WELCOME
to the
SERDP NICE Project Workshop
25-26 April 2024

Networked Infrastructures under Compound Extremes (NICE): State of the Project

Opening Session
25 April 2024

Bottom Line Up Front (BLUF)

Problem

- Ensure mission readiness of installations under compounding extremes with interdependent systems within an installation and interacting environment

Approach

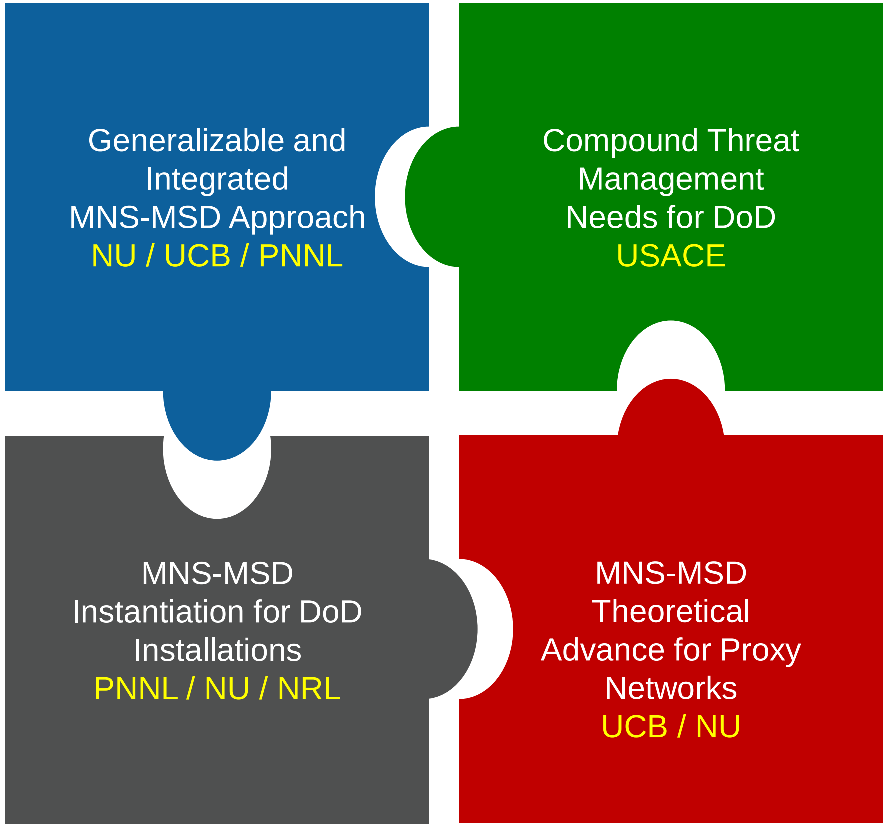
- Develop theory and methods for installation resilience based on multiplex network science (MNS) and multiscale system dynamics (MSD)
- Evaluate theories and methods based on proxies, simulations, and instantiations or case studies
- Translate the new understanding, methods, processes, software, and benchmarks to DoD's needs

Benefits

- Intellectual property for novel theory and method evaluated across scenarios
- New understanding on robustness and recovery of installation functionality subject to compound extremes
- Peer-reviewed literature, software and data products, and dissemination to DoD and other customers

Progress

- Generalizable MNS-MSD approach (*NU-UCB-PNNL*)
- Compound threat exposures and historical trends for DoD needs (*USACE*)
- Dimension reduction for resilience of proxy large-scale fuel resource flow networks (*UCB-NU*)
- MNS-MSD instantiation for a synthetic DoD installation (*PNNL-NU-NRL*)



Integrated NICE Vision

Accomplishments / Publications

DoD Engagements

- DCAT (Defense Adaptation Climate Toolkit) – Office of Deputy Assistant Secretary of Defense
- Army IEWP & Coastal Texas Project
- Lt. Col. Craig Poulin, US Air Force
- NPS SERDP Project Team

Patent Application

- NU/PNNL/UCB: A Methodology using Multiplex Network Science and Multiscale System Dynamics to quantify infrastructure resilience

Computational Workflows/Tools

- NU: Geospatial visualization tool for exposure of DoD installations to climate hazards
- UCB: Dimension reduction for networked dynamical systems
- PNNL/NU/NRL: Simulation for installation mobility impacts
- USACE: Hazard data analysis for compound threat exposure

Publications

- NRL/PNNL/NU: Chikkagoudar, Chatterjee, Bharadwaj, Ganguly, Kompella, Thorsen, "Assurance by Design for Cyber-physical Data-driven Systems," in IoT Defense/National Security, IEEE, 2023
- NU: "A Network Lens on the Resilience of Installations to Climate and Compound Extremes," Abstract accepted to ASCE INSPIRE 2023 Conference 16-18 November 2023
- NU: Ganguly, Pal, Das, Yadav; "Robustness of Urban Coastal Rail Network Under Projected Future Floods," Fragile Earth Workshop ACM KDD 2022 Conference and Society of Risk Analysis Student Merit Award
- NU/PNNL: Watson, Chatterjee, Ganguly, "Resilience of Urban Rail Transit Network Under Compound Natural and Opportunistic Failures," IEEE HST: International Symposium on Technologies for Homeland Security (2022) Best Paper
- NU: Ganguly, Das "Evaluation of Surface Runoff Projections from Earth Systems Models in Major River Basins of the World," Fragile Earth Workshop, ACM KDD Conference 2023
- PNNL/Indiana University: Chatterjee, Hussain, Khan, Brigantic, Halappanavar; "Disruption-Robust Community Detection using Consensus Clustering in Complex Networks," IEEE
- PNNL: Chatterjee, Bhattacharya, Purohit, Subasi; "Impact-Driven Sampling Strategies for Hybrid Attack Graphs," IEEE
- PNNL/NU/NRL: Chatterjee, Ganguly, Thomas, Chikkagoudar "A Network Science & System Dynamics Simulation Framework for Installation Resilience under Compound Extremes," MORS 6/2023
- UCB/NU: Salgado, He, Radke, Ganguly, Gonzalez. "Dimension Reduction Approach for Understanding Resource-Flow Resilience in the Face of Climate Change" Communications Physics 4/2023

Awards

- USACE (Trump & Linkov): Finalist for INFORMS Innovative Applications in Analytics Award (IAAA)
- NU (Watson): COE Outstanding Graduate Student Research Award
- NU (Das): Outstanding Graduate Student Teaching Award in CEE

Invited Presentations

- NU:(Ganguly & students): Invited talks at United Nations HQ in NYC on hybrid AI-physics methods for infrastructures during converging disasters for UNDRR event
- NU (Ganguly): Invited talk on resilience at ASCE INSPIRE conference
- PNNL (Chatterjee): Invited talks on installation resilience at MORS and REA symposiums

Publicity: Research & Workforce

2023: Forbes, Semafor,, Boston Globe, Newsweek, COE Award, UNDRR, NGN, ASCE, Lifewire, Experience, GCR, Phys.org, ReConnect, 2022: NYT

Networked Infrastructures under Compound Extremes (NICE): State of the Project

Presenters (introduced by Robyn Anderson, Northeastern University):

Auroop Ganguly – Northeastern University, Boston, MA

Sam Chatterjee – Pacific Northwest National Labs, Richland, WA

Satish Chikkagoudar – Naval Research Lab, Washington, DC

Marta Gonzalez – University of California, Berkeley, CA

Ben Trump – US Army Corps of Engineers, Raleigh, NC

SERDP

DOD ▪ EPA ▪ DOE

CREATING A QUANTITATIVE APPROACH FOR COMPOUNDING THREAT ASSESSMENT

DR. AUROOP GANGULY
NORTHEASTERN UNIVERSITY

Generalizable and Integrated MNS-MSD Approach
NU / UCB / PNNL

Presenter: Auroop Ganguly, NICE Lead PI

College of Engineering Distinguished Professor and Director of AI for Climate and Sustainability (AI4CaS), **Northeastern University**

Joint Appointee as Chief Scientist, Advanced Computing, Math, and Data Division, **Pacific Northwest National Laboratory**

Co-founder and Chief Scientific Officer, **risQ Inc.** (a startup, acquired by the Fortune 500 company Intercontinental Exchange)

SDS Lab PhD students **Puja Das** (middle) and **Ashis Pal** (4th from left) and SDS Lab and AI4CaS data scientist **August Posch** (2nd from left) with engineers of the Tennessee Valley Authority (TVA)

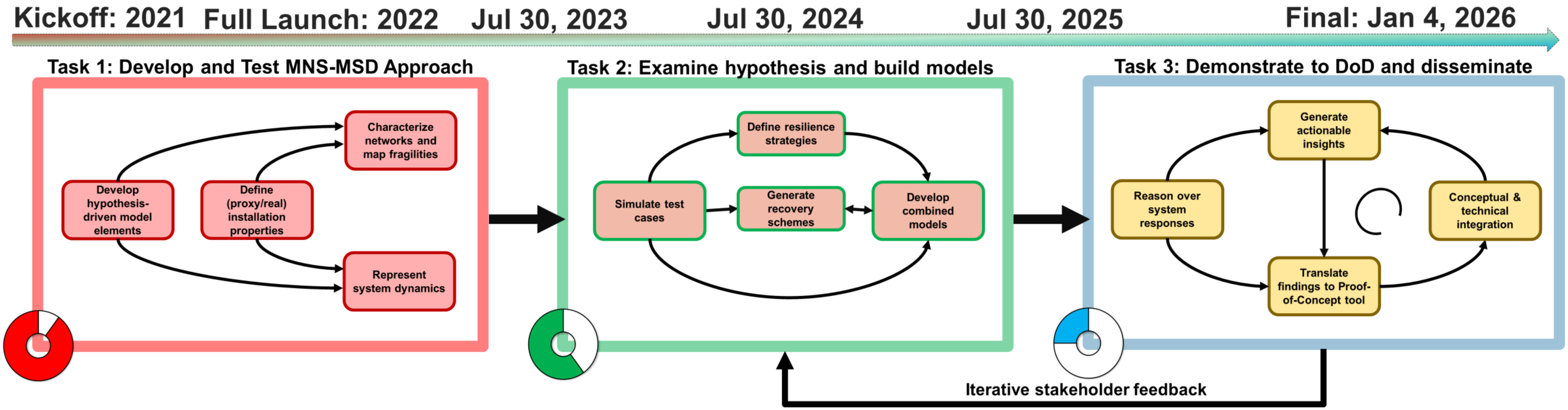
SDS Lab PhD student and PNNL intern **Jack Watson** (right) receiving the Student Merit Award at the Society of Risk Analysis (SRA) from the Resilience Analysis Specialty Group

SDS Lab

SUSTAINABILITY AND DATA SCIENCE LAB

https://sdslab.io/

State of the NICE Project



Task 1: MNS-MSD for Installations (90%)
- Developed Suite of MNS-MSD Methods
- Created IP Notification for Patent Filing
- Tested on Real Proxies and Realistic Sites

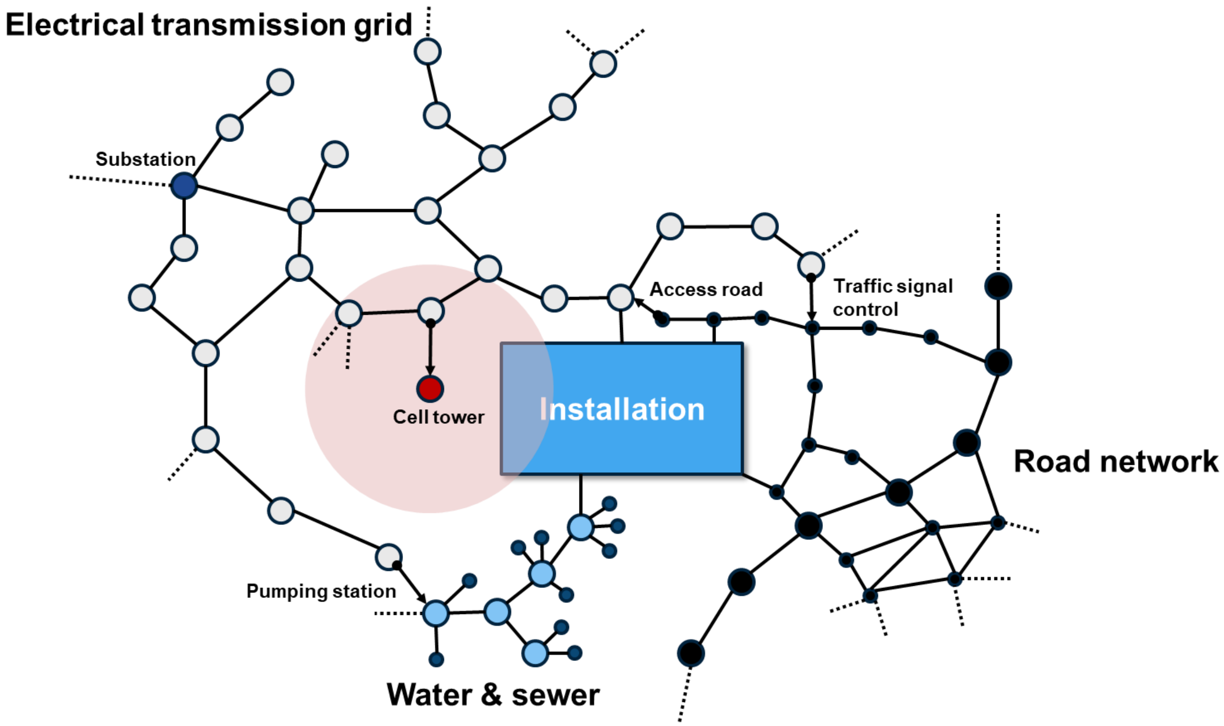
Task 2: Evaluate Cases & Scenarios (60%)
- Instantiated MNS-MSD on Installations
  - *Replaces NSB King's Bay as Case Study*
- Examined Urban (Transit & Fuel) Proxies
- Evaluated Compound Extremes Scenarios

Task 3: Demonstrate to DOD (25%)
- Defense Climate Adaptation Toolkit (DCAT)
- Army IEWP and Coastal Texas Project
- Installation Compound Threats

As of October 2023 (SERDP Fall IPR)

Invention Disclosure: *MNS-MSD for Installations*

"Multiplex network science and multiscale system dynamics: an approach to assessing the resilience of interdependent installations and infrastructure environments under compound extreme disruptions"



U.S. Provisional Patent Application No. 63/554,767

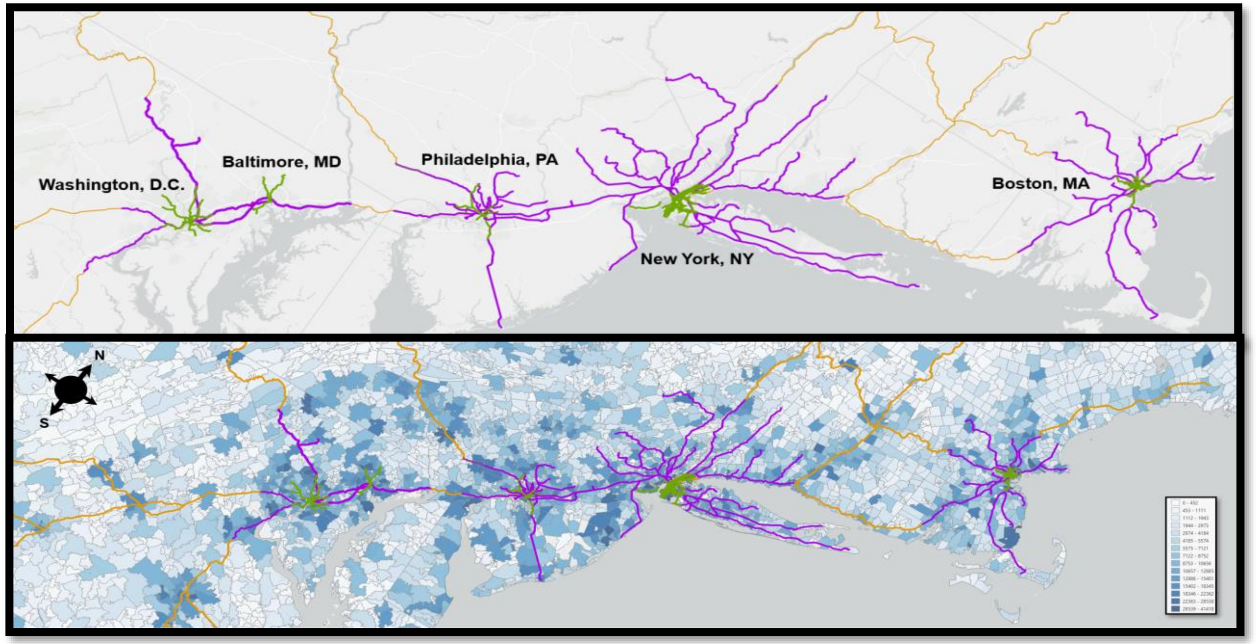
Northeastern University:
Jack Watson, PhD Candidate (Lead Inventor)
Ashis Pal, PhD Candidate
Auroop Ganguly, Distinguished Professor

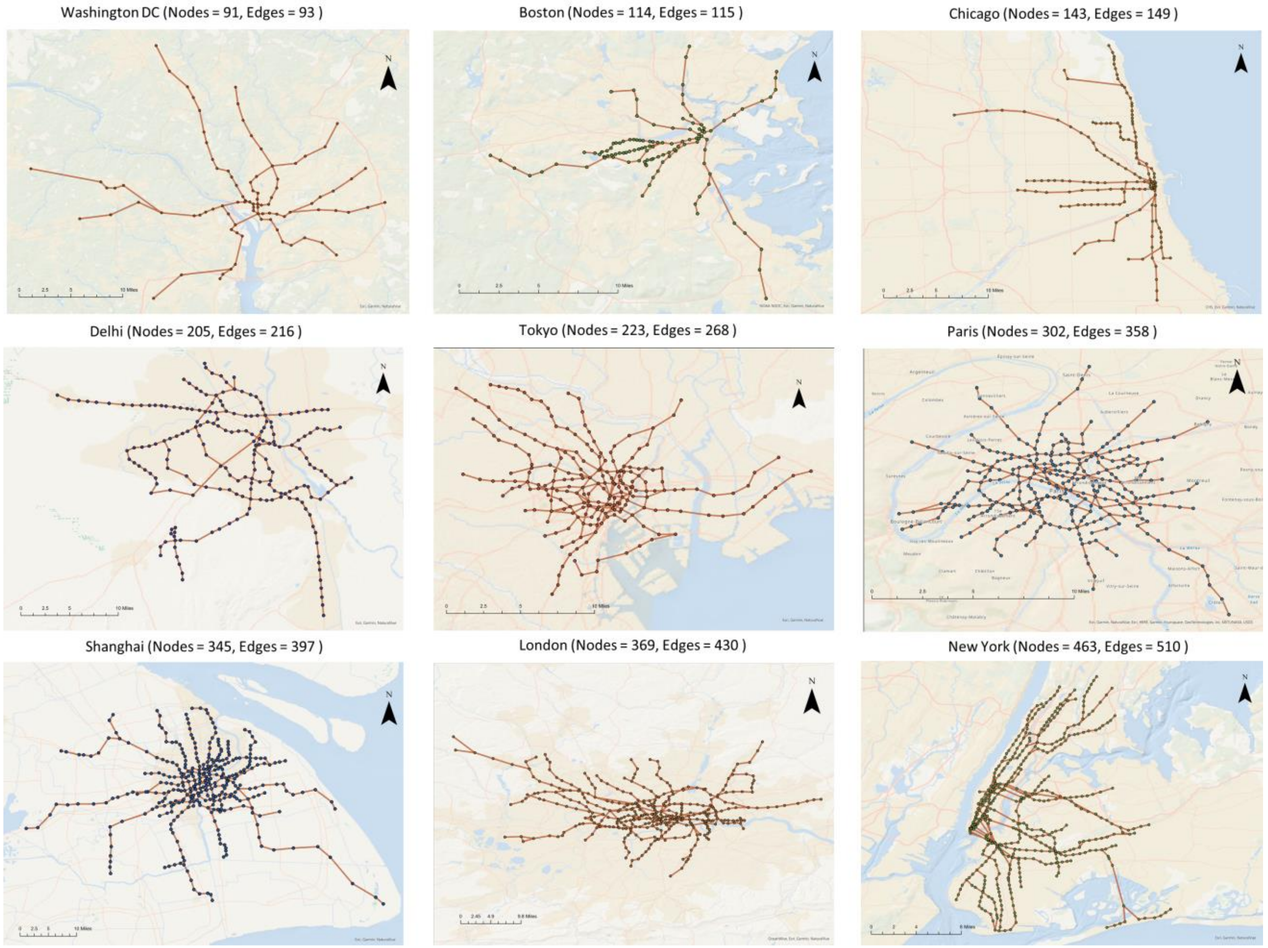
Pacific Northwest National Laboratory:
Samrat Chatterjee, Chief Data Scientist

University of California Berkeley:
Ariel Salgado, Postdoctoral Researcher
Marta Gonzalez, Professor

The multi-organization team of inventors

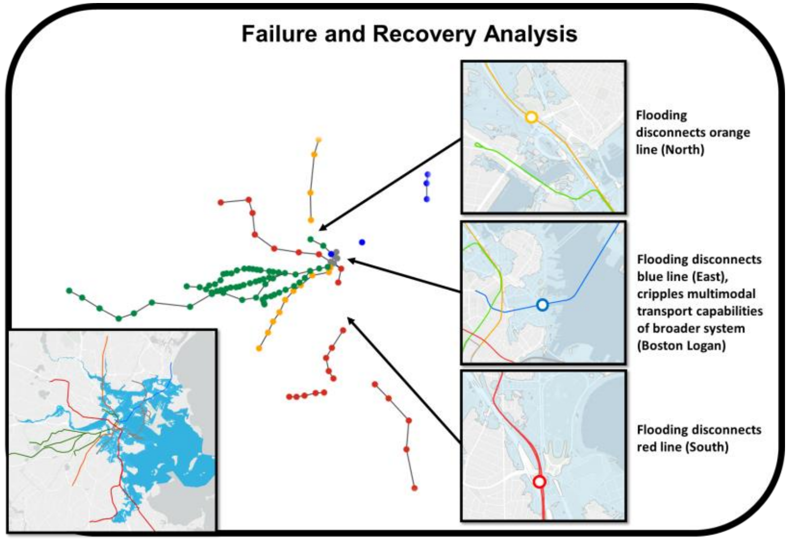
System Focus: *Railway Networks Resilience*

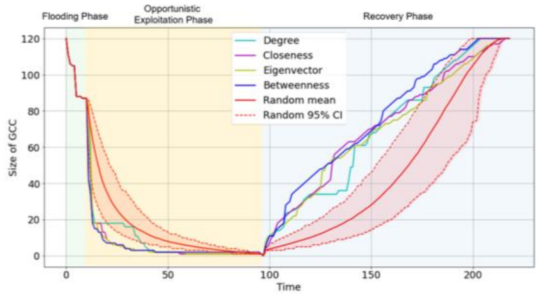




US Northeast Corridor Rail: *Urban & Regional Networks*

Urban Rail Metros: *DC, Boston, Chicago, Delhi, Tokyo, Paris, Shanghai, London, New York*



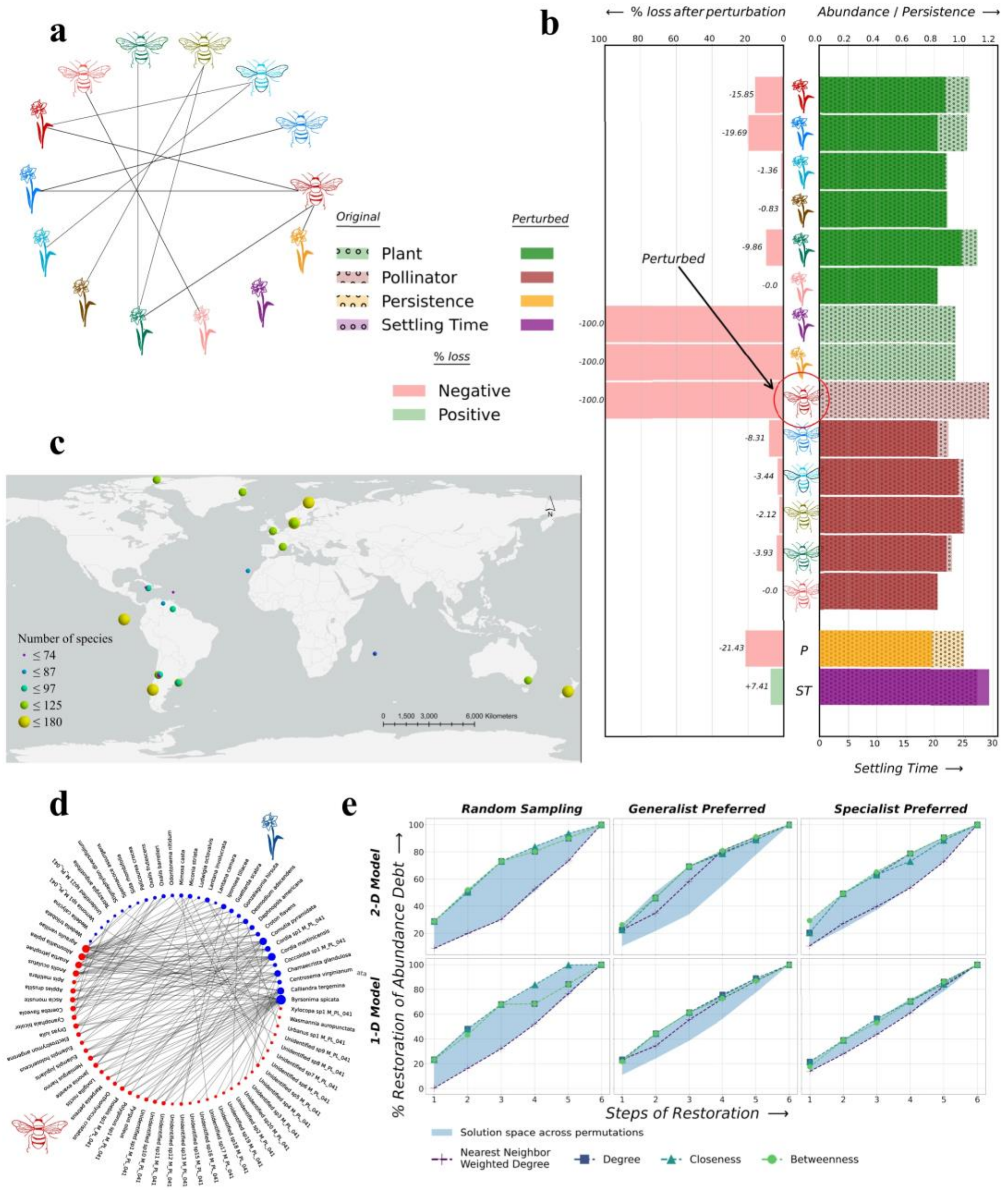


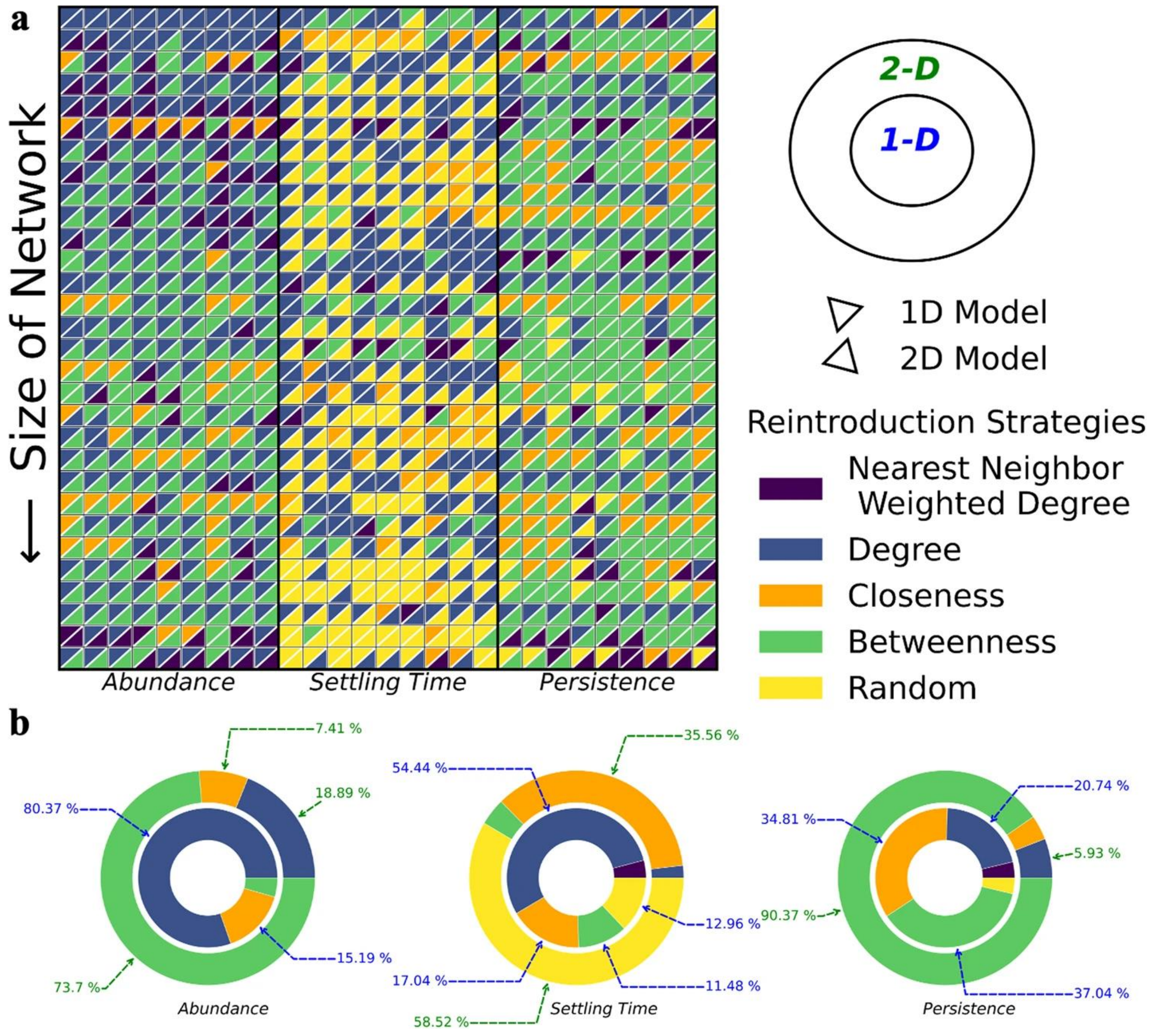
Boston Area MBTA: *Subway & Commuter*

NU: Jack Watson, Ashis Pal, Auroop Ganguly

PNNL: Sam Chatterjee

Science Implications: *Ecological Networks Recovery*





Bhatia, U., Dubey, S., Gouhier, T., and A.R. Ganguly. Network-based restoration strategies maximize ecosystem recovery. *Communications Biology* **6**, Nature Research, 1256 (2023). https://doi.org/10.1038/s42003-023-05622-3.

Broader Implications: *Outreach & Education*

9 from SDS Lab at the United Nations HQ: May 17, 2023

Climate Resilience in Nepal and India: Summer of 2023

Compound Threat Management Needs for DoD
USACE

CREATING A QUANTITATIVE APPROACH FOR COMPOUNDING THREAT ASSESSMENT

DR. BEN TRUMP, DR. MADISON SMITH, BETH ELLINPORT, DR. IGOR LINKOV*

US ARMY CORPS OF ENGINEERS

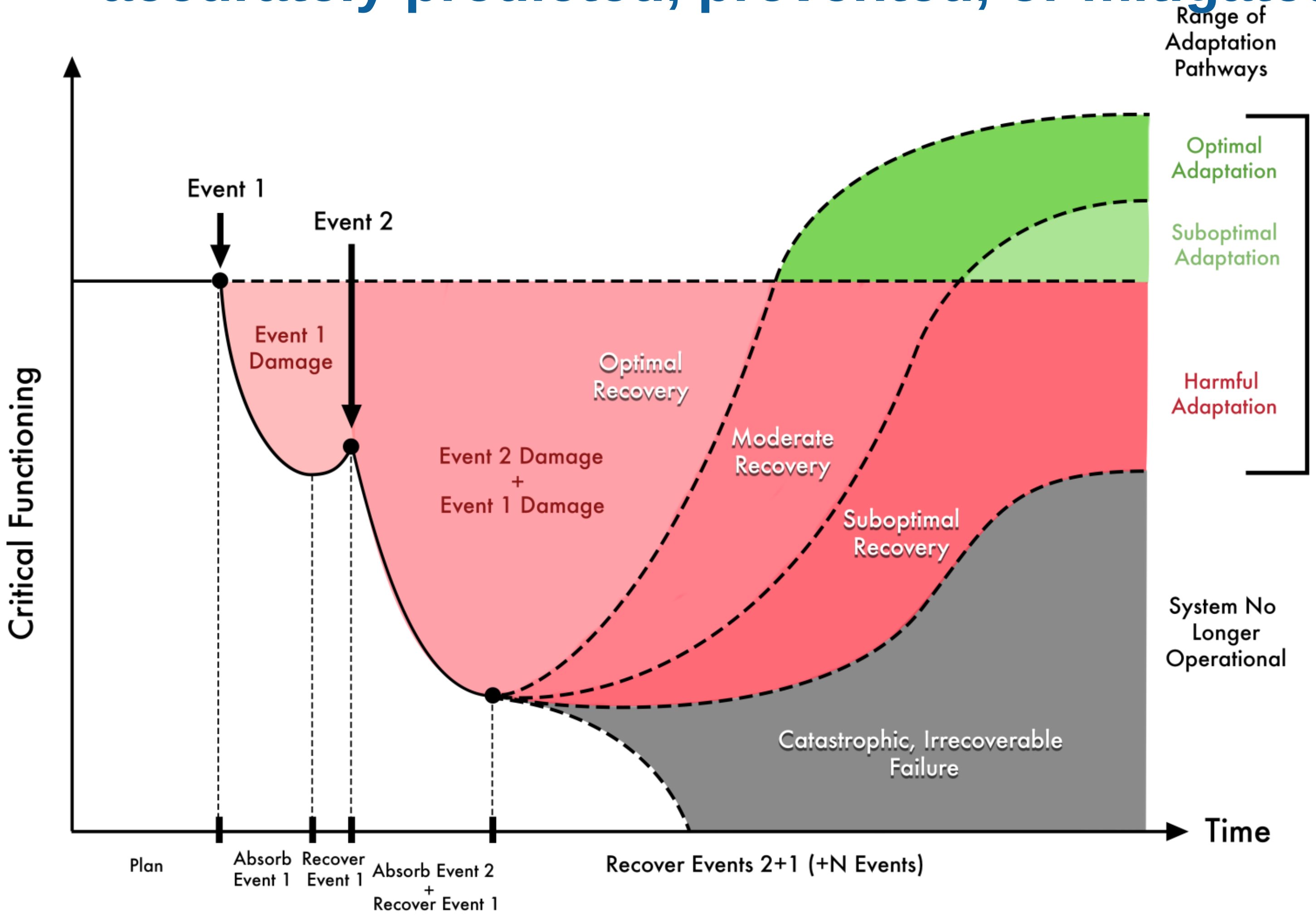
Command and Control of Compounding Threats: An Operating Definition

- Both operating and analytical definitions are surprisingly elusive.
  - ♦ David Alexander, Susan Cutter, and a few others have dipped into the field.

- "…two or more hazardous events and/or **threats that co-occur** such that they concurrently affect interdependent critical infrastructure systems, thereby presenting **multiplicative risks to the interconnected systems and population**…"
  - – Wells, E. M. et al. (2022). Modeling critical infrastructure resilience under compounding threats: A systematic literature review. *Progress in Disaster Science*, 100244.

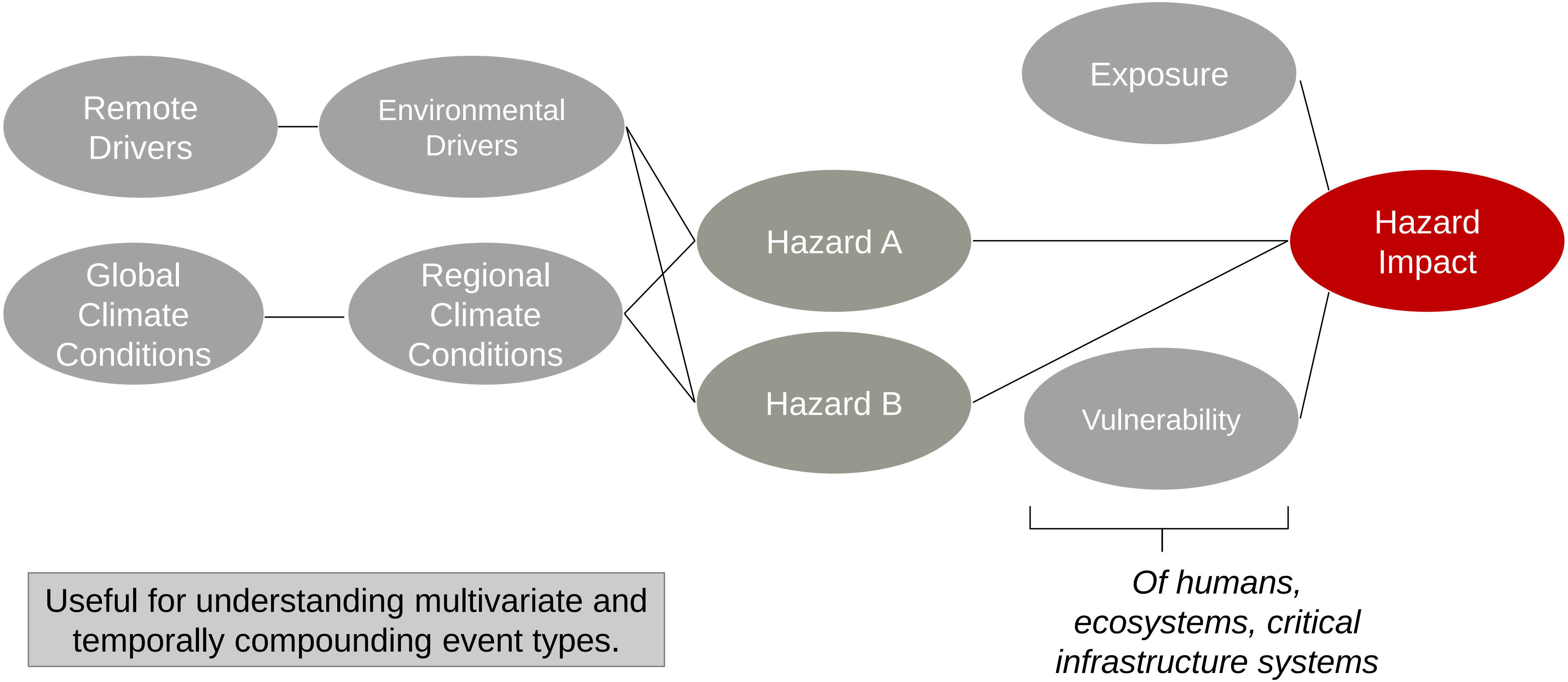
Resilience is more than a buzzword:

US Army Installations must plan for ‘right of boom’ as not all threats can be accurately predicted, prevented, or mitigated.



Publication writing in progress.

Research Question:
Are high-impact events more likely to be attributed to cascading/compounding hazards than singular hazards?



Useful for understanding multivariate and temporally compounding event types.

A Critical Note

- **Existing tools to map and analyze risk and resilience are helpful but not sufficient to address compounding threats.**
  - Limited data tracking of interaction effects.
  - Issues of time and location dependency – what the distance in time and space that the two or more threats arose?
  - Explicit mapping of recovery – what are the time and resource requirements needed for disrupted systems to recover back to full functionality?
- We focus on compounding **environmental** threats.

Data

- Main source: NCEI Storm Events Database

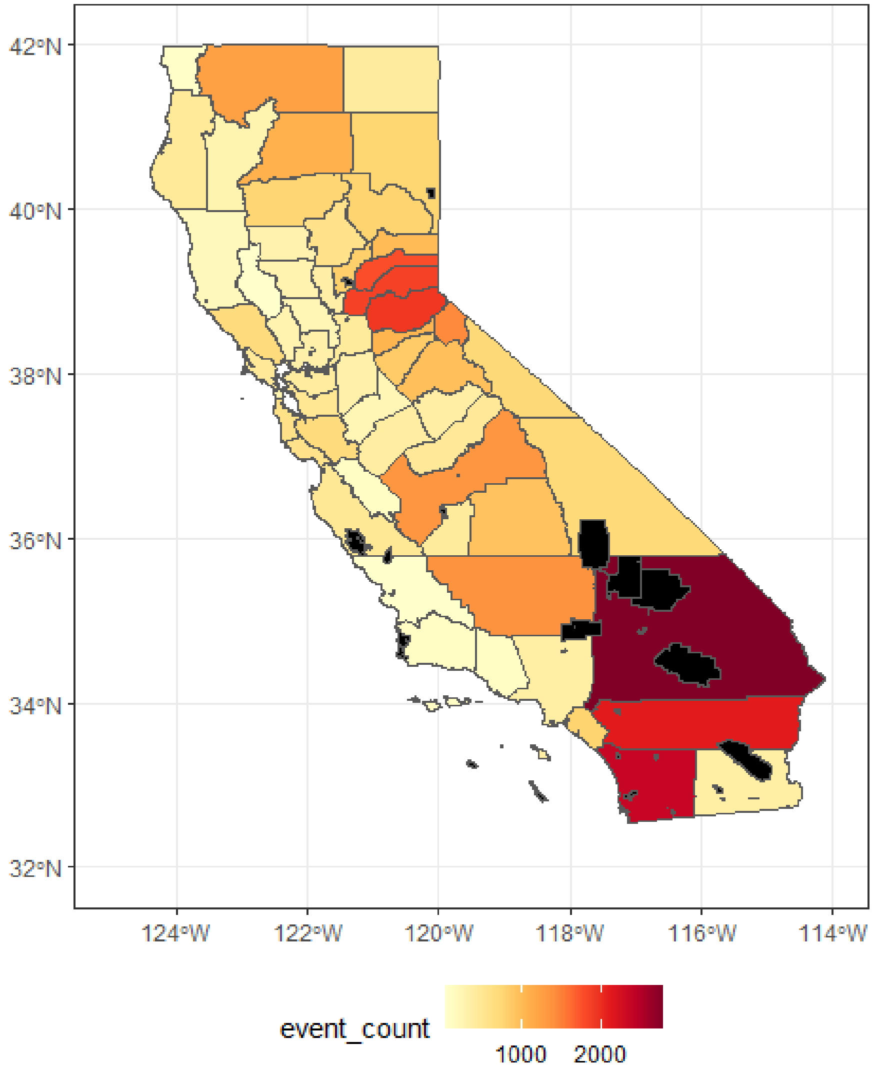
	NCEI Storm Events Data (2000 – 2022)
Data	Observed reports of environmental hazards/stressors Associated losses (USD property damages, USD agriculture losses, injuries, fatalities)
Hazard types	Avalanche, Drought, Earthquake, Flood, Fog, Hail, heat, Hurricane/Tropical Storm, Landslide, Lightning, Severe thunderstorm, Tornado, Tsunami, Volcano, Wildfire, Wind, Winter Weather
Data sources	National Centers for Environmental Information 34
Data limitations	County-level Hazard-level

URL https://www.ncdc.noaa.gov/stormevents/

- Additional sources: Meteostat (historical weather variables), GDP, Google News articles

Case Study: California

- Several important military installations in California
  - Fort Irwin (San Bernardino County)
  - Sierra Army Depot (Lassen County)
  - Edwards AFB (Kern, LA, and San Bernardino counties)
  - Camp San Luis Obispo (San Luis Obispo county)
- Wide array of damaging natural hazards (earthquakes, wildfires, floods, landslides, etc.)
- Strong spatial correlation in Southern CA for event counts → installations should be ready for their own recovery as well as surrounding areas
- Can explore where/when events occur via heatmaps



<u>Our goal is to create a compounding threat mapping and analysis platform for all counties, and all military facilities in USA</u>

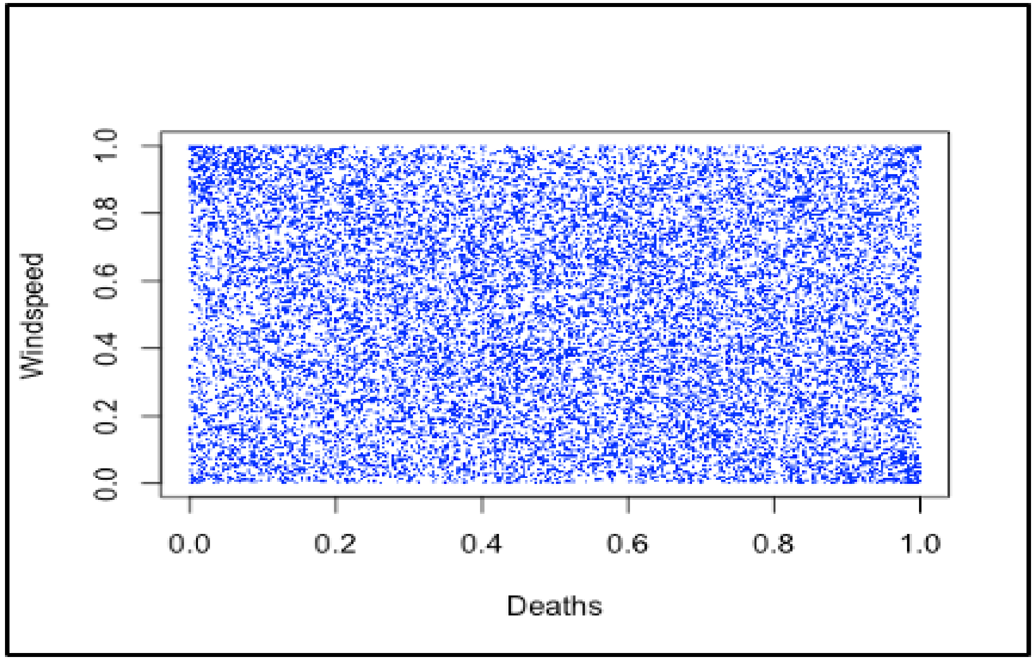
Publication writing in progress.

Copula Models: Tail Dependency:

Correlation between the extremes of two or more variables

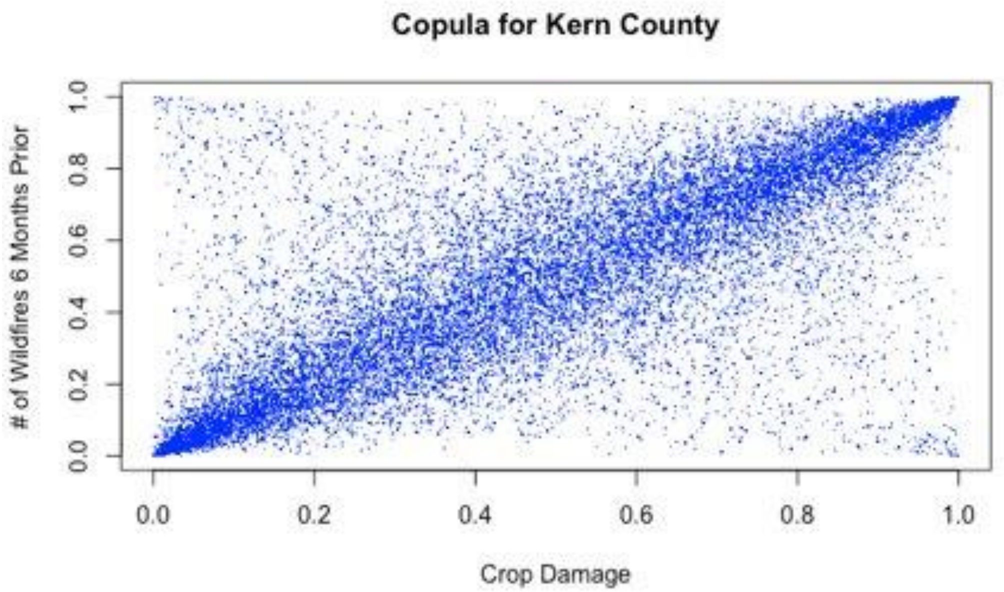
Publication writing in progress.

Observing no relationship:
Wildfire deaths dependent on windspeed



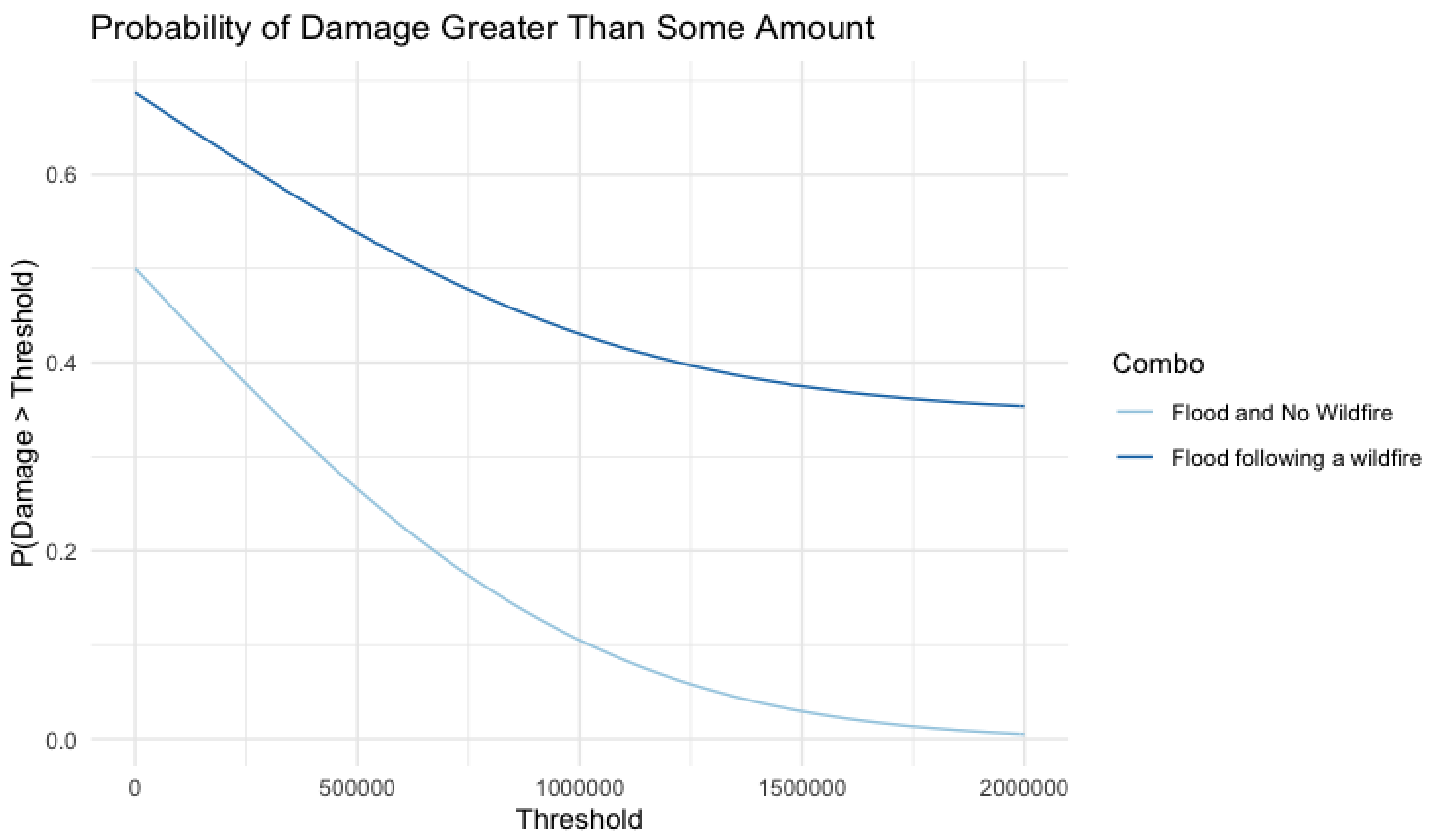
Takeaway: The number of deaths caused by wildfires shows no association with windspeed in San Bernardino County.

Observing a relationship:
Flood damage dependent on number of wildfires



Takeaway: Extreme number of wildfires prior to flooding results in more extreme flooding in Kern County

Do we see compounding effects within hazard pairs?



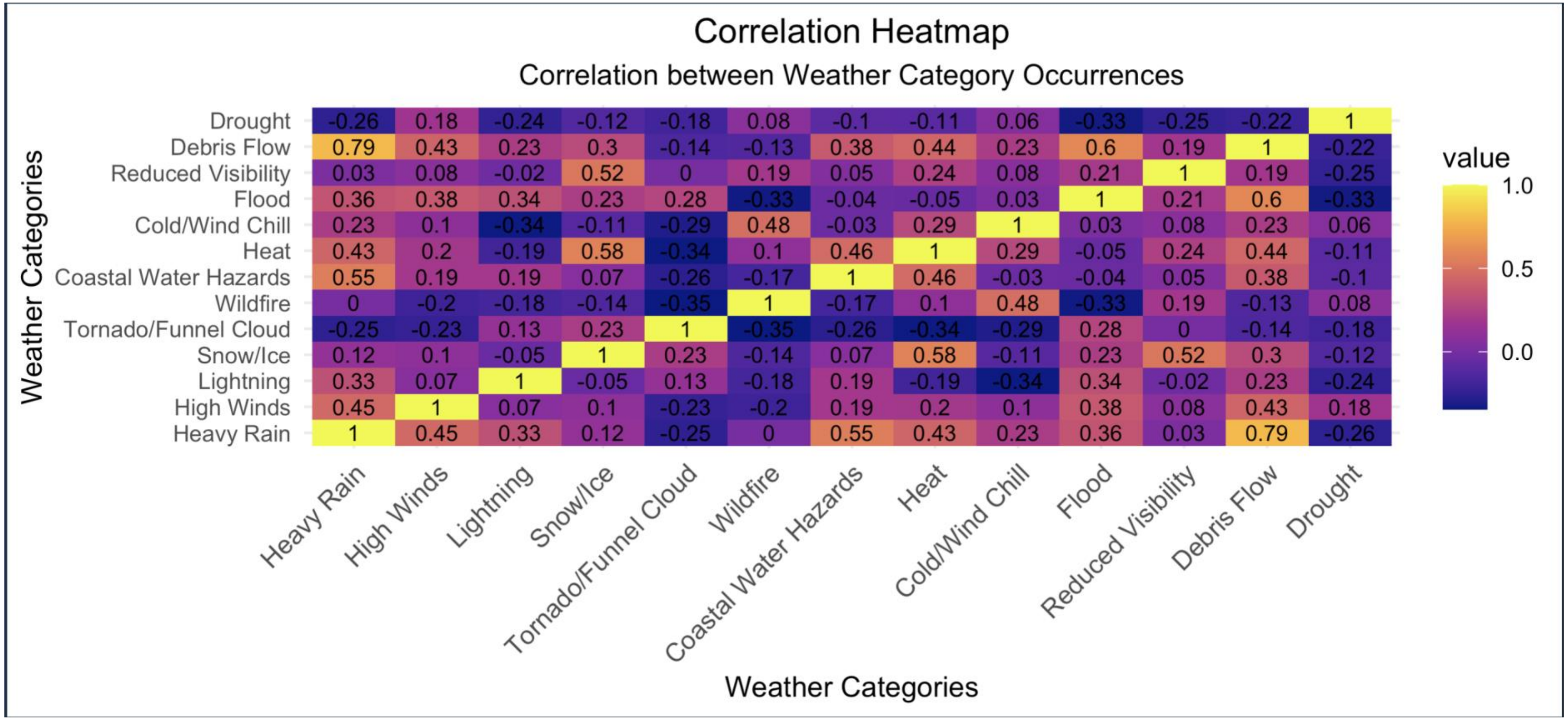
43% chance that damage is greater than $1M if Flood preceded by Wildfire

10% chance that damage is greater than $1M if Flood not preceded by Wildfire

Publication writing in progress.

Common hazard pairs

Correlations between hazard pairs on different timelines reveal common sense relationships



But this does not give us all of the pairs we might be interested in

Publication writing in progress.

Ongoing Work and Next Steps

Objectives

- Where/when do compounding events happen?
- How much worse are these events than single hazard events?
- What does this mean for Army and decision-makers?

Data

NCEI Storm Events Database (1996-2022)
- Location, time, event type, some damage info, narrative

Meteostat
- Historical weather conditions API
- Temperature, wind speed, precipitation

Socioeconomic data
- Population density, number of houses, GDP, base geographic footprint, etc.

Methods

Statistics
- Correlations between event types (spatial & temporal)
- Probability of damage thresholds
- Copulas for joint distributions of compound events

Machine Learning
- Predictive modeling for damages (classification & regression)
- NLP for event severity based on narrative

<u>Key need</u>: quantifying and mapping recovery post-disruption, given considerable data gaps.

MNS-MSD
Theoretical
Advance for Proxy
Networks
UCB / NU

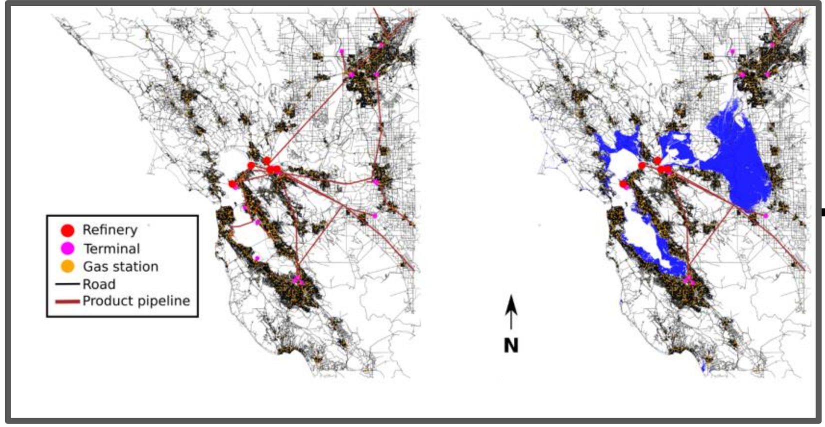
MNS-MSD THEORY AT SCALE

DR. MARTA GONZALEZ

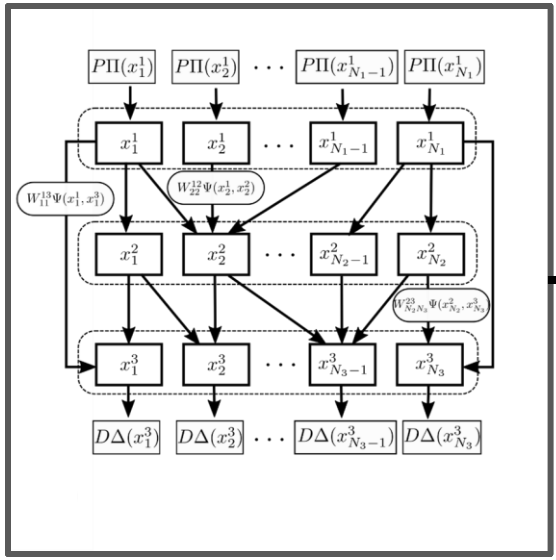
UNIVERSITY OF CALIFORNIA - BERKELEY

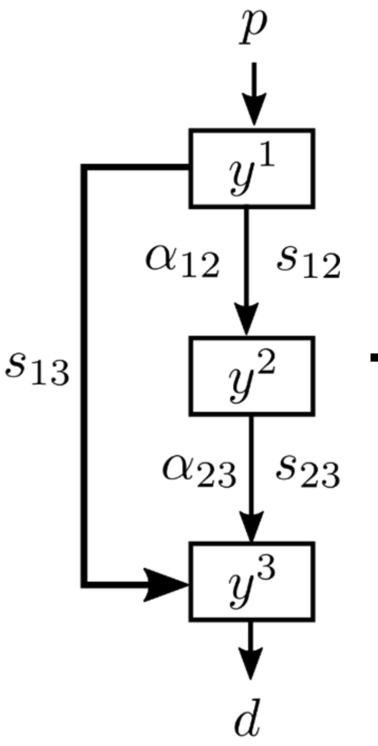
Dimension-reduction for Resilience of Resource Flow Networks

Networked spatial multiplex



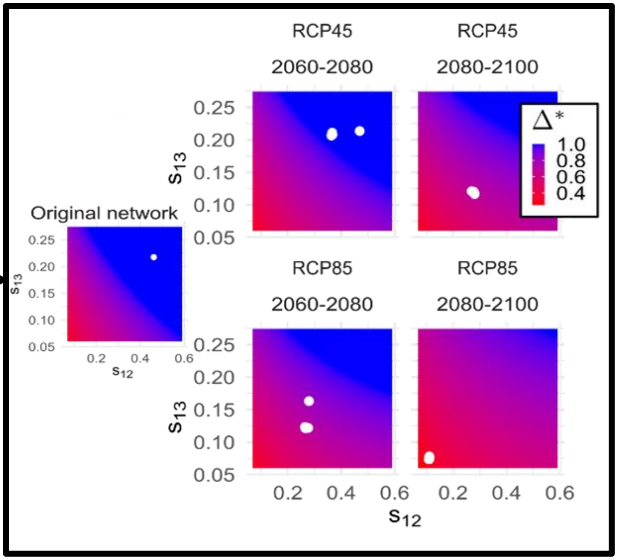
Networked flow dynamics

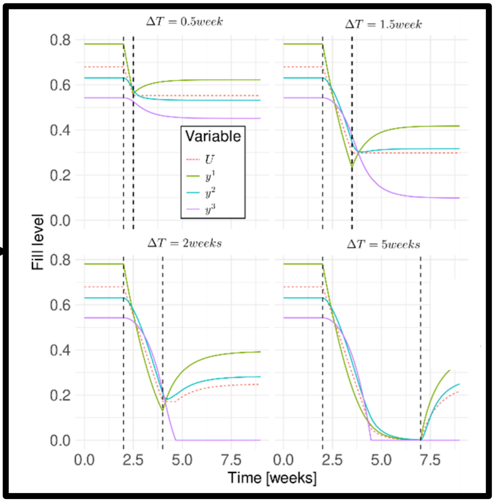




Reduced dimension layered representation

Demand stability

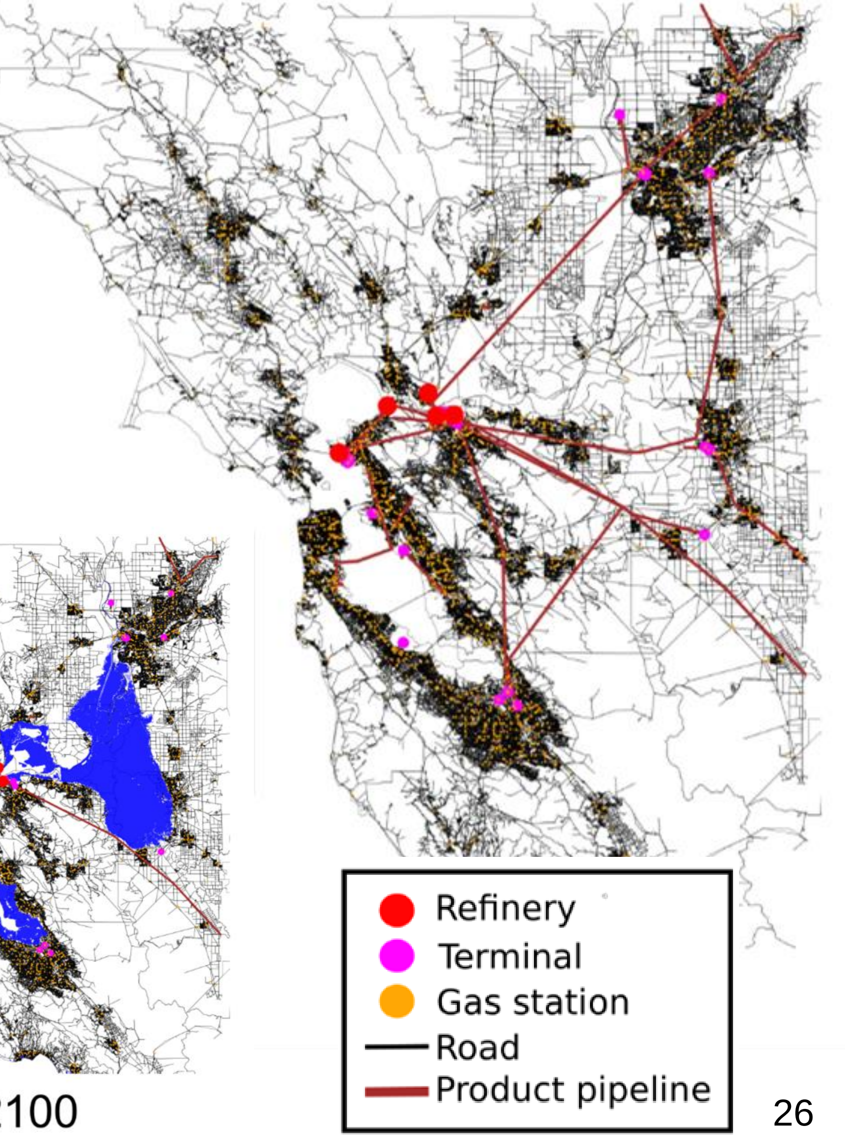




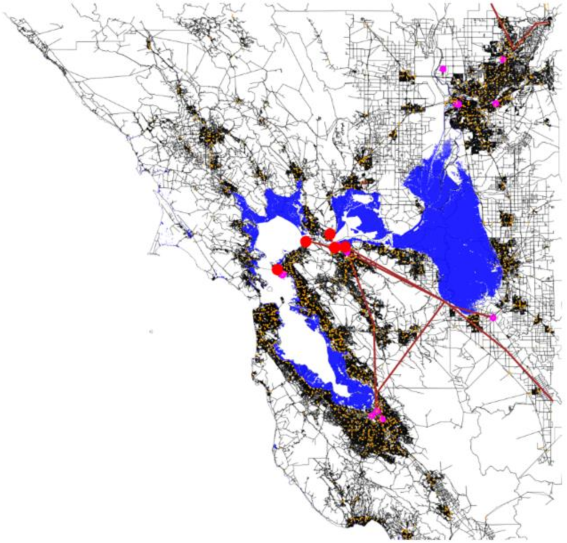
Survival time

Proxy Example – San Francisco Fuel Transportation

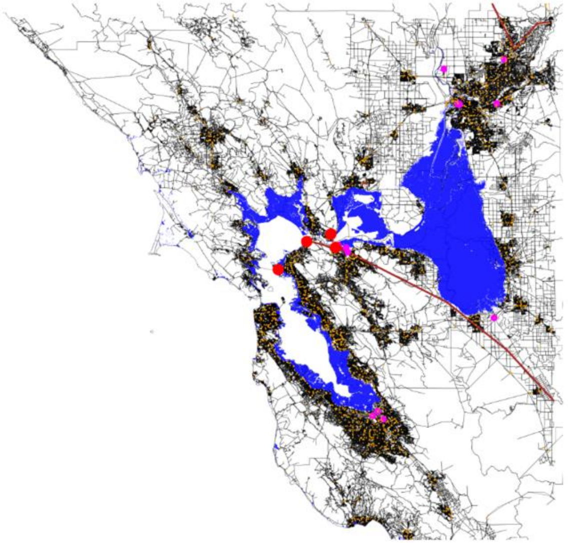
- **Spatial multiplex** capturing topology of resource transportation
- Focus on the three later stages: refineries **(production),** terminals **(storage)** and gas stations **(consumption).**
- Susceptible to coastal flooding due to **sea level rise**
- SLR scenarios are based on **IPCC climate predictions**



96 flooding scenarios:
4 circulation models ***x***
4 time horizons ***x***
2 RCPs ***x***
3 SLR percentiles



2060-2080



2080-2100

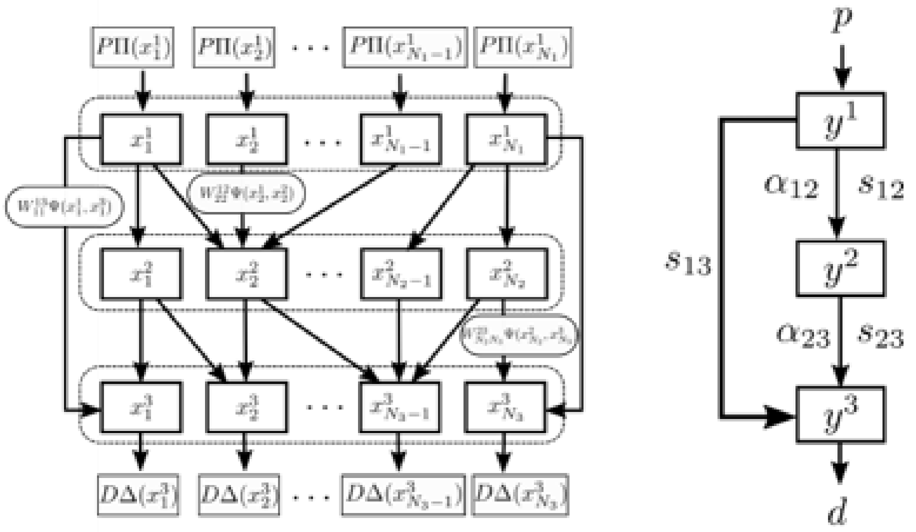
SFFTN Dynamical Representation

- Dimensional reduction captures dynamics between layers
- **3456 Eqs**. are transformed into **3 Eqs.**
- ***y^q*** corresponds to the **fill level** of a facility at layer ***q***.
- Parameters capture network topology

Refineries

Terminals

Gas stations



Normalized prod. and demand

$$p = \frac{Ref.\ Prod.}{Ref.\ Capacity},\quad d = \frac{G.S.\ Dem.}{G.S.\ Capacity}$$

Normalized average flow capacity

$$s_{qr} = \frac{Flow\ Capacity\ q \to r}{Layer\ q\ Capacity}$$

Capacity ratio

$$\alpha_{qr} = \frac{Layer\ r\ Capacity}{Layer\ q\ Capacity}$$

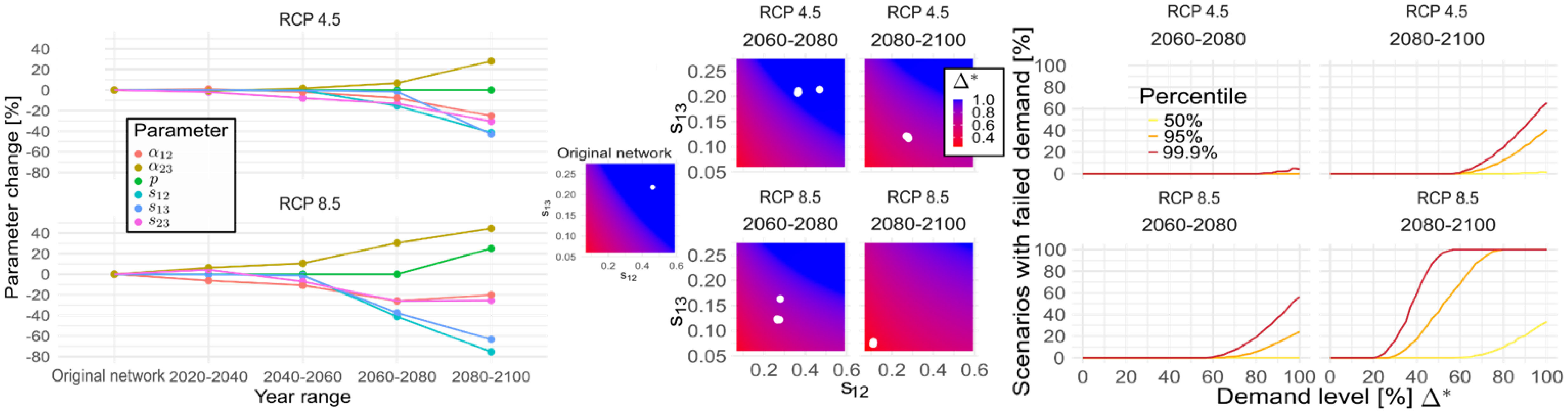
$$\dot{y}^1 = p\Pi(y^1) - s_{12}\Psi(y^1, y^2) - s_{13}\Psi(y^1, y^3)$$

$$\dot{y}^2 = \frac{s_{12}}{\alpha_{12}}\Psi(y^1, y^2) - s_{23}\Psi(y^2, y^3)$$

$$\dot{y}^3 = -d\Delta(y^3) + \frac{s_{13}}{\alpha_{12}\alpha_{23}}\Psi(y^1, y^3) + \frac{s_{23}}{\alpha_{23}}\Psi(y^2, y^3)$$

Reduced dimension representation

Demand Stability under different Sea Level Rise Scenarios



$$p = \frac{Ref.\ Prod.}{Ref.\ Capacity},\ d = \frac{G.S.\ Dem.}{G.S.\ Capacity}$$

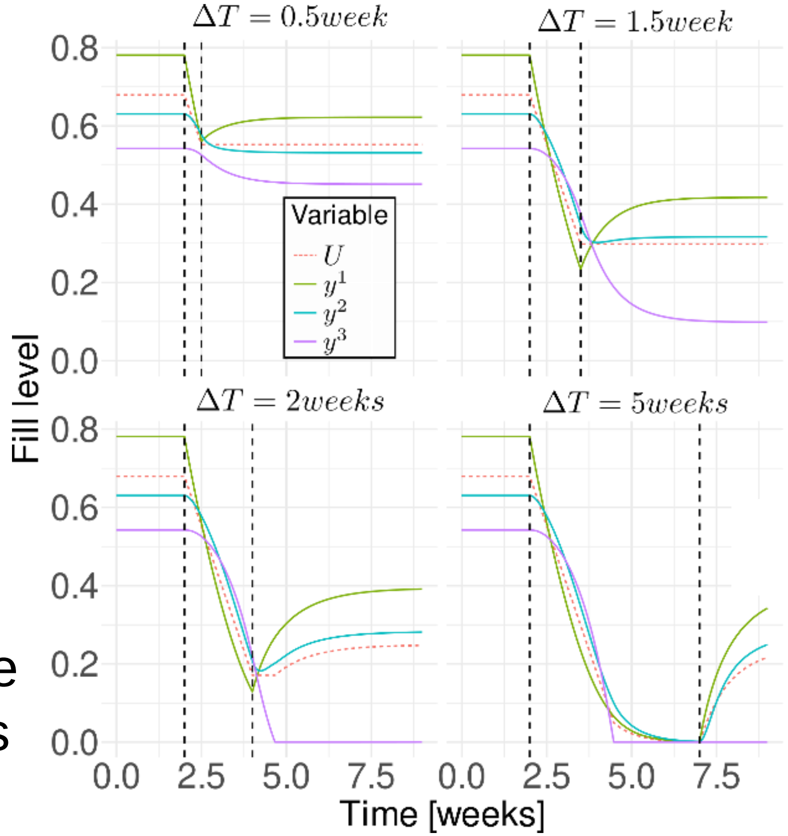
$$s_{qr} = \frac{Flow\ Capacity\ q \rightarrow r}{Layer\ q\ Capacity}$$

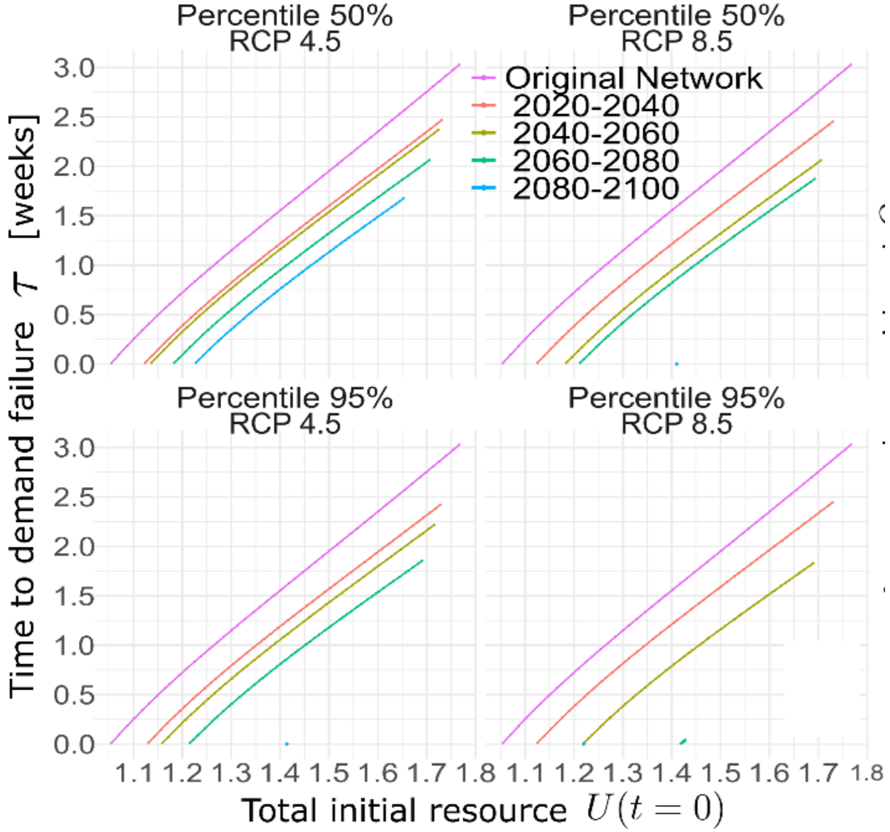
$$\alpha_{qr} = \frac{Layer\ r\ Capacity}{Layer\ q\ Capacity}$$

- **Network disruption** due to SLR is reflected in **parameter changes.**
- To maintain system functionality, higher flows are required, while also flow capacities are reduced.
- **Combining topology and stable dynamics**, the framework provides **lower bound estimates to demand failure probability**

Dynamics of production failure under IPCC Sea Level Rise Scenarios

- Compound threat intertwining a **production stoppage with the coastal flooding.**
- We analyze **survival time without production.**
- Coastal flooding hampers the survival time at the same stock level, but also reduces the maximum stable stock.





Total (normalized) stock

$$U = y^1 + \alpha_{12}(y^2 + \alpha_{23} y^3)$$

$$\alpha_{qr} = \frac{N_r C_r}{N_q C_q}$$

Summary

- Extended the dimension-reduction [Gao2016-Nature] approach from ecology to the context of flow dynamics. It characterizes system level response to failures, even with limited information.

- The approach is presented in a general fashion, where different steps involved in resource transportation can be considered.

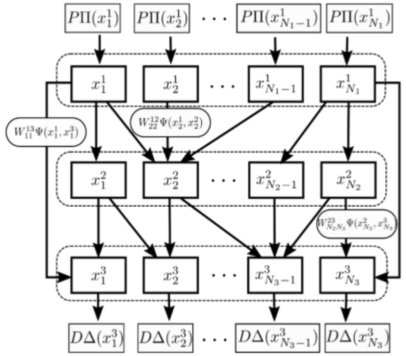
- Consumption points can be identified with DoD missions, and thus the approach is useful for assessing resilience of the systems providing support to the mission.

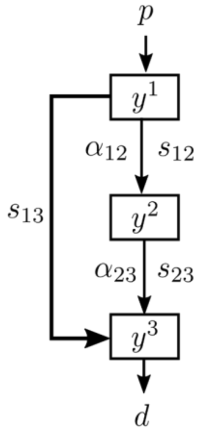
- Paper accepted in Communication Physics (2024)

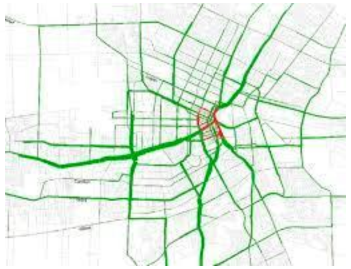
Multi-scale dynamics of Urban Mobility

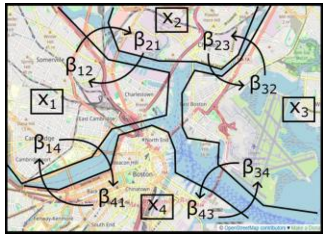
Project Extension

- Use Differential Equations to model congestion spread
- Apply dimension reduction concepts to study MSD
- Validate the dynamics using traffic data



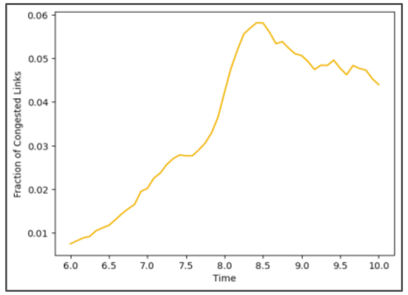




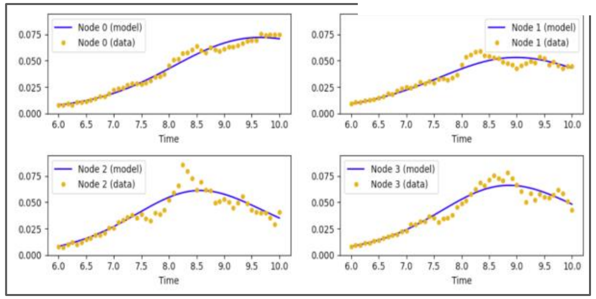


Multi-Scale Dynamics

- Congestion dynamics at the finer (smaller) scale are **informed** by the congestion dynamics of the coraser (larger) scale



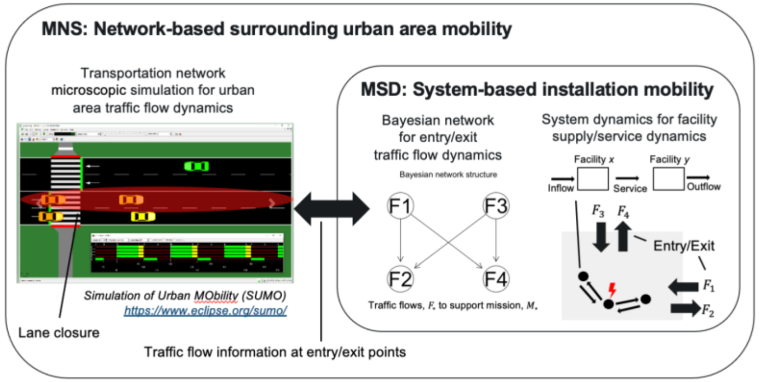
Congestion curve for SF Bay Area



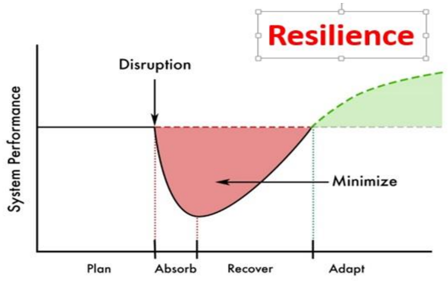
Congestion curve for 4 counties

Tasks Integration

- Analyzing congestion spread near and around a facility, and on a city level
- Different modelling approach, using contagion (SIR) models



$$\mathbb{R} = \frac{1}{T}\int_{t=0}^{t=T} \mathbb{P}(\mathbb{X}(t))dt - \mathbb{P}(\mathbb{X}(0))$$



After Linkov and Trump, 2019

Congestion dynamics at the finer scales are informed from that at the coarser scale by regularization, based on Dimensionality Reduction

Trips + Road Network Data

Road Links, SF Bay

$$\dot{c_{\text{eff}}} = \sum_i w_i \dot{c_i}$$

The effective dynamics become:

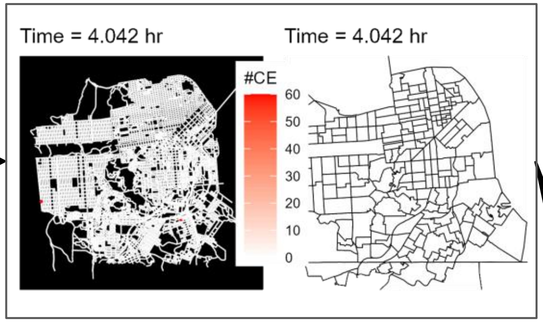
$$\dot{c_{\text{eff}}} = (1 - c_{\text{eff}} - r_{\text{eff}})\beta_{\text{eff}} c_{\text{eff}} - \mu_{\text{eff}} c_{\text{eff}}$$

Utilizing dimensionality reduction techniques, we derive the effective parameters to be:

$$\beta_{\text{eff}} = \sum_{i,j} w_i \beta_{ji}$$

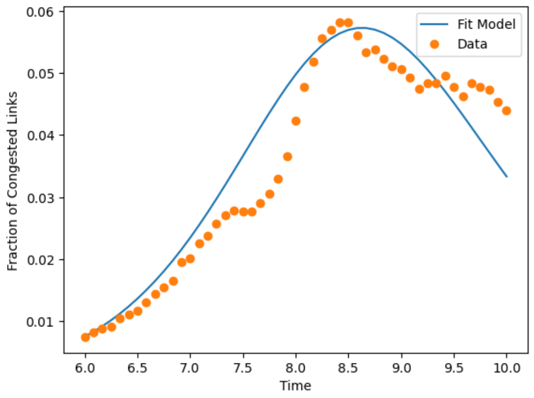
$$\mu_{\text{eff}} = \sum_i w_i \mu_i$$

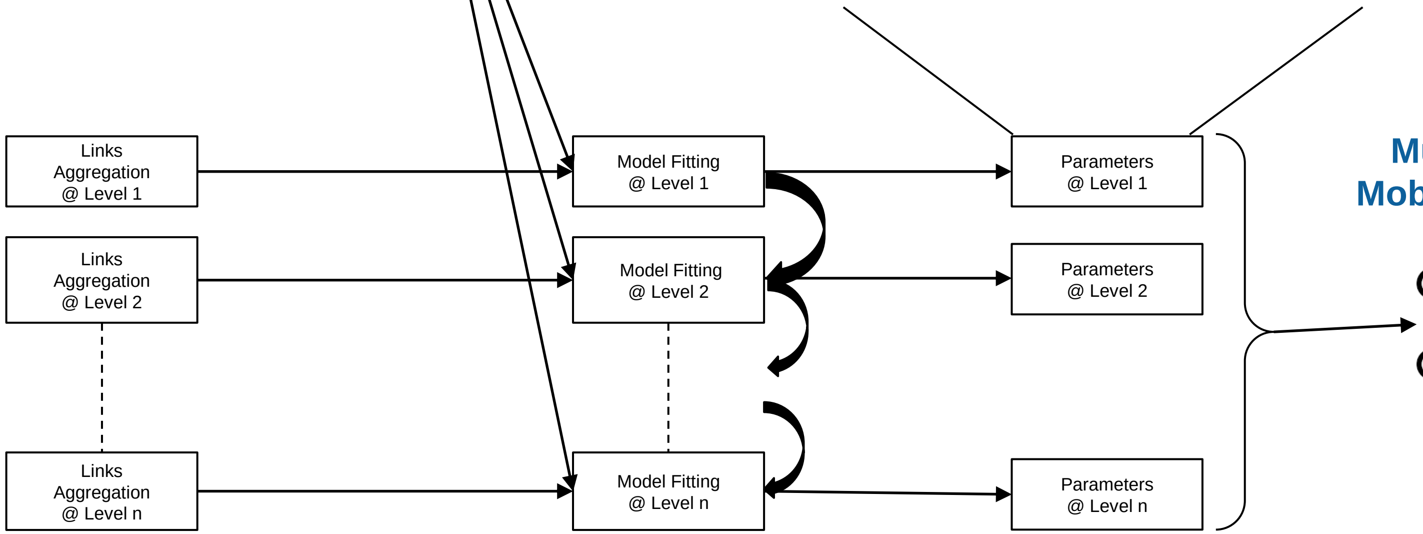
Congestion Simulation



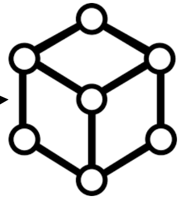
Level 1: Full-Region, Macro Scale
Level n: Smaller regions, micro Scale

S.I.R. Model Fitting





Multi-Scale Mobility Model



Next Steps

- Calibration of multi scale mobility dynamics to find coupling network
- Maximize resilience: how the knowledge of coupling allows us to protect areas of interest?
- Test the limits of dimension reduction: how effective parameters can describe microscopic system?

MNS-MSD
Instantiation for DoD
Installations
PNNL / NU / NRL

MNS-MSD INSTANTIATION FOR DOD INSTALLATIONS

DR. SAM CHATTERJEE

PACIFIC NORTHWEST NATIONAL LAB

Presenter: Sam Chatterjee, NICE Co-PI

Chief Data Scientist and Team Lead
Data Sciences and Machine Intelligence
Pacific Northwest National Laboratory

Affiliate Professor
Civil and Environmental Engineering
Northeastern University

External Research Fellow
Center for Risk and Economic Analysis
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Mahantesh Halappanavar

Robert Brigantic

Salman Shuvo

Arnab Bhattacharya

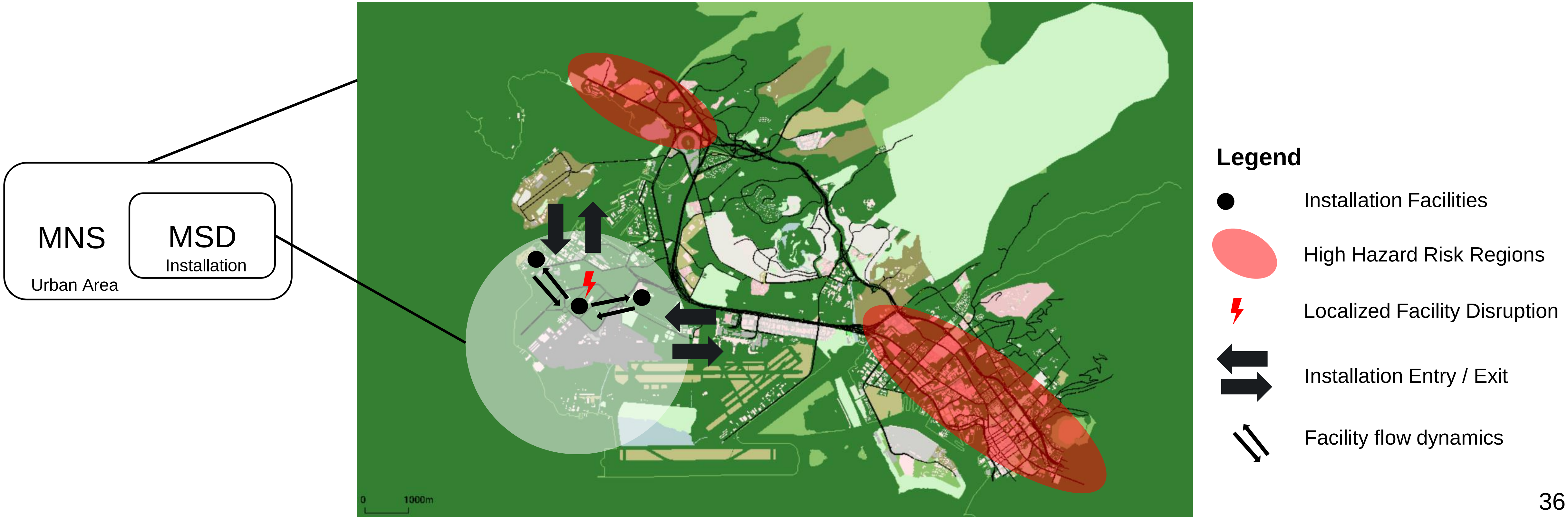
Omer Subasi

Md Taufique Hussain

Narmadha M Mohankumar

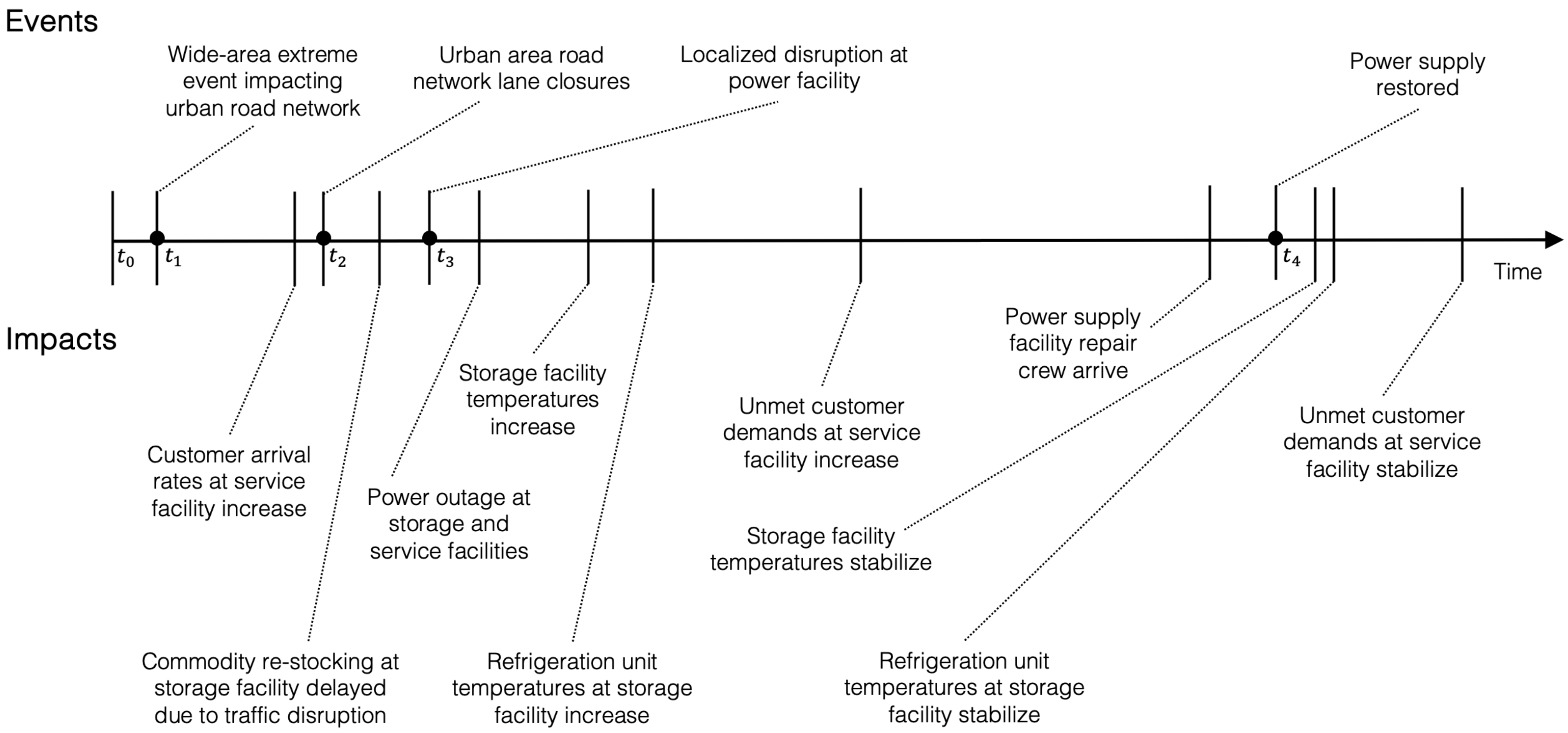
Mobility Within and Around an Installation

- Mobility function supports multiple installation missions
- Use urban area road network for installation mobility simulation with trucks and passenger cars
- Incorporate wide area hazard effects in conjunction with localized facility disruption
- Assess mobility impacts via network and entry/exit delays, and storage/service/power facility disruptions



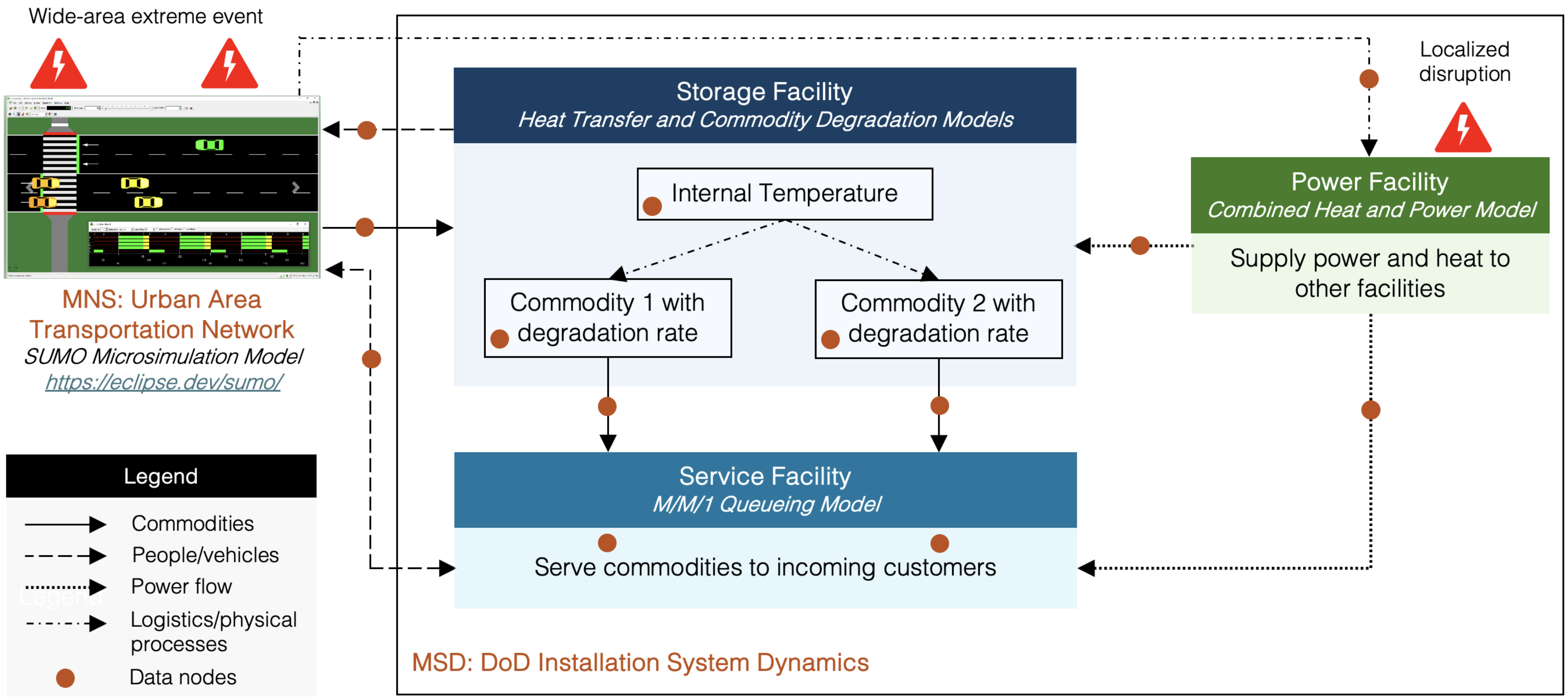
Scenario Definition

- Notional scenario timeline with context for proof-of-concept modeling and simulation workflow



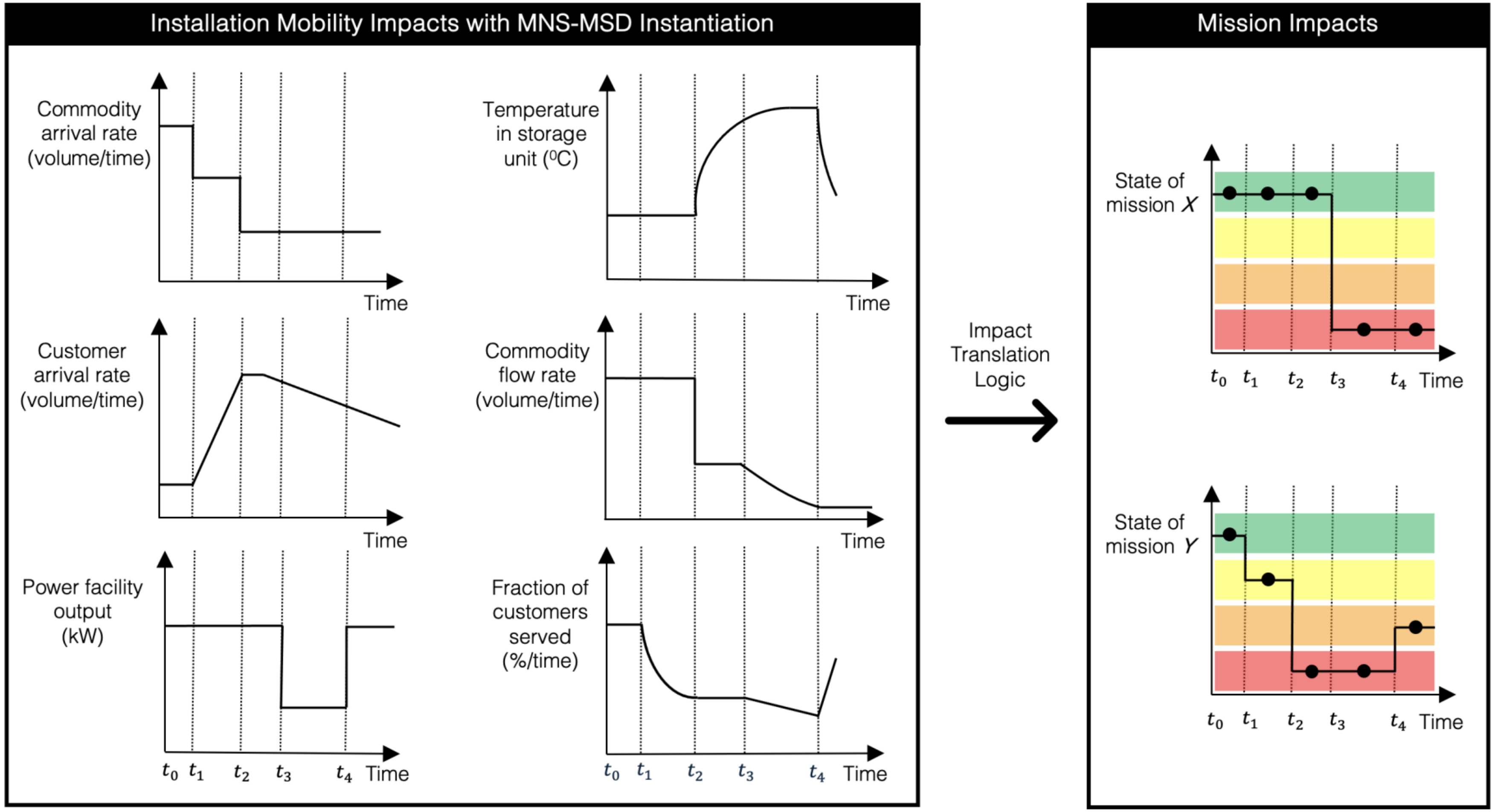
Modeling and Simulation Workflow

- Leverage **network-** and **system-based approaches** based on data/information availability

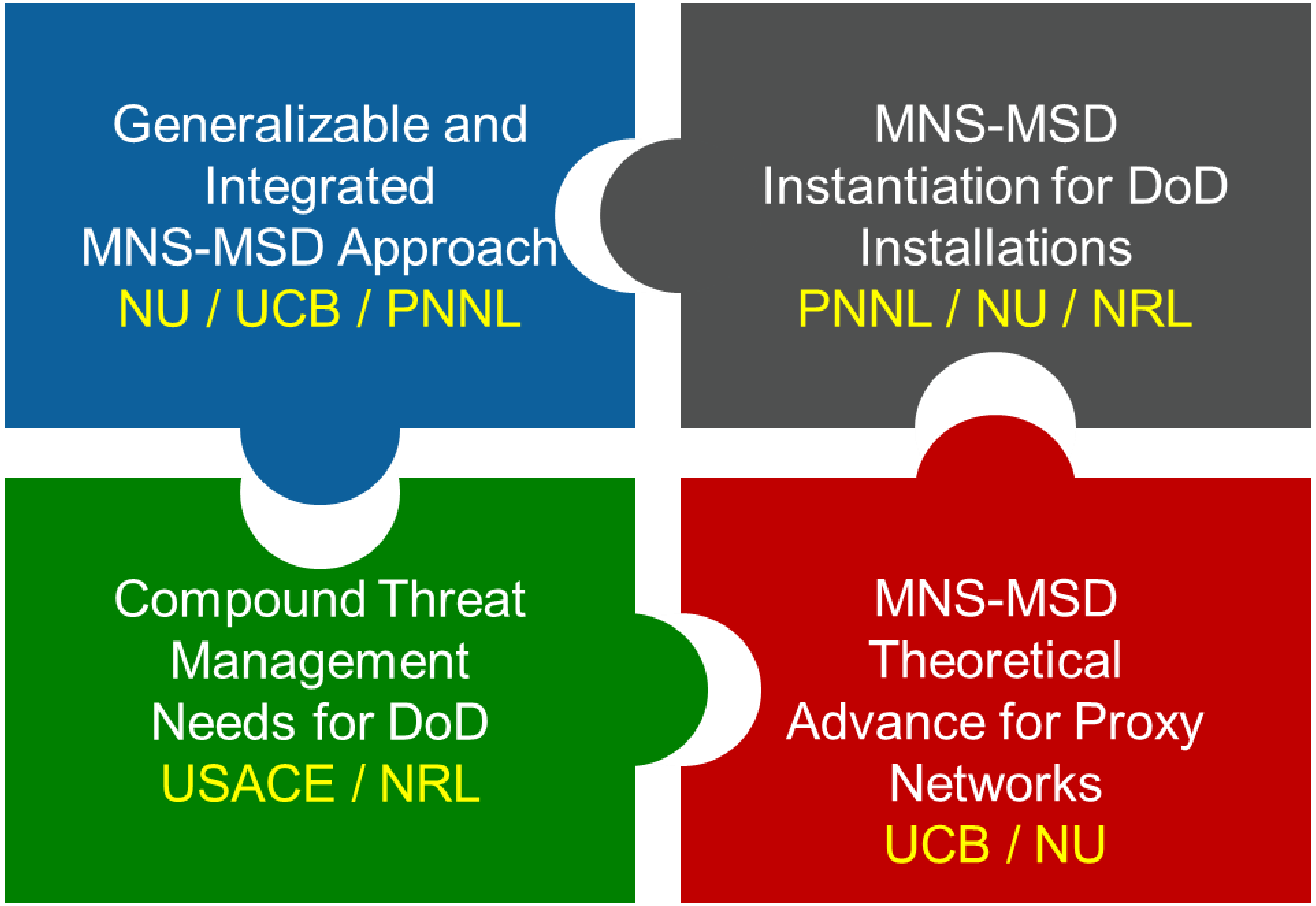


Impact Assessment

- Further integrate proof-of-concept MNS and MSD modeling and simulation parameters
- Develop installation resilience metrics based on mobility impacts
- Translate mobility impacts to mission impacts via installation resilience metrics



Integrated NICE Vision



Integrated NICE Vision

Where we came from?

What is next?

Networked Infrastructures under Compound Extremes (NICE): State of the Project

Presenters (introduced by Robyn Anderson):

Auroop Ganguly – Northeastern University, Boston, MA

Sam Chatterjee – Pacific Northwest National Labs, Richland, WA

Marta Gonzalez – University of California, Berkeley, CA

Ben Trump – US Army Corps of Engineers, Raleigh, NC

Satish Chikkagoudar – Naval Research Lab, Washington, DC

SERDP

DOD ▪ EPA ▪ DOE

Moderated Q&A: Robyn Anderson, NICE Project Manager

Thank You!

This concludes our “State of the NICE Project” Review

Questions?