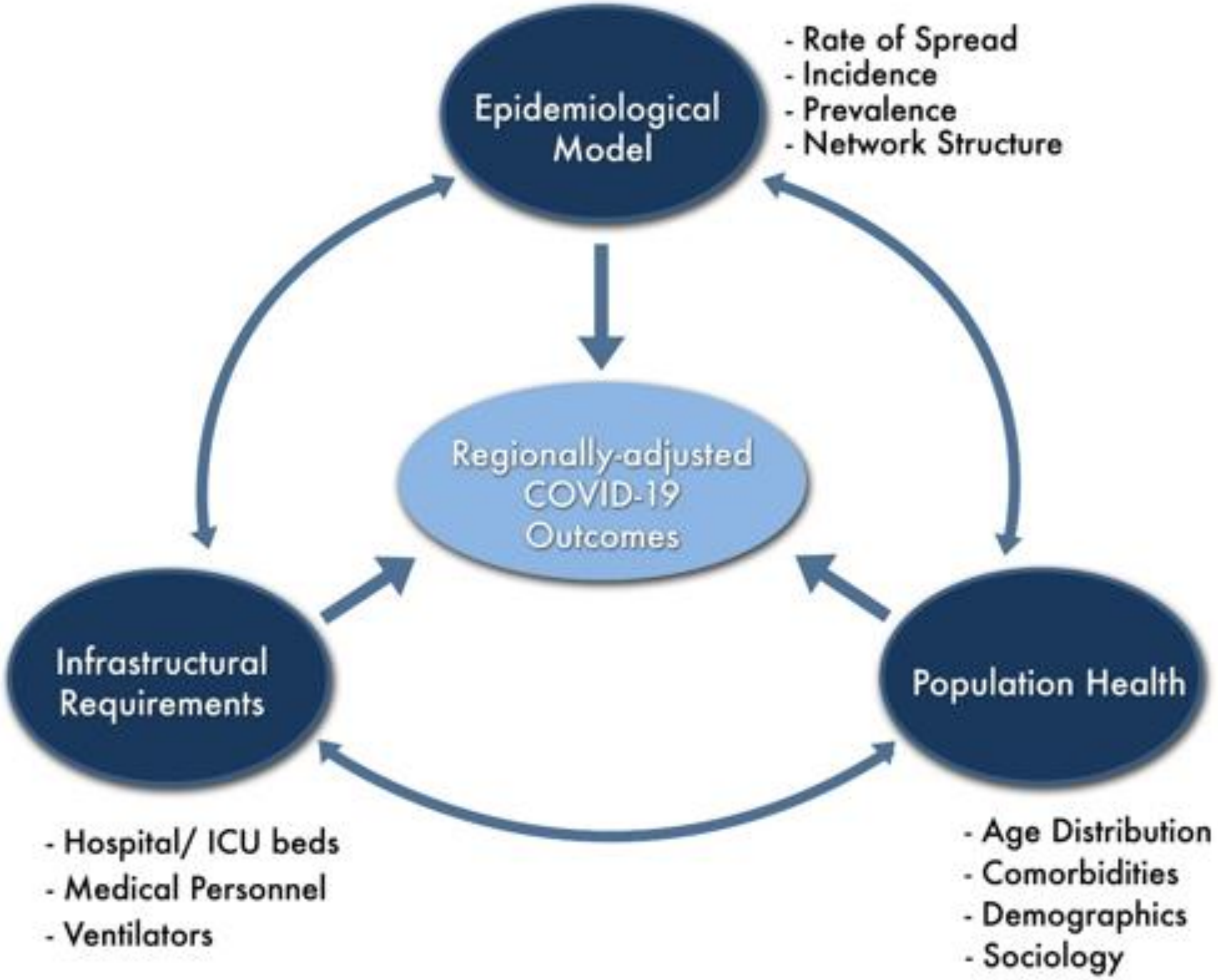
COVID in FEMA/ASPR Reg. 1: Resilience



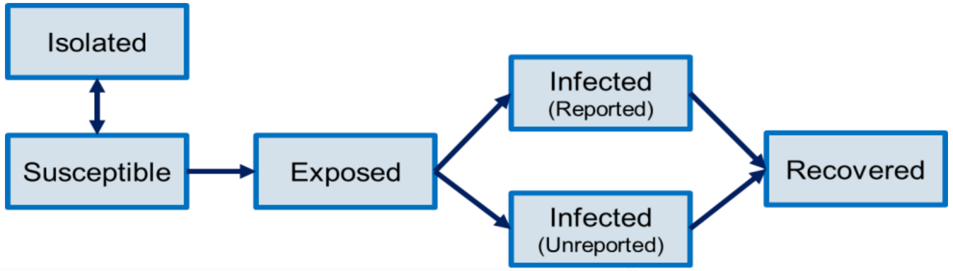
- The Section is co-led by the Federal Emergency Management Agency (FEMA) and the Assistant Secretary for Preparedness and Response (ASPR), and includes personnel from the United States Army Corps of Engineers (UASCE)
- The FEMA/ASPR Region 1 Data Analytics Section was established to support the Regional Response Coordination Center (RRCC) COVID-19 response efforts
- The Section provides modeling and analysis to support and inform decisionmakers on the distribution of resources, fatality management, the Reopening of America efforts, and second wave scenarios

How Can This Be Achieved?

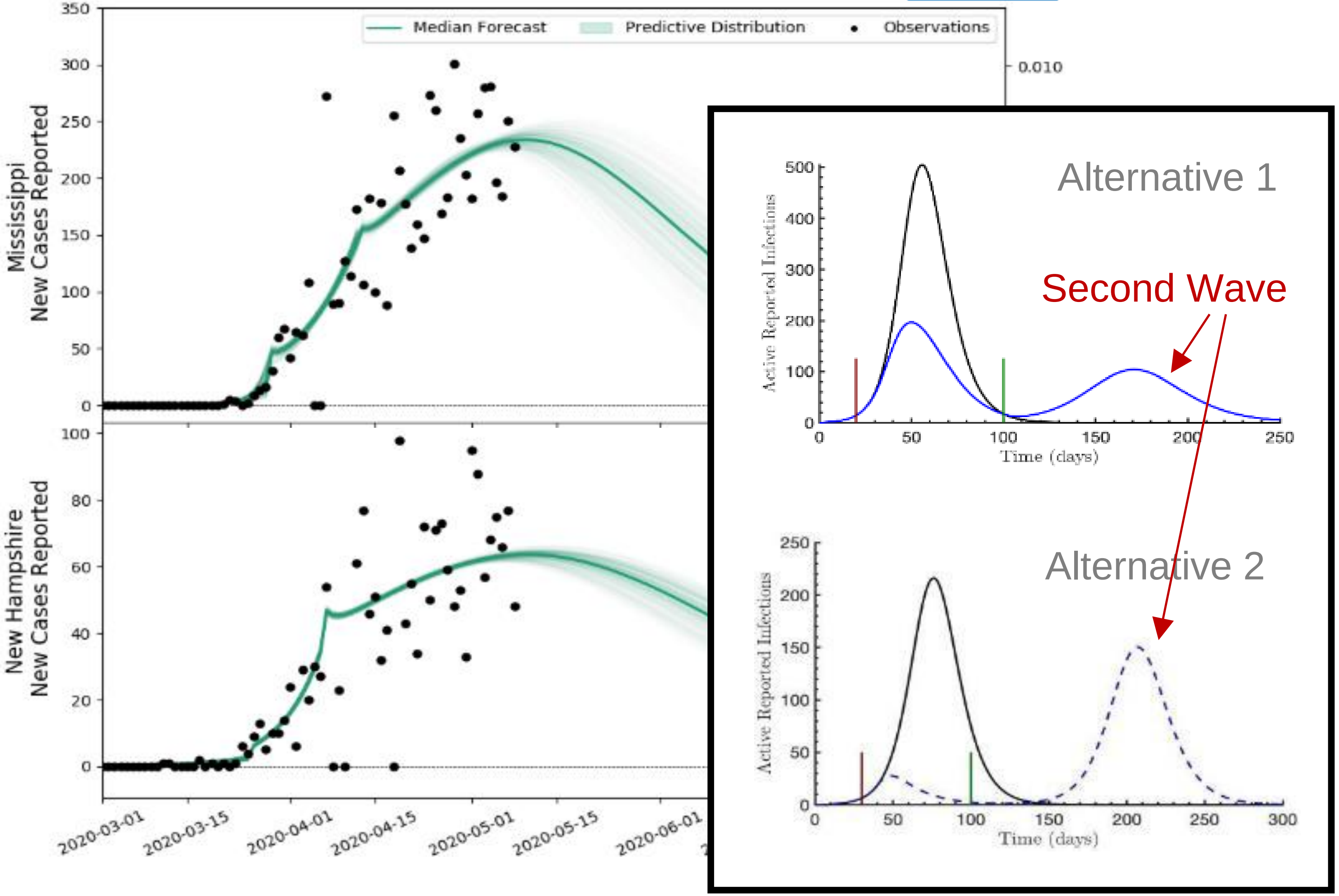
- Modeling Epidemics in New England
- New England Health and Institutional Requirements
- Modeling Recovery and 2nd Wave



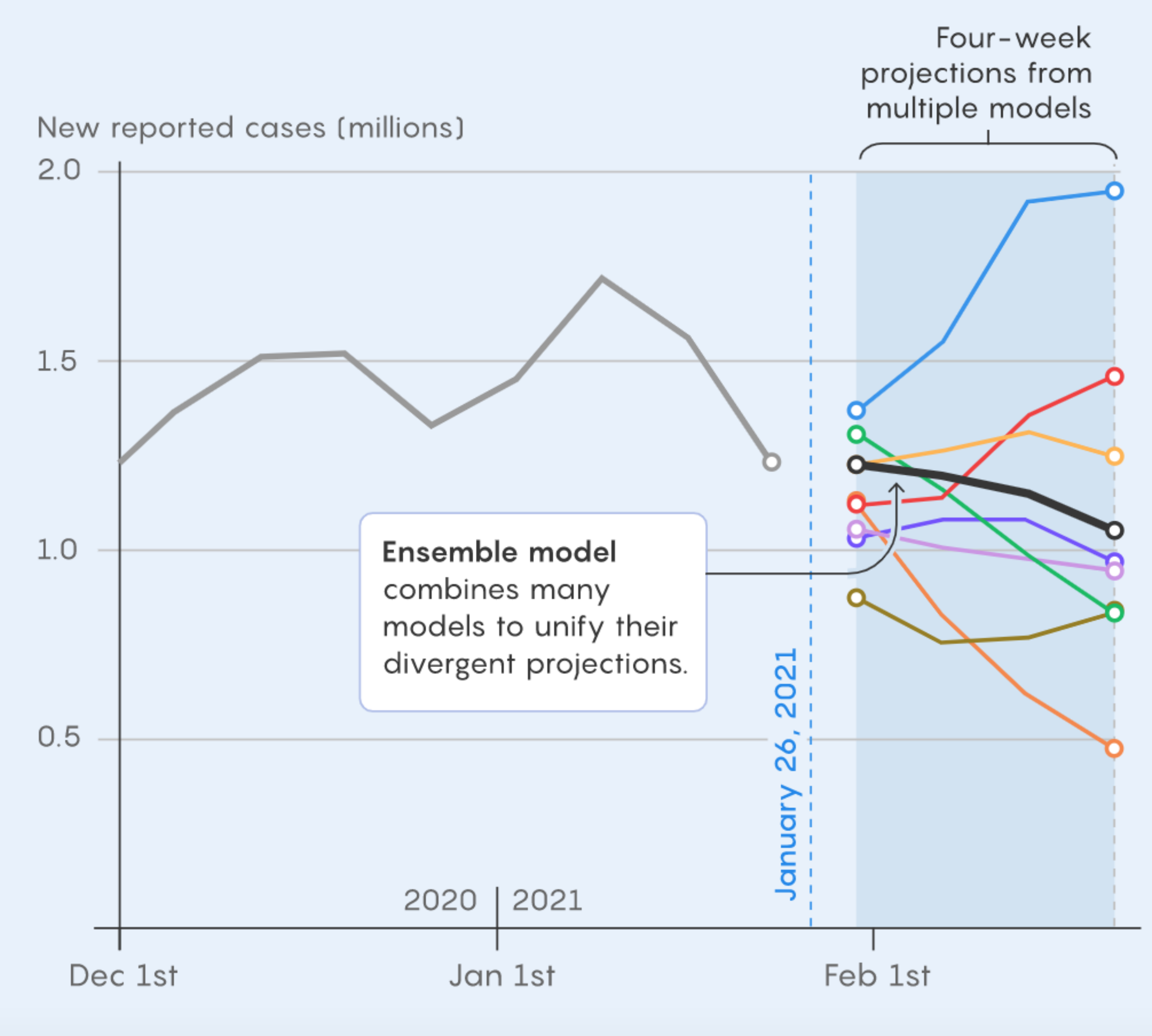
ERDC SEIR Model



- Adapted SEIR approach - Splits Infected population into “reporte and “unreported
- Dynamics statistically combined with observations and SME knowledge
- Parameters updated daily with new data
- Model parameters change with varying social distancing restrictions
- Prediction uncertainty from unconstrained parameters is characterized

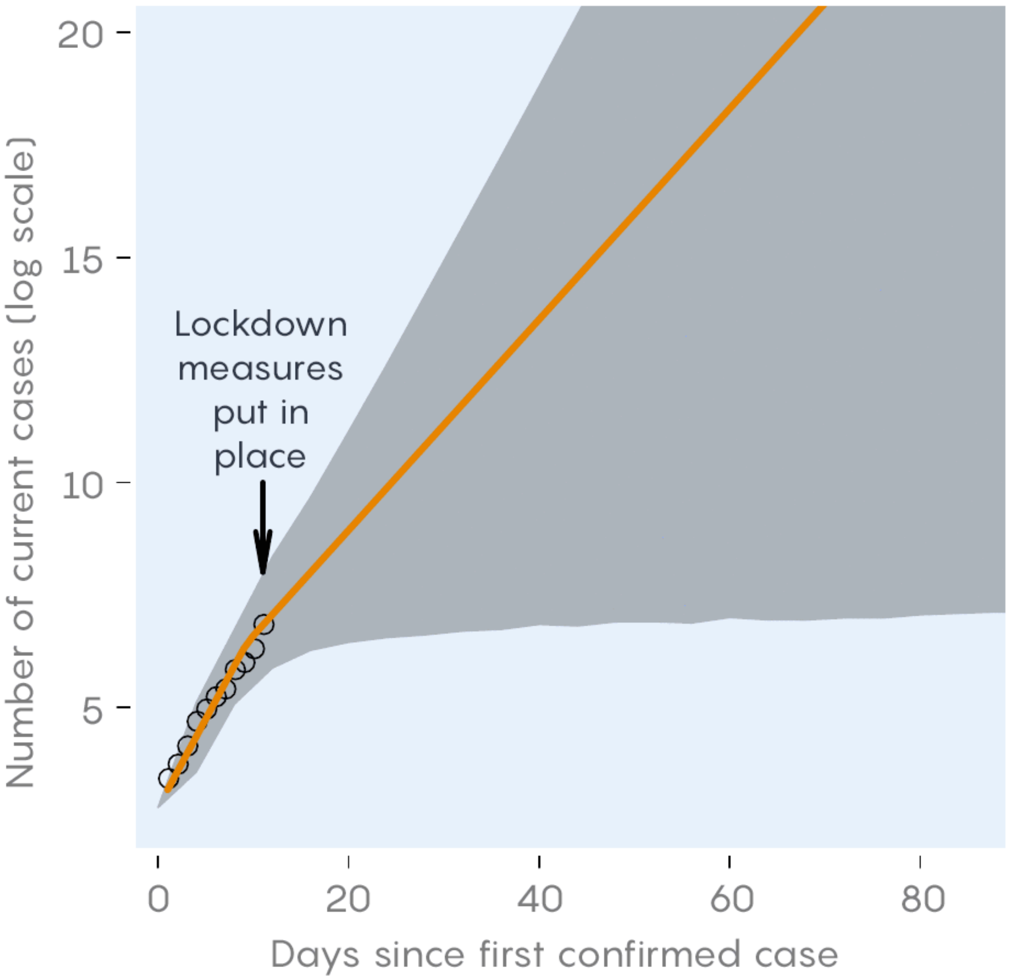


CDC Ensemble Forecast

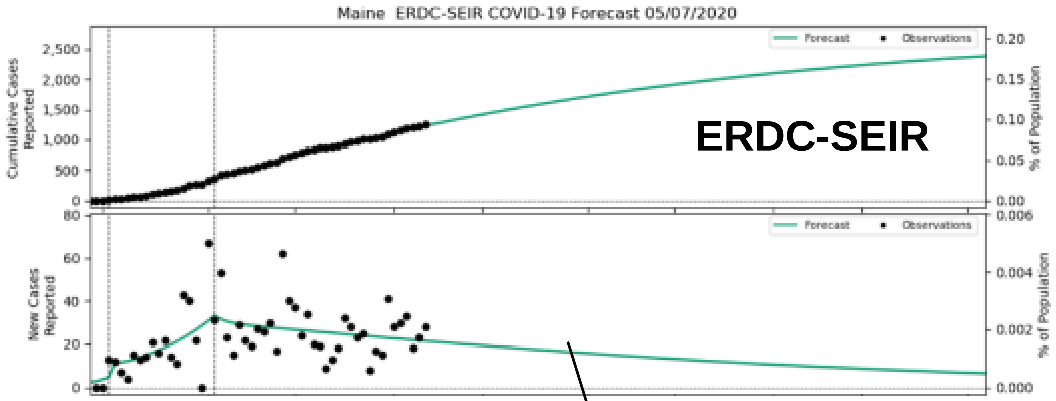


Fluctuating Uncertainties

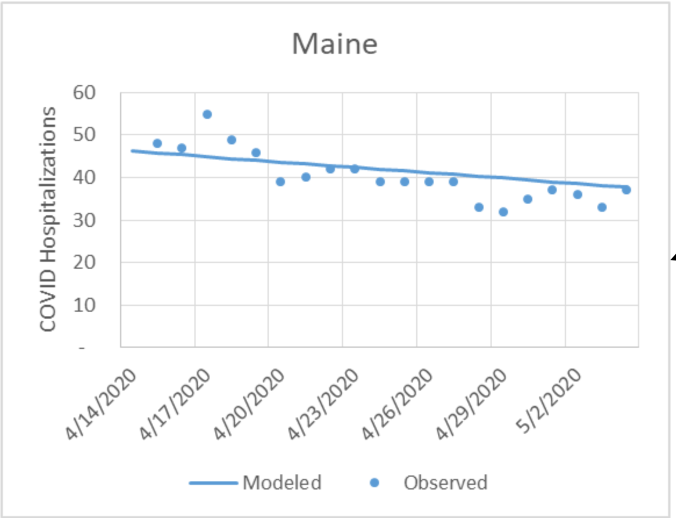
A model can never provide a true prediction of the future. Even as this epidemiological model gets fitted to past data — and as more data points are added to that fit — the uncertainty in its projections can fluctuate wildly.



FEMA R1-Tool:
Translating Model into Institutional Requirements



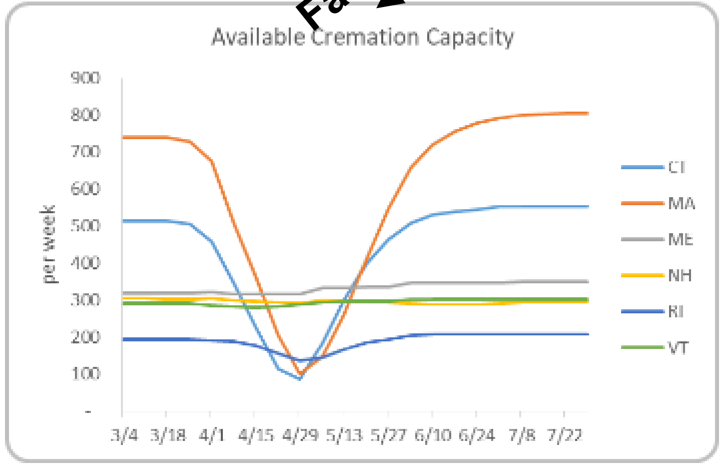
Hospitalizations



Beds

	Beds Needed for COVID Patients					
week	CT	MA	ME	NH	RI	VT
3/18/2020	72	155	17	12	10	10
3/25/2020	408	859	31	40	43	36
4/1/2020	804	1,658	49	73	96	59
4/8/2020	1,255	2,510	51	84	233	61
4/15/2020	1,562	3,296	47	98	446	50
4/22/2020	1,586	3,615	44	113	563	26
4/29/2020	1,453	3,606	41	129	558	10
5/6/2020	1,061	3,191	38	145	408	4
5/13/2020	657	2,403	35	161	213	2
5/20/2020	369	1,607	33	176	95	1
5/27/2020	196	994	30	189	40	0
6/3/2020	101	587	28	199	17	0
6/10/2020	51	337	25	206	7	0
6/17/2020	26	190	23	209	3	0

Fatality Management



PPE

	CONVENTIONAL BURN RATES					
	N95s or other respirators					
week	CT	MA	ME	NH	RI	VT
5/6/2020	146,576	471,367	6,025	22,265	53,767	469

	CONTINGENCY BURN RATES					
	N95s or other respirators					
week	CT	MA	ME	NH	RI	VT
5/6/2020	67,569	219,276	2,823	10,515	24,627	211

	CRISIS BURN RATES					
	N95s or other respirators					
week	CT	MA	ME	NH	RI	VT
5/6/2020	12,400	39,703	506	1,862	4,562	40

Compounding Threats: COVID + Hurricanes

npj | urban sustainability www.nature.com

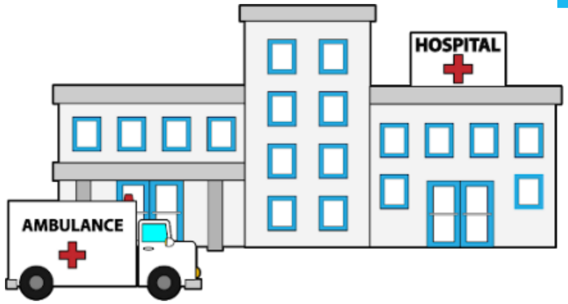
COMMENT OPEN

The importance of compounding threats to hurricane evacuation modeling

Jeffrey C. Cegan[1], Maureen S. Golan[1], Matthew D. Joyner[1] ✉ and Igor Linkov[1]

Flood Inundation Modeling

Modeling of Pandemic Consequences



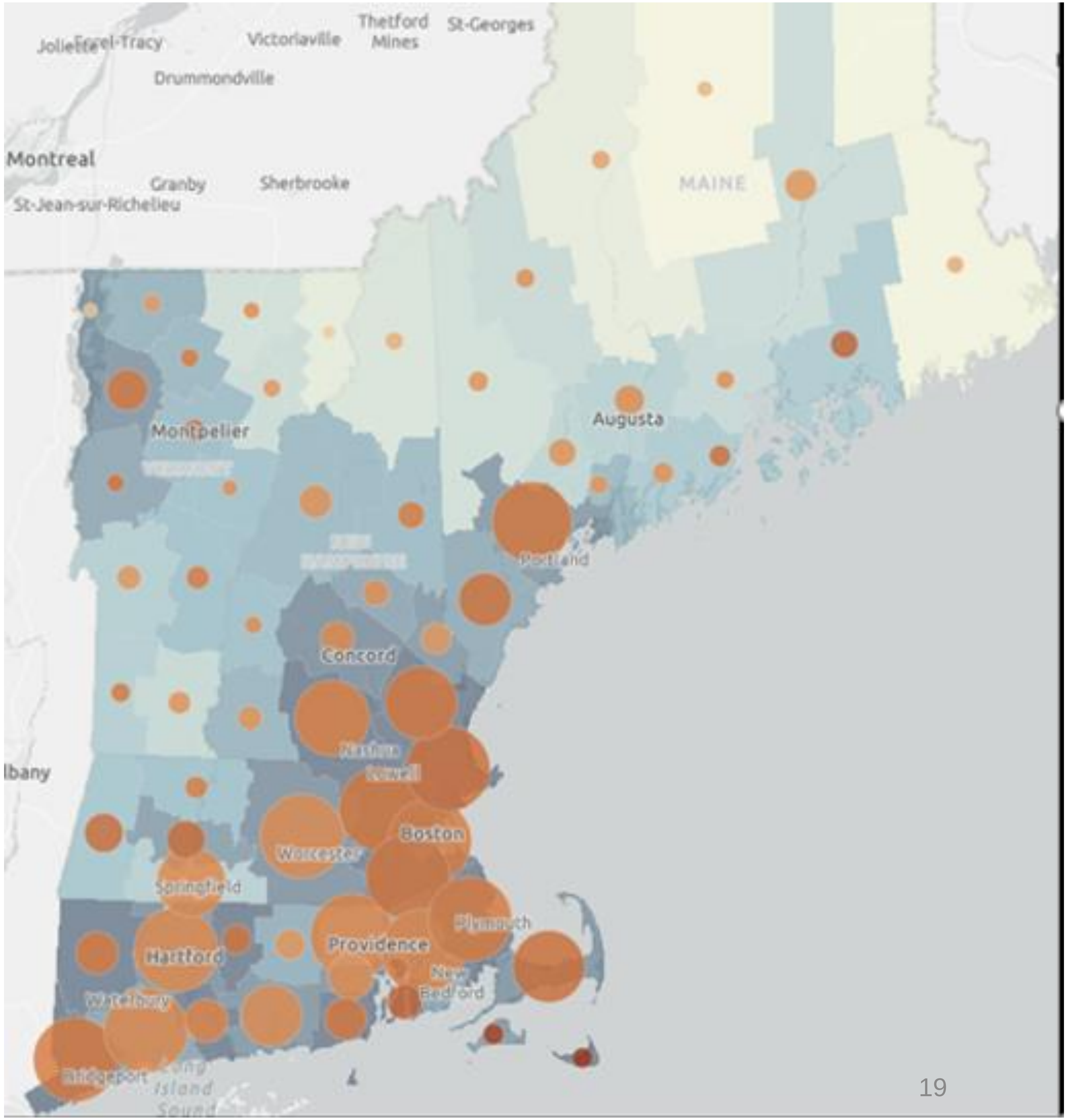
Outcomes:

- Additional PPE needs for shelter workers and emergency management personnel
- Needs for additional shelters to maintain social distancing
- Resource needs to maintain functionality of critical healthcare facilities
- Potential impacts on vulnerable communities (e.g. elderly)

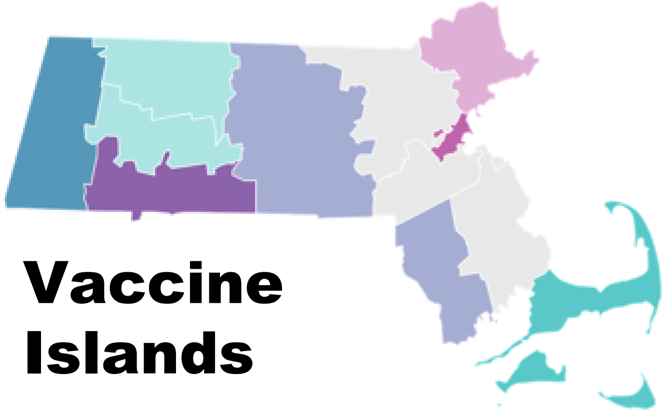
Is Financial Support Efficient?

Loan Penetration for Food Services

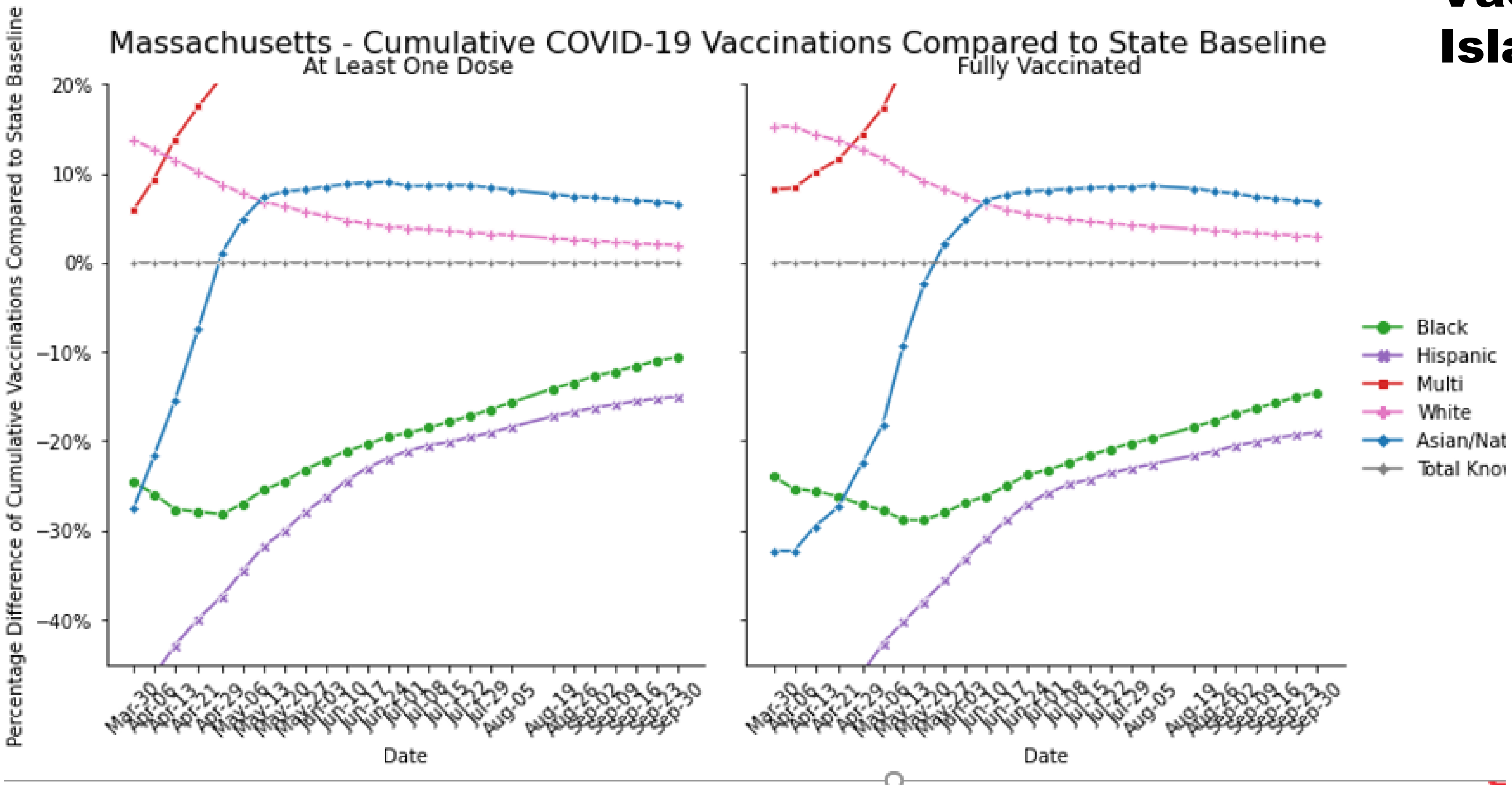
- The Small Business Administration (SBA) backs loans to small businesses affected by the pandemic through the Paycheck Protection Program (PPP).
- Low penetration rates in remote areas



Equity Issues



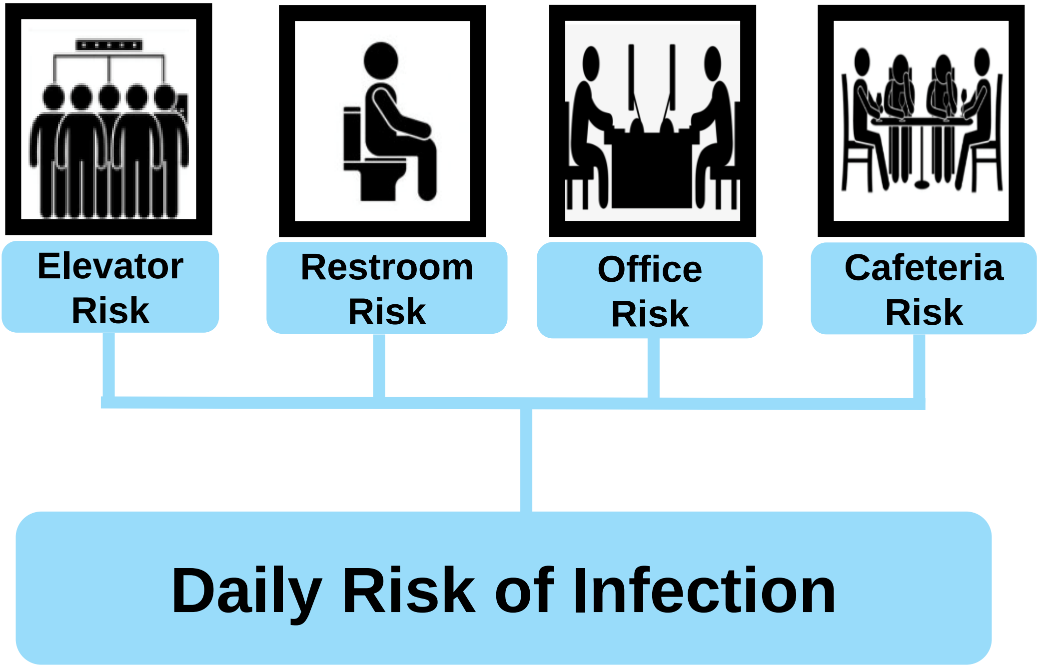
Vaccine Islands



Micro Exposure Model (MEM)

Nature Exposure Science (in press)

- We interpret risk as the probability of an uninfected employee becoming infected after an encounter.
- Any risk can be described in a probability framework using spatial and temporal parameters



- Use Monte Carlo simulations to account for specific workplace environments and individual employee behavior
- Input parameters are nation wide infection percentage and mask efficacy statistics

MEM Integrates elements of both SEIR and ABM to capture behavioral uncertainty in viral exposure and infection, considering environmental conditions at workplaces

www.nature.com/jes
Journal of Exposure Science & Environmental Epidemiology

ARTICLE
Check for updates

Assessment of the COVID-19 infection risk at a workplace through stochastic microexposure modeling

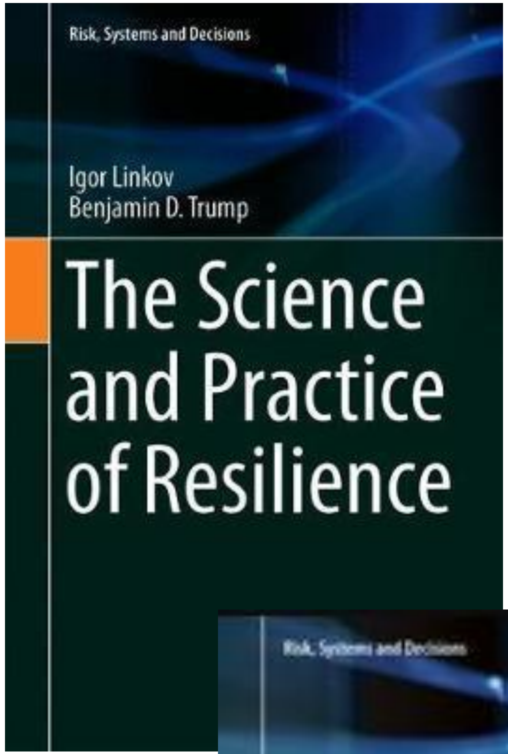
Sergey Vecherin[1], Derek Chang[1], Emily Wells[1,2], Benjamin Trump[1], Aaron Meyer[1], Jacob Desmond[1], Kyle Dunn[1], Maxim Kitsak[3] and Igor Linkov[1,2]

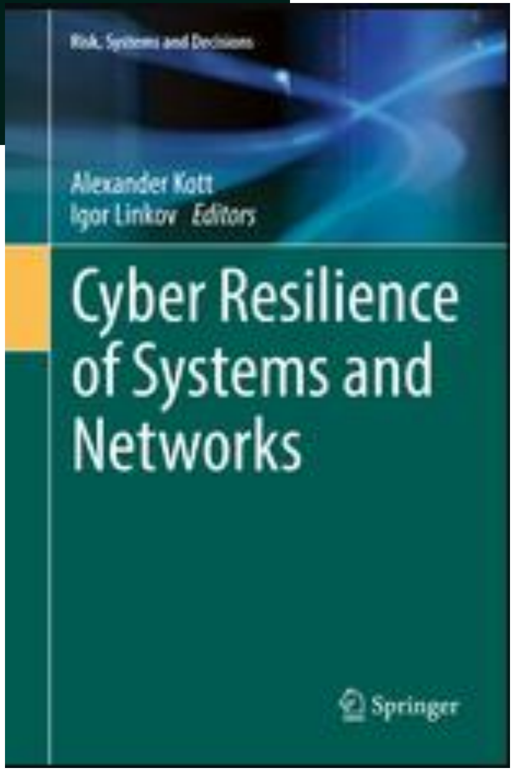
1

Don't conflate risk and resilience

'Risk' and 'resilience' are fundamentally different concepts that are often conflated. Yet maintaining the distinction is a policy necessity. Applying a risk-based approach to a problem that requires a resilience-based solution, or vice versa, can lead to investment in systems that do not produce the changes that stakeholders need.

30 | NATURE | VOL 555 | 1 MARCH 2018





COMPUTER PUBLISHED BY THE IEEE COMPUTER SOCIETY

2

To Improve Cyber Resilience, Measure It

Alexander Kott, U.S. Army DEVCOM Army Research Laboratory
Igor Linkov, U.S. Army Engineer Research and Development Center

NATURE ENERGY Check for updates comment

Building resilience will require compromise on efficiency

3

nature
CORRESPONDENCE · 08 DECEMBER 2020

Combine resilience and efficiency in post-COVID societies

Benjamin D. Trump, Igor Linkov & William Hynes

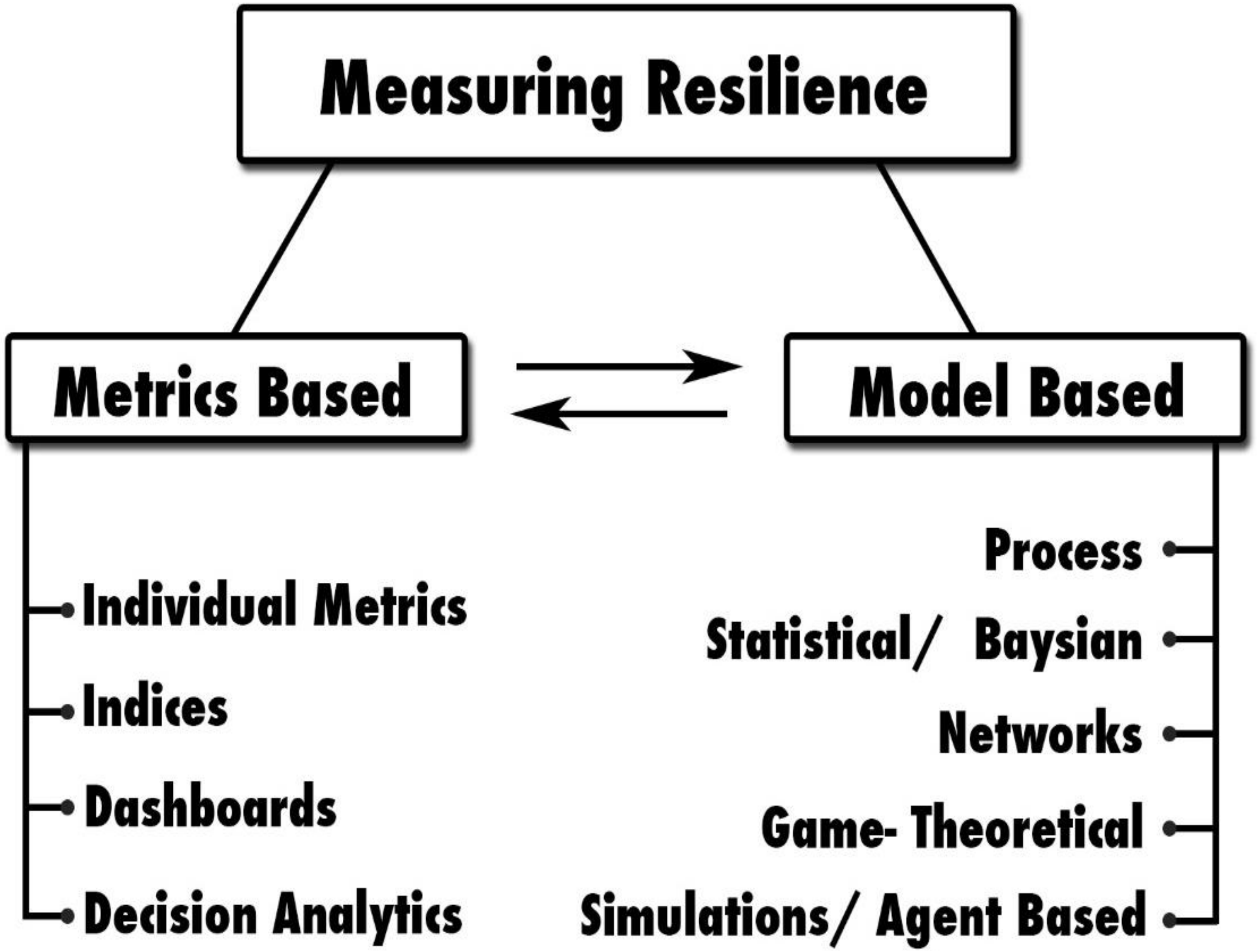
112 COMPUTER PUBLISHED BY THE IEEE COMPUTER SOCIETY

4

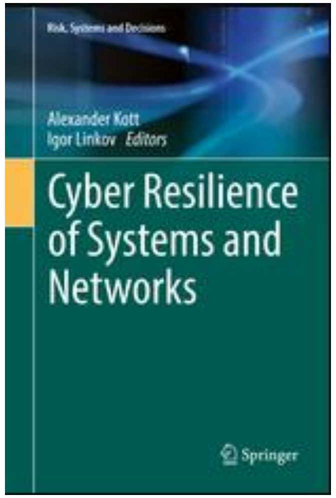
Cyber Resilience: by Design or by Intervention?

Alexander Kott, U.S. Army DEVCOM Army Research Laboratory
Maureen S. Golan, U.S. Engineer Research and Development Center and Credere Associates
Benjamin D. Trump, U.S. Engineer Research and Development Center and University of Michigan
Igor Linkov, U.S. Engineer Research and Development Center and Carnegie Mellon University

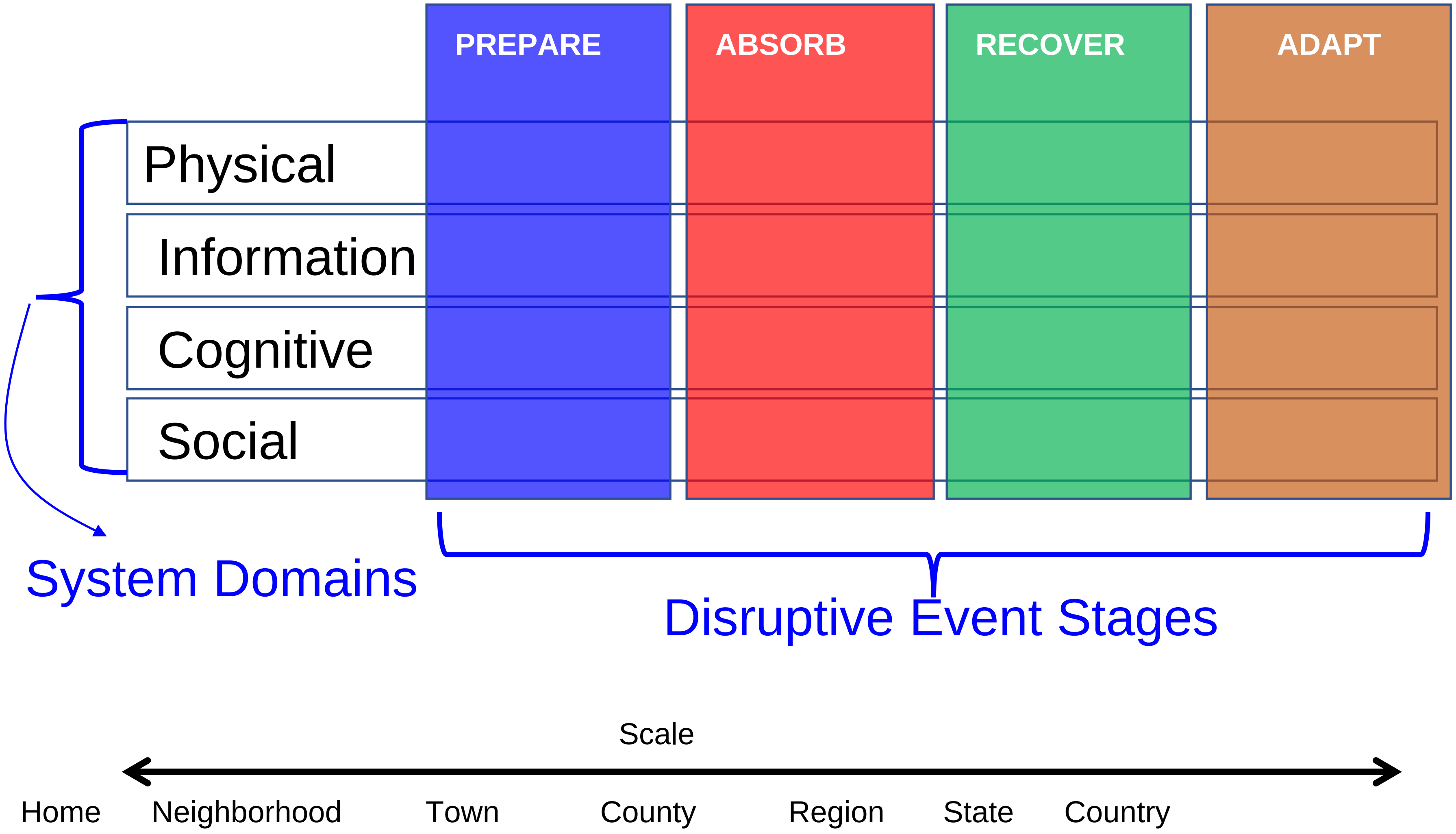
How to Quantify Resilience?



After
2019



Resilience Matrix



Assessment using Stakeholder Values

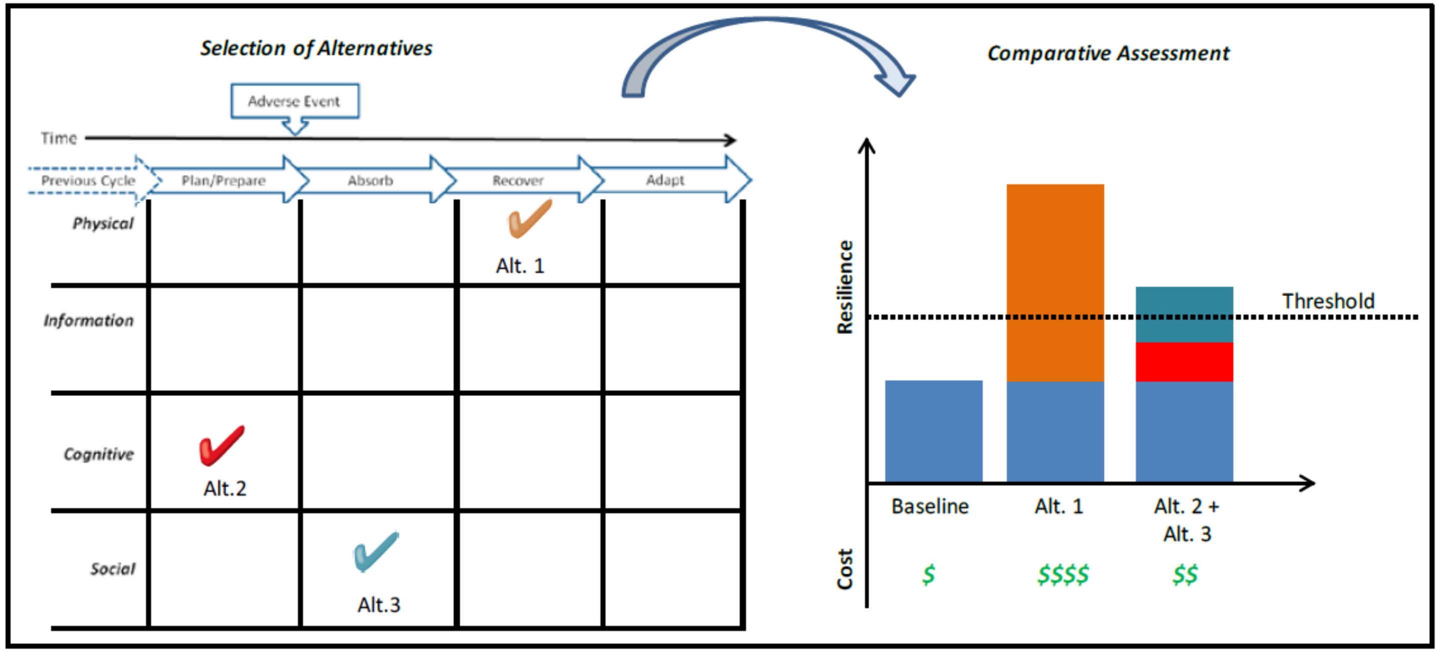


Figure 5: Comparative Assessment of Resilience-Enhancing Alternatives

Use developed resilience metrics to comparatively assess the costs and benefits of different courses of action

After Fox-Lent et al., 2015

Resilience Matrix: Cyber

Table 1 The cyber resilience matrix

Plan and prepare for	Absorb	Recover from	Adapt to
Physical			
(1) Implement controls/sensors for critical assets [S22, M18, 20]	(1) Signal the compromise of assets or services [M18, 20]	(1) Investigate and repair malfunctioning controls or sensors [M17]	(1) Review asset and service configuration in response to recent event [M17]
(2) Implement controls/sensors for critical services [M18, 20]	(2) Use redundant assets to continue service [M18, 20]	(2) Assess service/asset damage	(2) Phase out obsolete assets and introduce new assets [M17]
(3) Assessment of network structure and interconnection to system components and to the environment	(3) Dedicate cyber resources to defend against attack [M16]	(3) Assess distance to functional recovery	
(4) Redundancy of critical physical infrastructure		(4) Safely dispose of irreparable assets	
(5) Redundancy of data physically or logically separated from the network [M24]			
Information			
(1) Categorize assets and services based on sensitivity or resilience requirements [S63]	(1) Observe sensors for critical services and assets [M22]	(1) Log events and sensors during event [M17, 22]	(1) Document incident's impact and cause [M17]
(2) Documentation of certifications, qualifications and pedigree of critical hardware and/or software providers	(2) Effectively and efficiently transmit relevant data to responsible stakeholders/ decision makers	(2) Review and compare systems before and after the event [M17]	(2) Document time between problem and discovery/discovery and recovery [S41]
(3) Prepare plans for storage and containment of classified or sensitive information			(3) Anticipate future system states post-recovery
(4) Identify external system dependencies (i.e., Internet providers, electricity, water) [S31]			
(5) Identify internal system dependencies [S63]			
Cognitive			
(1) Anticipate and plan for system states and events [M18]	(1) Use a decision making protocol or aid to determine when event can be considered "contained"	(1) Review physical a in order to decisions	

Environ Syst Decis (2013) 33:471–476
DOI 10.1007/s10669-013-9485-y

PERSPECTIVES

Resilience metrics for cyber systems

Igor Linkov · Daniel A. Eisenberg ·
Kenton Plourde · Thomas P. Seager ·
Julia Allen · Alex Kott

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Short Communication

Metrics for energy resilience

Paul E. Roege[a], Zachary A. Collier[b], James Mancillas[c], John A. McDonagh[c], Igor Linkov[b,*]

Resilience Matrix: Energy

	Plan and Prepare for	Refs	Absorb	Refs	Recover from	Refs	Adapt to	Refs
Physical	Reduced reliance on energy/increased efficiency	A,B, E,F, H	Design margin to accommodate range of conditions	B,C, I,J,K	System flexibility for reconfiguration and/or temporary system installation	C,D, F,H, K	Flexible network architecture to facilitate modernization and new energy sources	C,D, F,K
	Energy source diversity/ local sources	A,E, F,H, K	Limited performance degradation under changing conditions	B,C, F,I,K	Capability to monitor and control portions of system	B,I, K	Sensors, data collection and visualization capabilities to support system performance trending	D,E, I,K
	Energy storage capabilities/ presaged equipment	B,H, K	Operational system protection (e.g., pressure relief, circuit breakers)	I,K	Fuel flexibility	C,D, E,F	Ability to use new/alternative energy sources	C,F, H
	Redundancy of critical capabilities	D,E, I,K	Installed/ready redundant components (e.g., generators, pumps)	D,I, K	Capability to re-route energy from available sources	C,D, F,I,K	Update system configuration/ functionality based upon lessons learned	C,D, L,F,I, K
	Preventative maintenance on energy systems	I,K	Ability to isolate damaged/ degraded systems/ components (automatic/ manual)	E,I,K	Investigate and repair malfunctioning controls or sensors	I	Phase out obsolete or damaged assets and introduce new assets	A,C, D,I, K
	Sensors, controls and communication links to support awareness and response	H,I, K	Capability for independent local/sub-network operation	D,K	Energy network flexibility to re-establish service by priority.	F,I,K	Integrate new interface standards and operating system upgrades	D,I, K
	Protective measures from external attack (physical/ cyber)	A,D, I,K	Alternative methods/ equipment (e.g., paper copy, flashlights, radios)	B,H, K	Backup communication, lighting, power systems for repair/recovery operations	I,K	Update response equipment/ supplies based upon lessons learned	D,L
Information	Capabilities and services prioritized based on criticality or performance requirements	B	Environmental condition forecast and event warnings broadcast	E,H, I	Information available to authorities and crews regarding customer/community needs/ status	D,I	Initiating event, incident point of entry, associated vulnerabilities and impacts identified	A,D, H,I, K
	Internal and external system dependencies identified	B,G, H	System status, trends, margins available to operators, managers and customers	D,E, H,I, K	Recovery progress tracked, synthesized and available to decision-makers and stakeholders	D,I	Event data and operating environment forecasts utilized to anticipate future conditions/ events	D,H, I,K
	Design, control, operational and maintenance data archived and protected	B,I	Critical system data monitored, anomalies alarmed	D,E, I,K	Design, repair parts, substitution information available to recovery teams	K	Updated information about energy resources, alternatives and emergent technologies available to managers and stakeholders	D,F, H,I
	Vendor information available	B	Operational/troubleshooting/ response procedures available	I,K	Location, availability and ownership of energy, hardware and services available to restoration teams	K	Design, operating and maintenance information updated consistent with system modifications	F,I,K

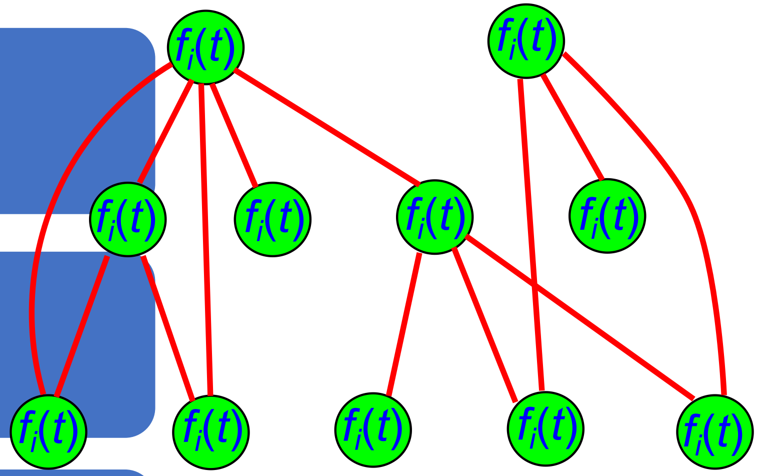
Network-based Resilience Theory?

System's *critical functionality* (K)

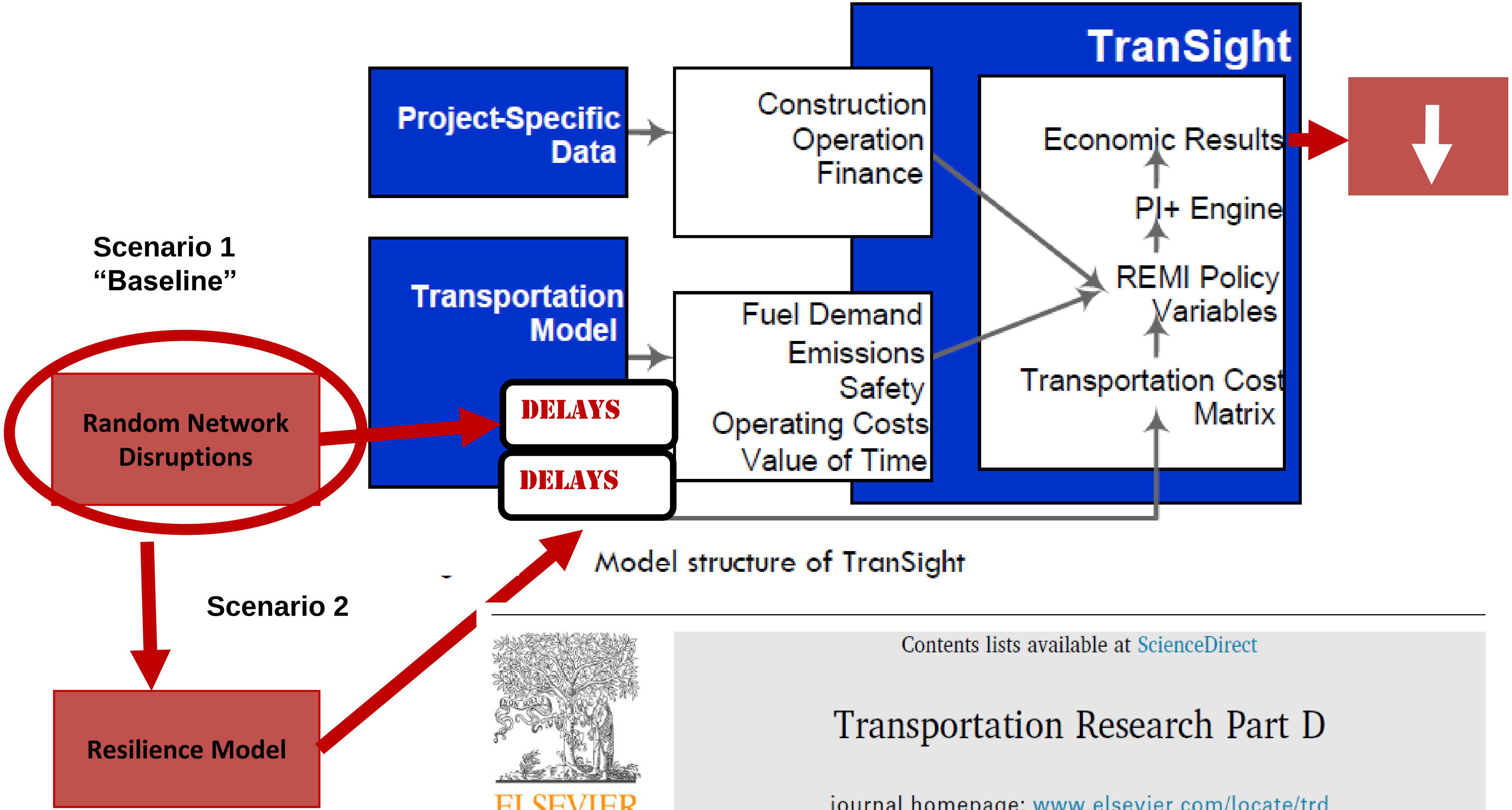
Network topology: *nodes* ($\mathcal{N}$) and *links* ($\mathcal{L}$)

Network *adaptive algorithms* ($\mathcal{C}$) defining how nodes' (links') properties and parameters change with time

A *set of possible damages* stakeholders want the network to be resilient against ($\boldsymbol{E}$)



$$R = f(\mathcal{N}, \mathcal{L}, \mathcal{C}, \boldsymbol{E})$$



Model structure of TranSight

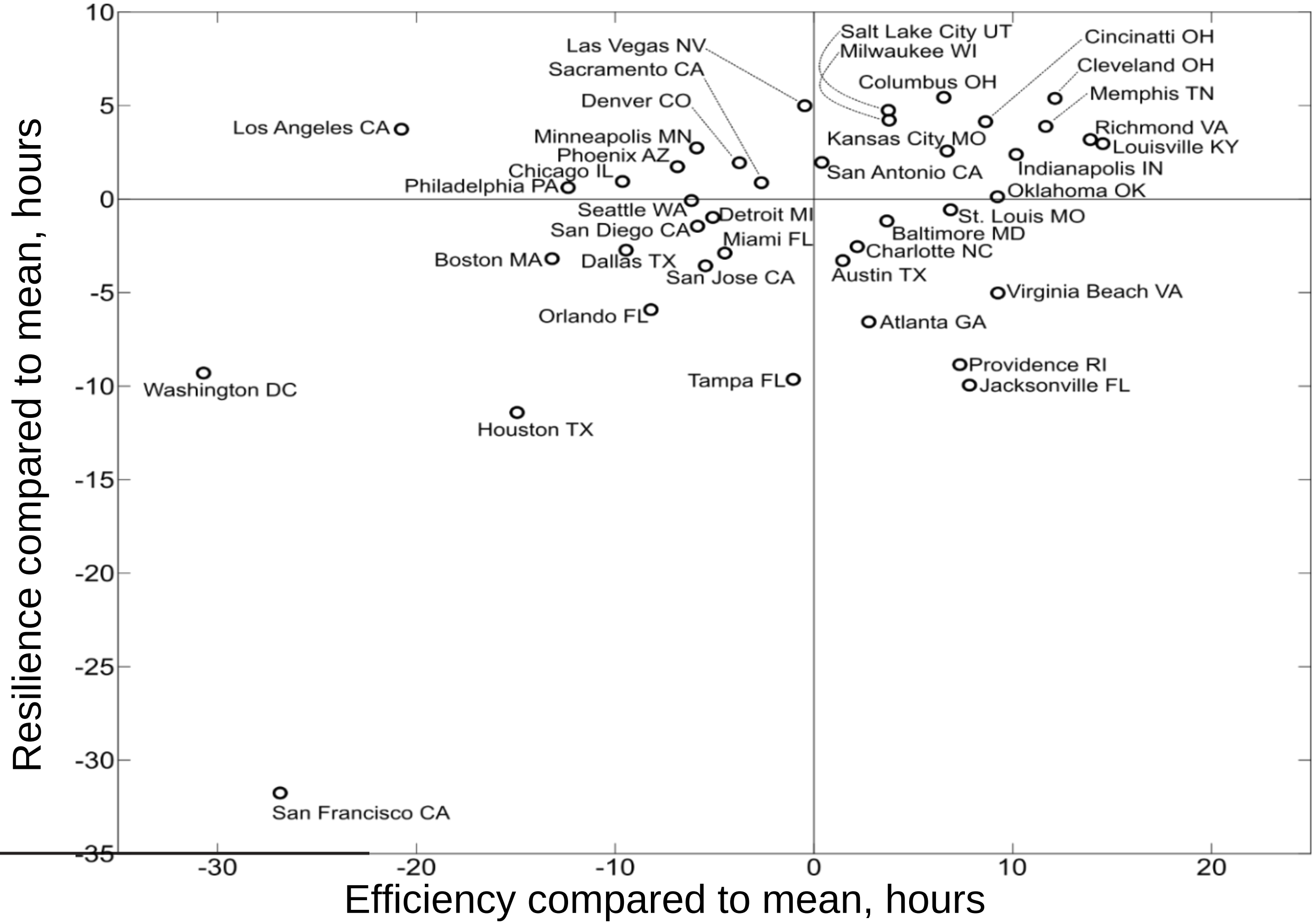
Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Lack of resilience in transportation networks: Economic implications

Resilience vs Efficiency at 5% disruption



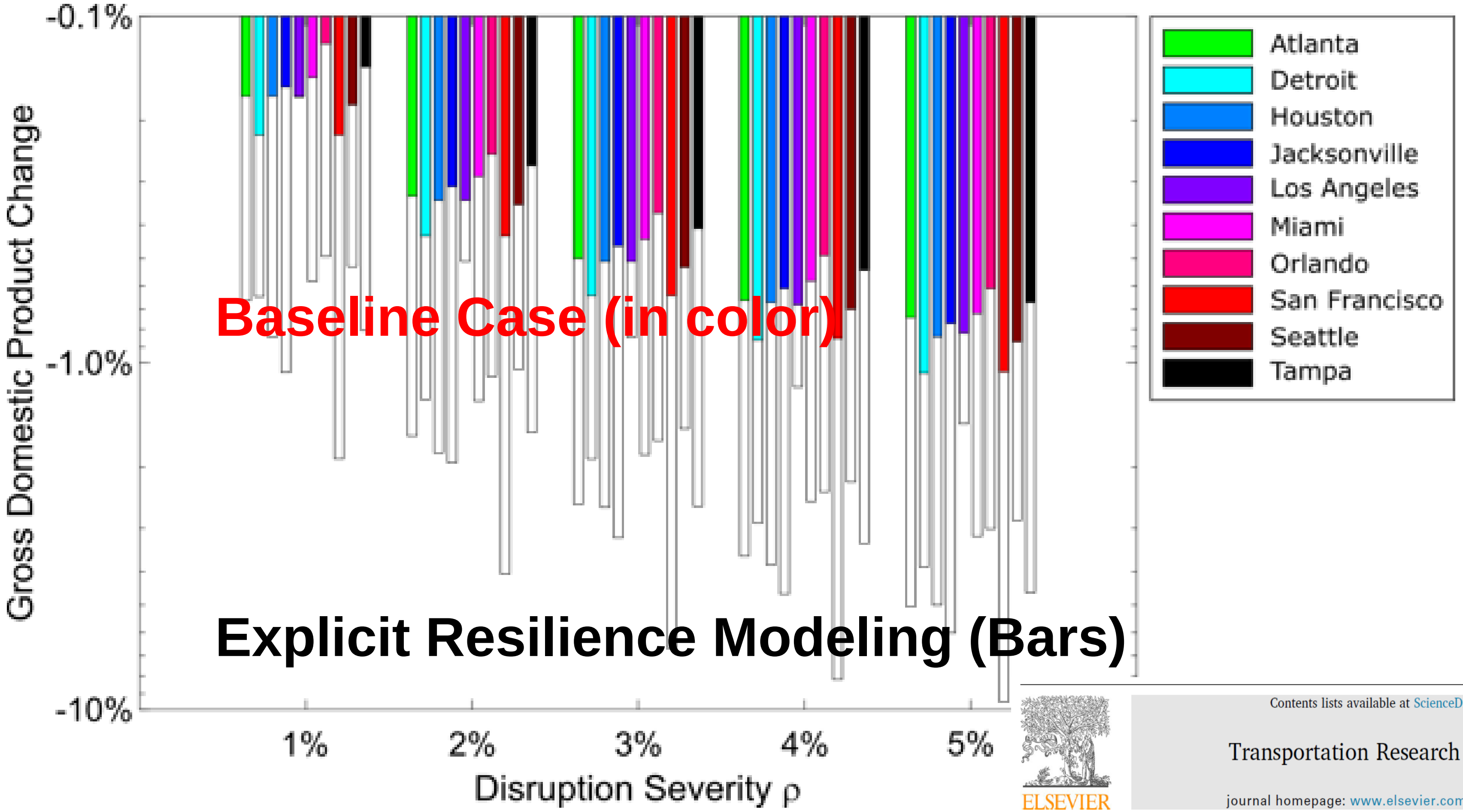
SCIENCE ADVANCES | RESEARCH ARTICLE

NETWORK SCIENCE 2017

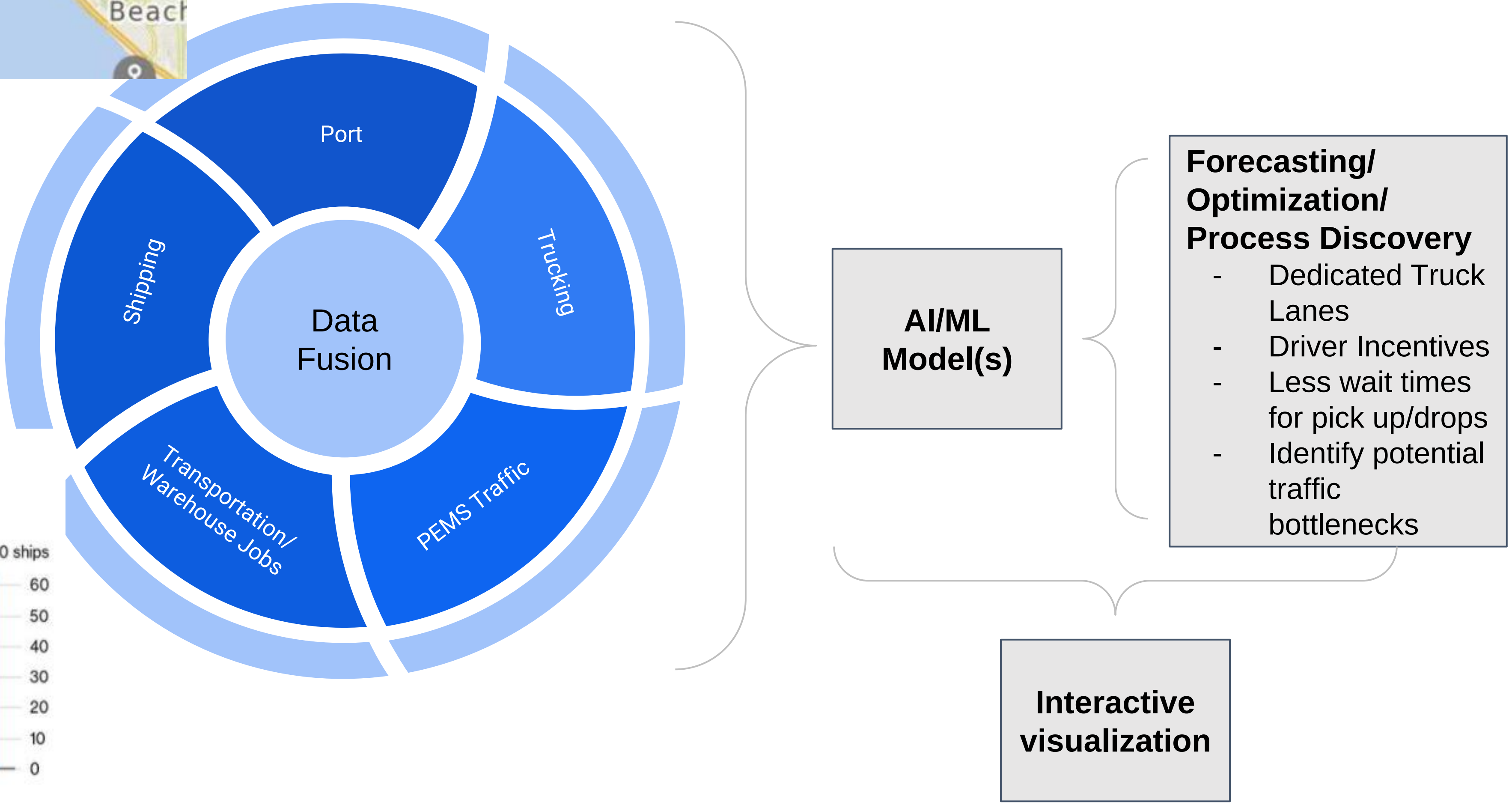
Resilience and efficiency in transportation networks

Alexander A. Ganin,[1,2] Maksim Kitsak,[3] Dayton Marchese,[2] Jeffrey M. Keisler,[4]
Thomas Seager,[5] Igor Linkov[2]*

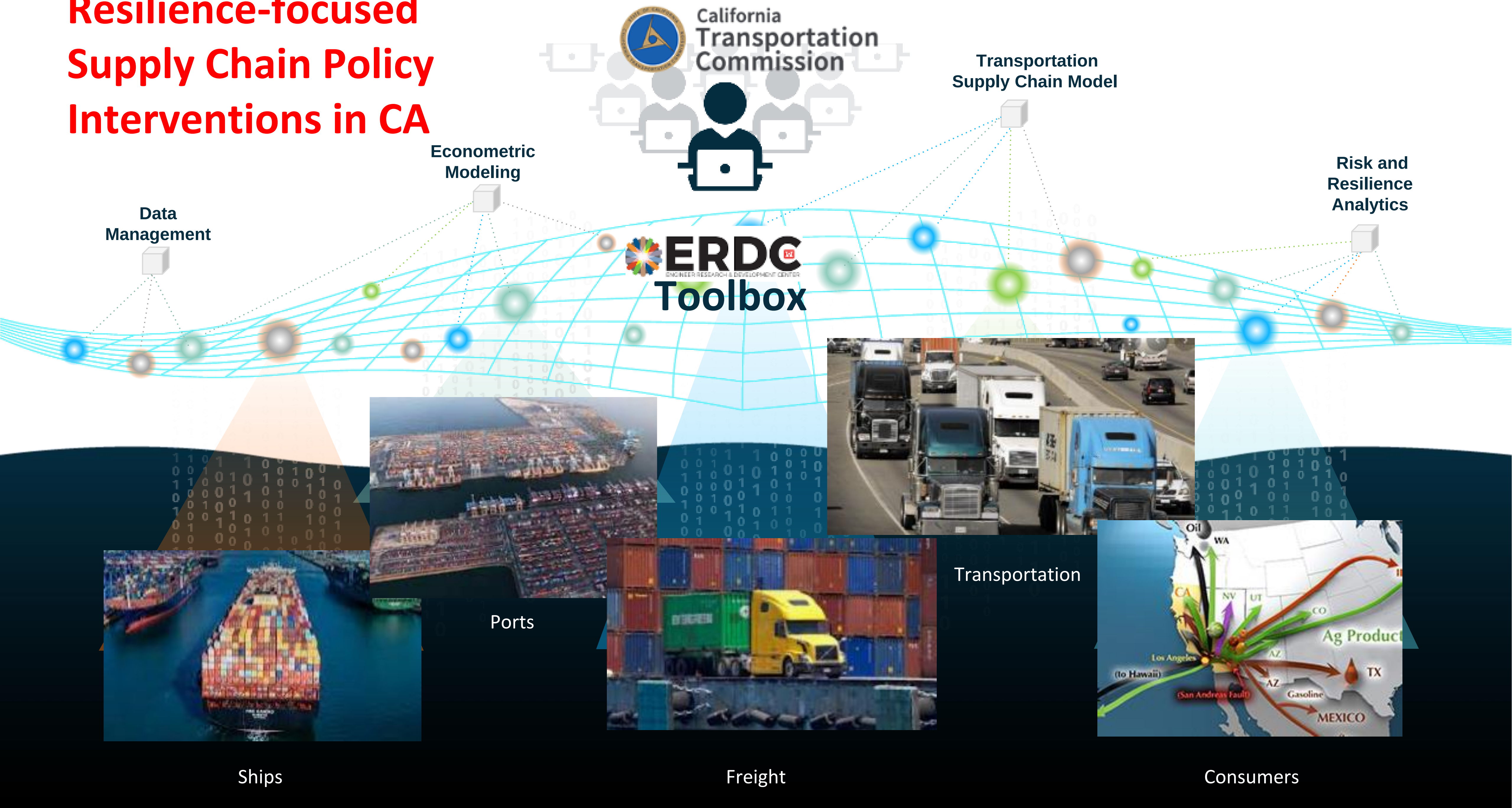
Lack of Resilience: Impact on GDP



Supply Chains Crisis in CA



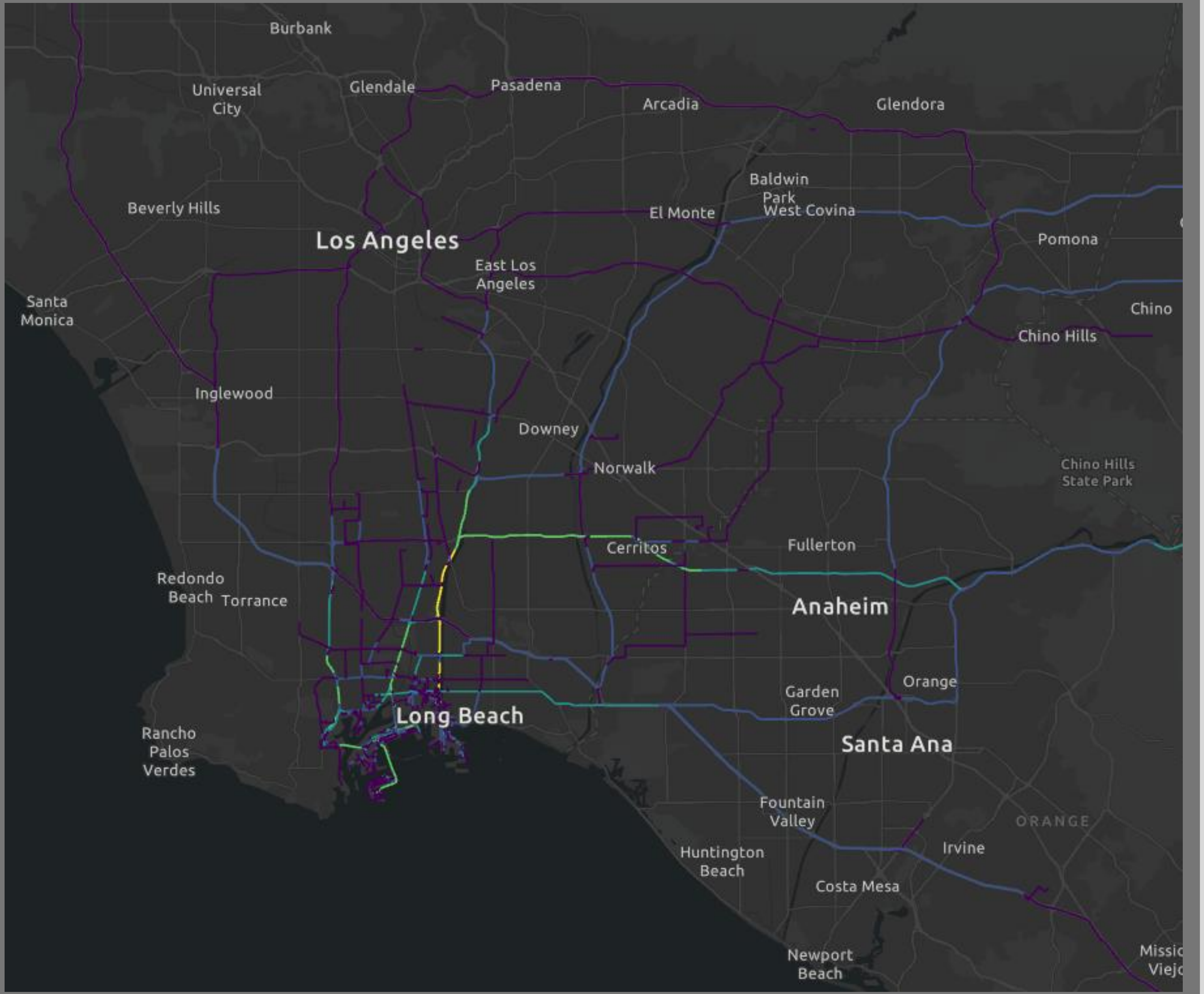
Resilience-focused Supply Chain Policy Interventions in CA



Technical Approach: Aggregate Freight Flows

- The optimization can be performed using:
  - Aggregate Flows:
  - Individual Commodity Flows (such as refrigerated goods or car parts)
  - Short vs Long Haul

*Presenter notes: shown on the right here is the aggregate flows



ENVIRONMENTAL LABORATORY

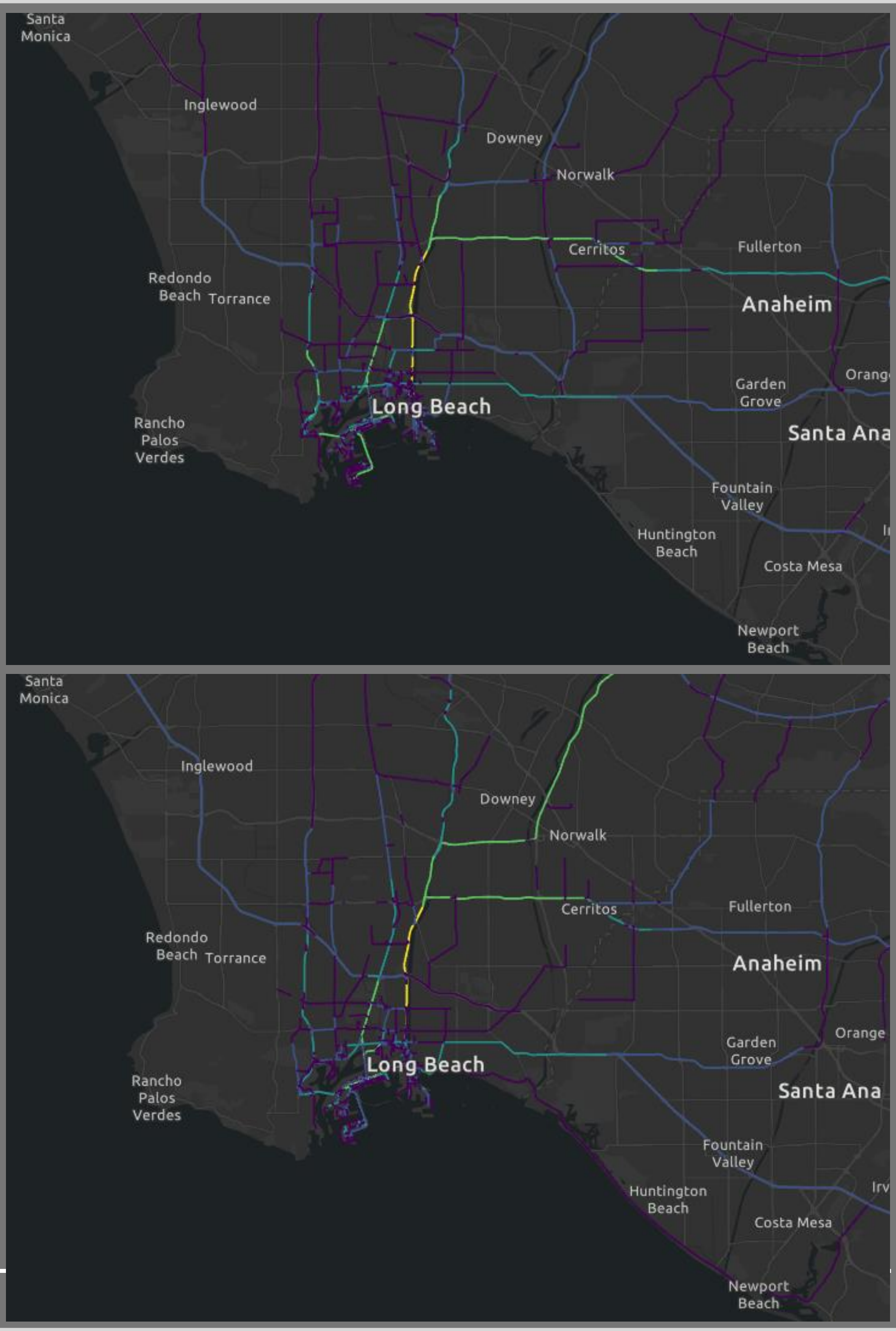
Application 1: Traffic Policy Decision Tool Project Goal

- **Challenge:** Having a reliable way to compare the relative impact of different policies and investments on freight transit times

- **Solution:** Using AI Model to compare Avoidance and Mitigation Strategies
  - Key Freight corridor expansion
  - Diverting or prioritizing traffic on specific highway segments, lanes, times of day
  - Land use planning controls
  - Investment in infrastructure of alternative modes
  - Incentives to balance variance in round-trip under stress

Scenario 1

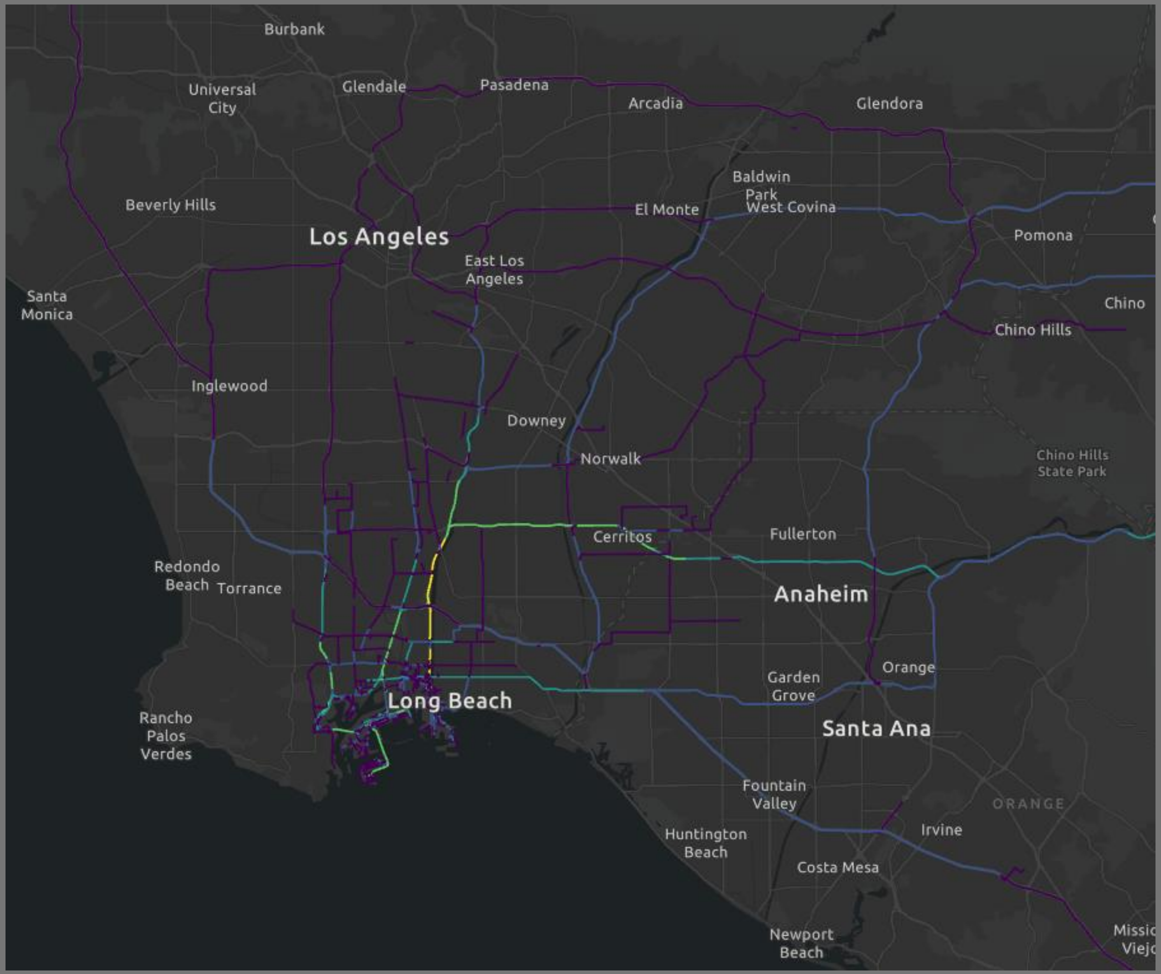
Scenario 2



ENVIRONMENTAL LABORATORY

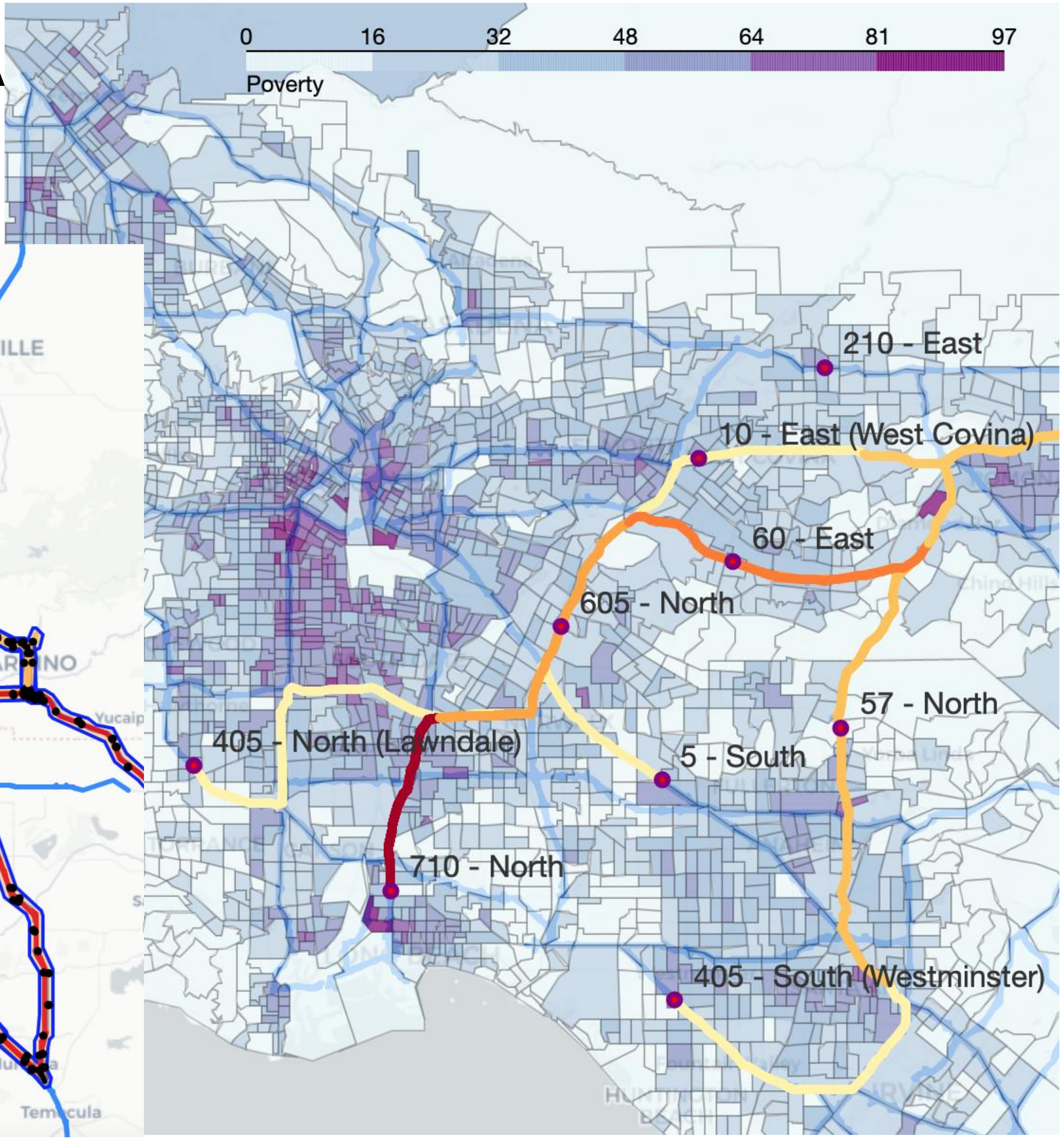
Application 2: Optimizing the Location of Medium- and Heavy-Duty Hydrogen Dispensing Stations
Technical Approach: Calculating Total Additional Route Diversion

1. Define gas stations which are candidates for conversion
2. Leverage State-Wide freight flows being developed for CTC
3. Compute the total travel time added by making all truck routes pass through a set of gas stations
4. Find the set of gas stations which minimize the additional travel time
5. Overlap results with additional information



ENVIRONMENTAL LABORATORY

Locating Hydrogen Refueling Stations in CA



Cyber Resilience by Design or by Intervention?

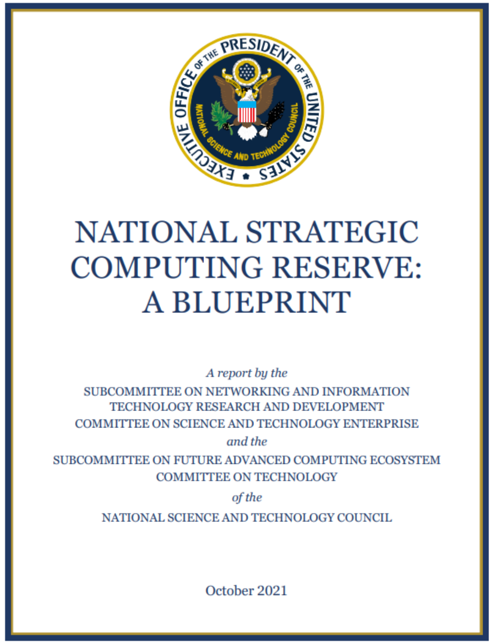
Alexander Kott, U.S. Army DEVCOM Army Research Laborat

Maureen S. Golan, U.S. Engineer Research and Developmen
Credere Associates

Benjamin D. Trump, U.S. Engineer Research and Developme
University of Michigan

Igor Linkov, U.S. Engineer Research and Development Cente
Carnegie Mellon University

	Risk management	RBD	RBI
Objective	Harden individual components	Design components to be self-reorganizable	Rectify disruption to components and stimulate recovery by external actors
Capability	Predictable disruptions, acting primarily from outside the system components	Either known/predictable or unknown disruptions, acting at a component or system level	Failure in the context of societal needs; there may be a constellation of networks across systems
Consequence	Vulnerable nodes and/or links fail as a result of a threat	Degradation of critical functions in time and capacity to achieve system's function	Degradation of the critical societal function due to cascading failure in interconnected networks
Actor	Either internal or external to the system	Internal to the system	Ext
Corrective action	Either loosely or tightly integrated with the system	Tightly integrated with the system	Loc
Stages/ analytics	Prepare and absorb (the risk is a product of a threat, vulnerability, and consequences, and is time independent)	Recover and adapt (explicitly modeled as time to recover system function and the ability to change system configuration in response to threats)	Pre (ex to r soc the


NATIONAL STRATEGIC COMPUTING RESERVE: A BLUEPRINT

A report by the
SUBCOMMITTEE ON NETWORKING AND INFORMATION TECHNOLOGY RESEARCH AND DEVELOPMENT
COMMITTEE ON SCIENCE AND TECHNOLOGY ENTERPRISE
and the
SUBCOMMITTEE ON FUTURE ADVANCED COMPUTING ECOSYSTEM
COMMITTEE ON TECHNOLOGY
of the
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

October 2021

Stress-test the resilience of critical infrastructure

INTEGRATED RISK/RESILIENCE STRESS TESTING

WHO DOES ANALYSIS?		*"Identify the functions and failures"* INPUTS	*"Perform the stress test"* RISK	RESILIENCE	*"Fortify the system"* OUTPUTS
Policy Analysts, Generalists	TIER 1	Qualitative information, component data	Develop scenarios for shocks and stresses affecting specific vulnerabilities	Identify critical functions of systems and cascading failures	**"Quick win" improvements**
Risk Assessors, engineers, decision analysts	TIER 2	System structure, connectivity	Assess risk of component failure under stress scenario separately per domain	Identify connections across multiple system domains that are difficult to recover	**System wide resilience strategy**
Specialists, modelers	TIER 3	Detailed system information, advanced data	Advance probabilistic risk assessment across multiple domains/compounding threats	Network science/AI techniques to assess failures in interconnected networks	**Targeted Changes + Interventions**

Cyber Resilience by Design or by Intervention?

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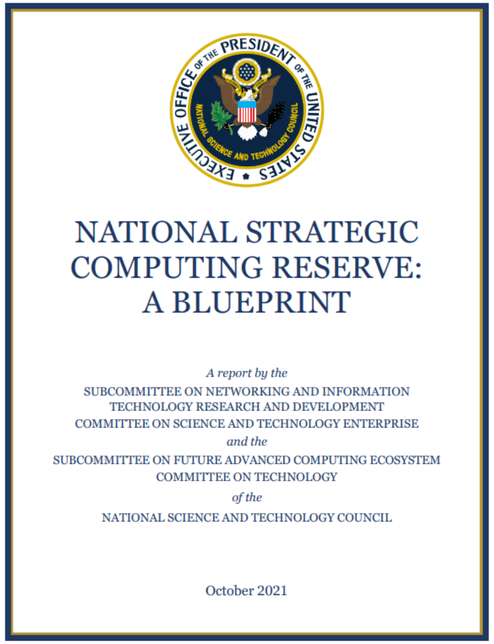

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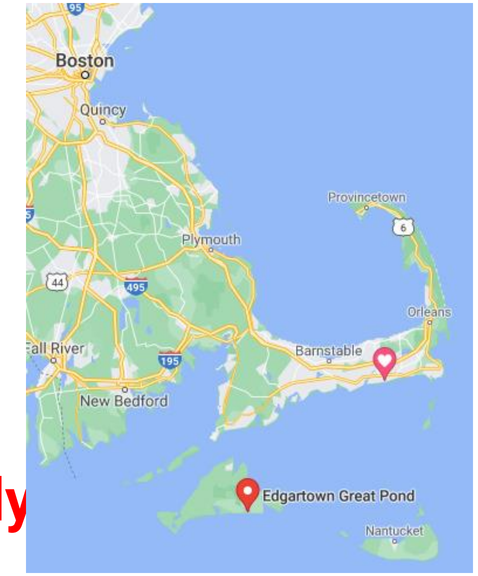
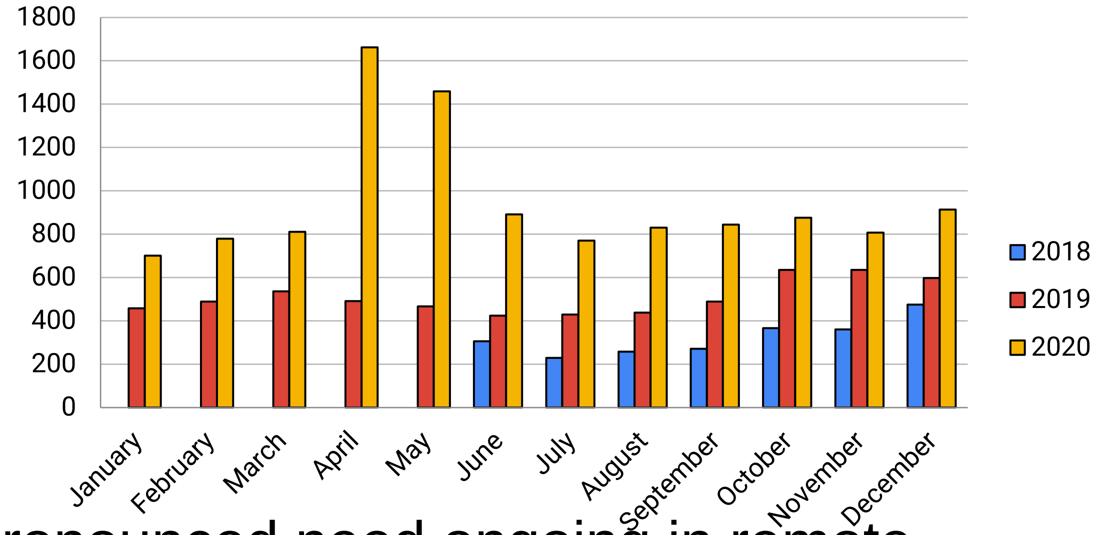
October 2021

	Traditional Supply Chain Management Approaches	Resilience-by-Design	Resilience-by-Intervention
Threats to Food Security /Supply Chains	Systemic (Climate change, social and economic changes) and shocks (pandemics, cyber attacks, natural disasters)		
Actions and Analytics/Stages	Hardening the system based on assessing largely known or predictable risks (i.e. product of threat, vulnerability, and consequence)for prepare and absorb stages.	Engineering systems to be recoverable and adaptable in response to both predicted and unknown threats based on modeling loss of critical system functionality over time.	Resources outside an individual SC (e.g., stockpiles, services, community stakeholder, etc.) available to facilitate recovery and adaptation of systems in case of disruptions
Advantages of Approach	Methodology is well developed and practiced, allows system to retain functionality without disruptions. Works well for known or predictable threats.	System is designed for self-healing and able to quickly respond to either known/predictable or unknown disruptions in the context of its own needs and abilities.	Combined resources and capabilities allows cost saving as well as flexibility to adapt to a much broader range of possible disruptions.
Disadvantages of Approach	Limited to known or predictable threats; cost increases exponentially once low probability high consequence disruptions are considered. Possible catastrophic failure since system are not designed for recovery.	System needs to maintain redundant capabilities and training of personnel to maintain and act accordingly. May be quite expensive.	Necessary cooperation and resource allocation among stakeholders, regulators, and other SC players limits speed/viability of corrective action development. Cost may be substantial, but lower than in by-design.

Islands and Remote Communities: Food Supply Chains



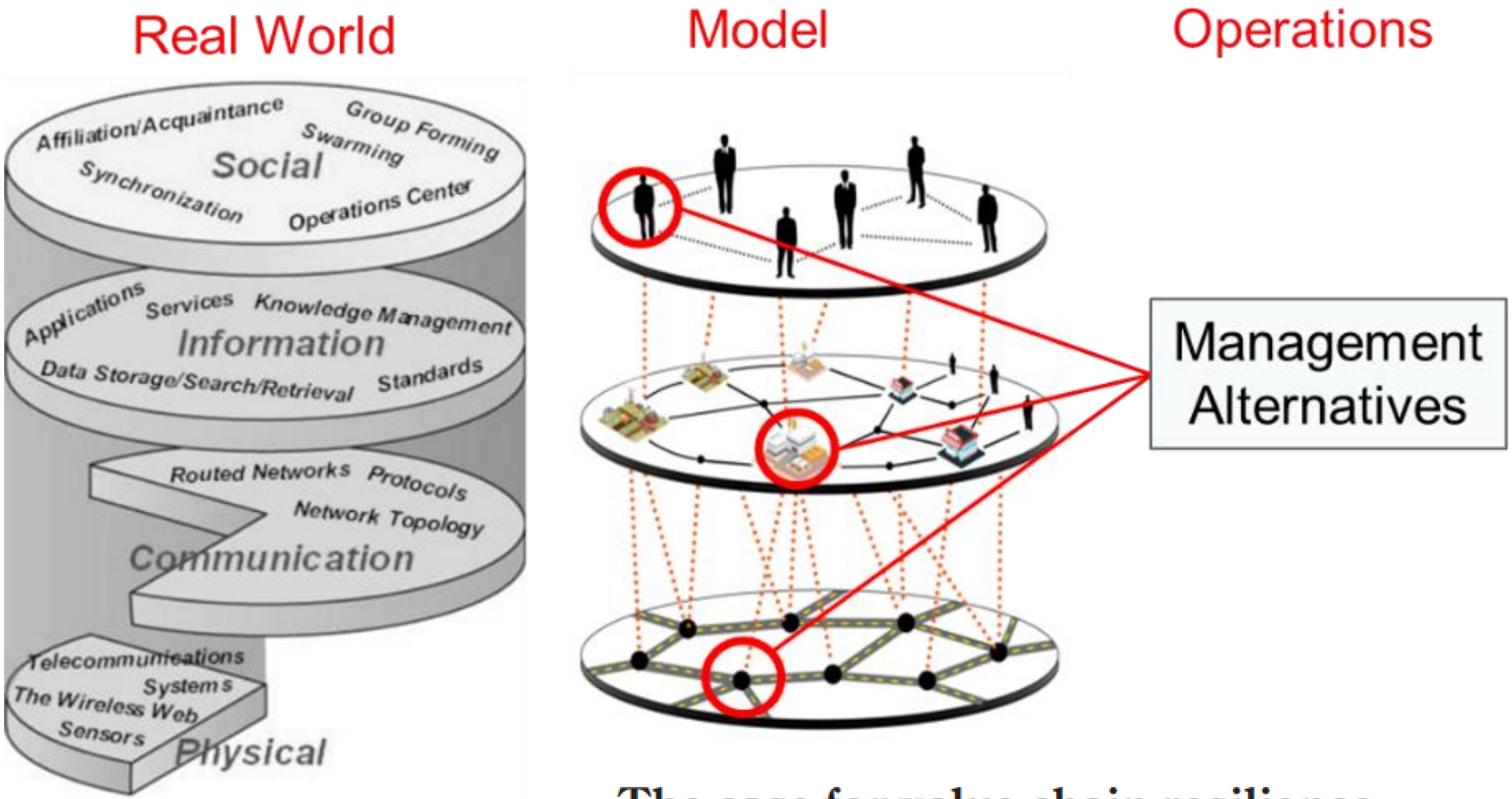
Martha's Vineyard: Monthly Visits



Pronounced need ongoing in remote, austere, or island communities –Tribal communities on Martha's Vineyard.

Nature Communications (in press)

Vision for System Resilience: Social Science/Communication Integration



The case for value chain resilience

Igor Linkov, Savina Carluccio, Oliver Pritchard, Áine Ní Bhreasail, Stephanie Galaitsi, Joseph Sarkis and Jeffrey M. Keisler

Management Research Review

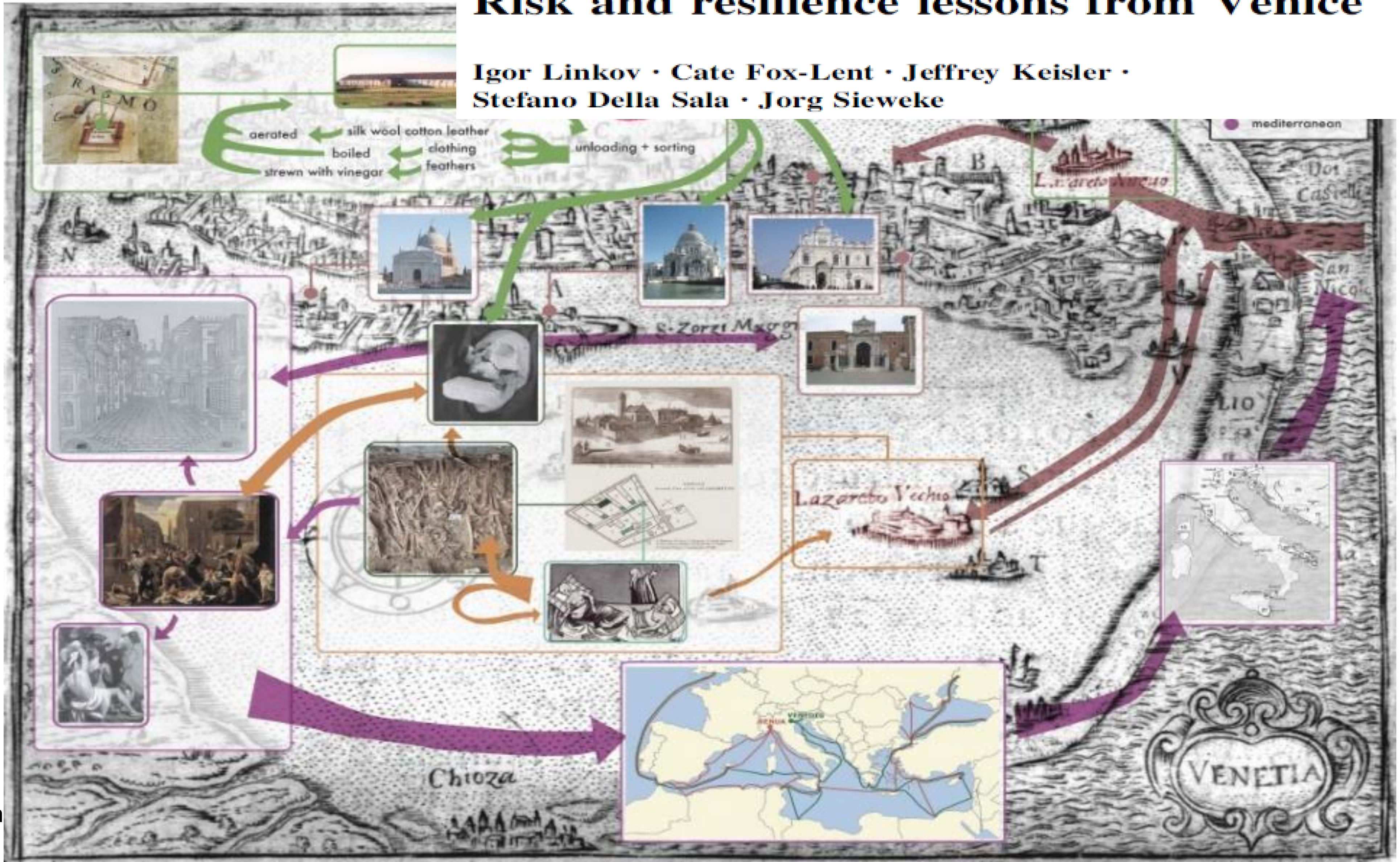
2040-8269
DOI 10.1108/MRR-08-2019-0353

Environ Syst Decis (2014) 34:378–382
DOI 10.1007/s10669-014-9511-8

PERSPECTIVES

Risk and resilience lessons from Venice

Igor Linkov · Cate Fox-Lent · Jeffrey Keisler ·
Stefano Della Sala · Jorg Sieweke



From Un

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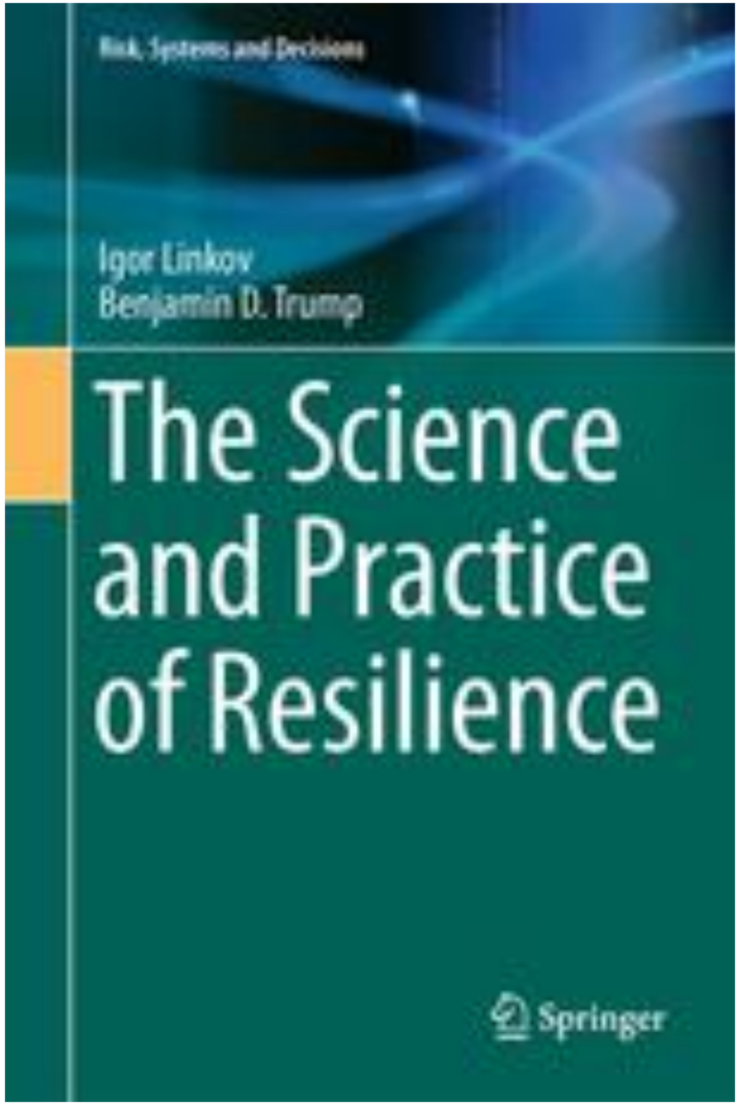
Risk, Systems and Decisions
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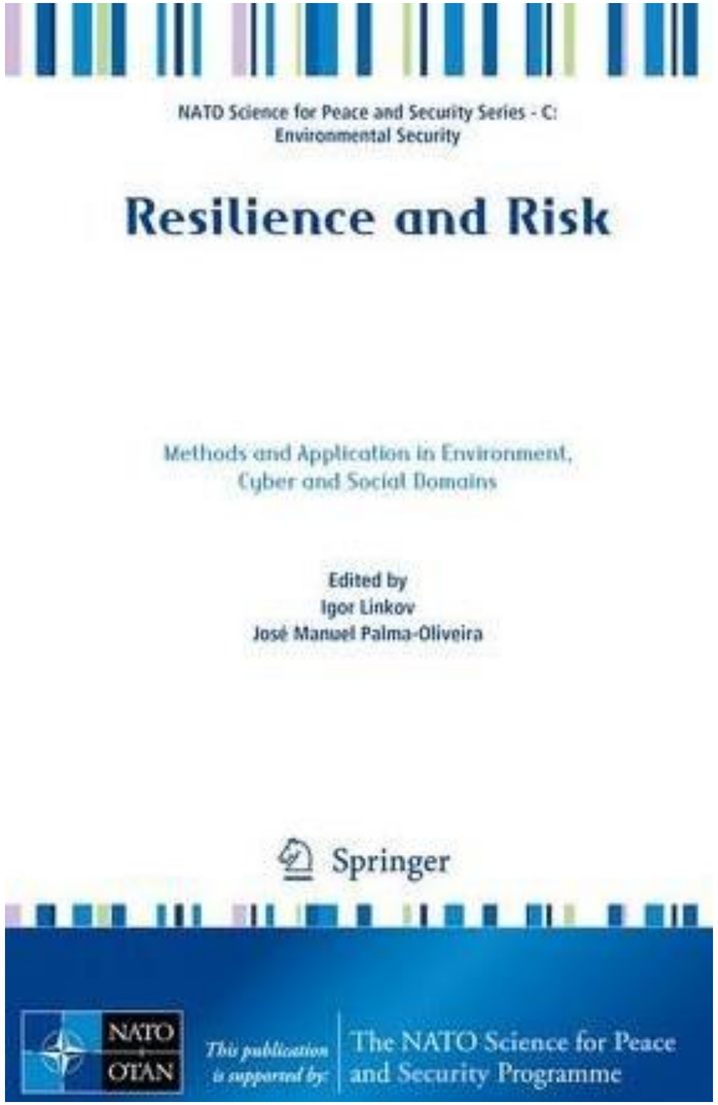
Springer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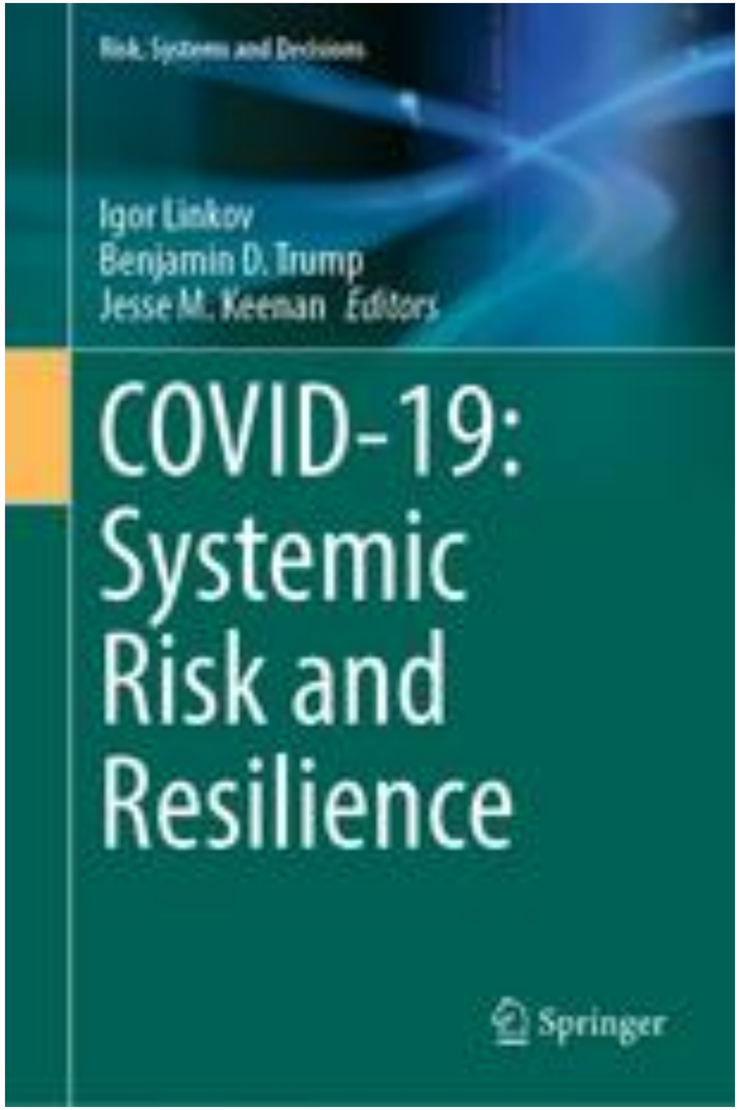
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