



COLLEGE OF **ENGINEERING**

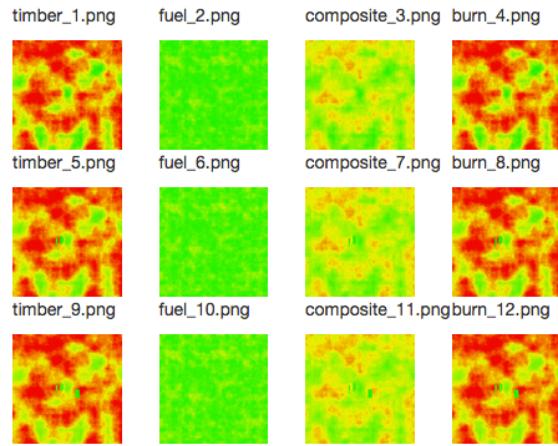
# Facilitating Testing and Debugging of Markov Decision Processes with Interactive Visualization

Sean McGregor, Hailey Buckingham,  
Thomas G. Dietterich, Rachel Houtman,  
Claire Montgomery, and Ronald Metoyer

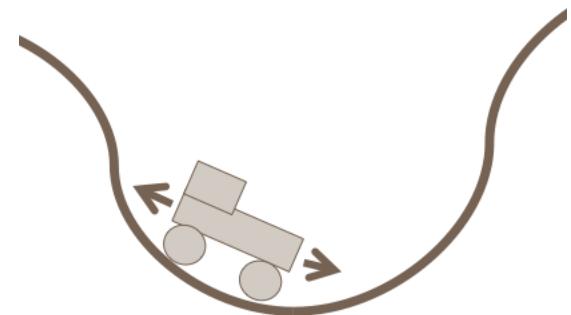


# What are Markov Decision Processes (MDPs)?

## Sequential Decision Making Under Uncertainty



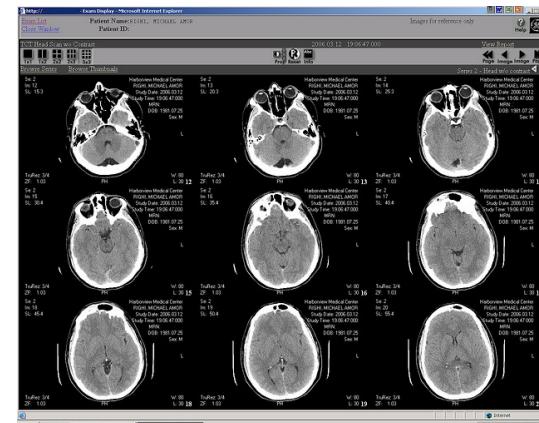
Wildfire Suppression

Autonomous Helicopter<sup>0</sup>

Mountain Car



1

Logistics<sup>1</sup>Medical Diagnosis<sup>2</sup>

# Outline

1. Markov Decision Processes (MDPs)
  - | Basic Introduction
  - | Testing
2. MDPvis
  - | Design
  - | Testing Examples
  - | MDPvis Use Case Study
3. Concluding

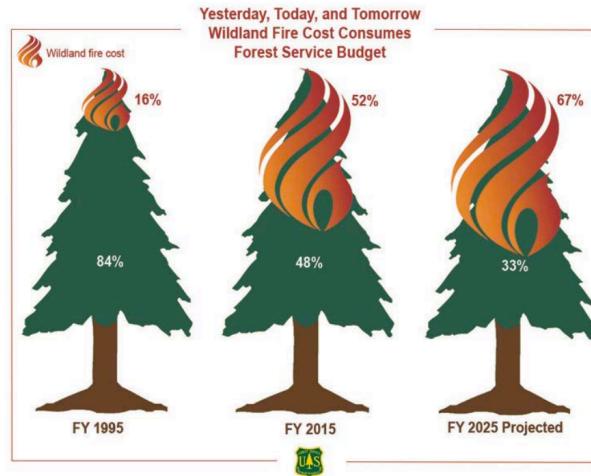
Notation,  $M = \langle S, A, P, R, \gamma, P_0 \rangle$

$S$	All States of the World
$P_0$	Starting State Distribution
$A$	Available Actions
$R(s, a)$	Rewards
$\gamma \in (0, 1)$	Discount
$P$	State Transition Probabilities (Simulators)
$\pi(s) \rightarrow a$	Policy

Puterman, M. (1994). Markov Decision Processes: Discrete Stochastic Dynamic Programming (1st ed.). Wiley-Interscience.

## Motivating Domain of Wildfire

Starting in 1935, the United States adopted the **"10 AM policy"**



We need a more nuanced approach.



Houtman, R. M., Montgomery, C. A., Gagnon, A. R., Calkin, D. E., Dietterich, T. G., McGregor, S., & Crowley, M. (2013). Allowing a Wildfire to Burn: Estimating the Effect on Future Fire Suppression Costs. *International Journal of Wildland Fire*, 22(7), 871–882.

<http://www.fs.fed.us/sites/default/files/2015-Fire-Budget-Report.pdf>

## Modeling Wildfire

$S$	All the possible configurations of trees / ignitions
$P_0$	A snapshot of the current forest, with a random fire
$A$	Suppress or let-burn
$R(s, a)$	Timber harvest, Suppression Expense
$\gamma \in (0, 1)$	0.96 (Forest Service Standard)
$P$	Several Simulators
$\pi(s) \rightarrow a$	Suppress all fires

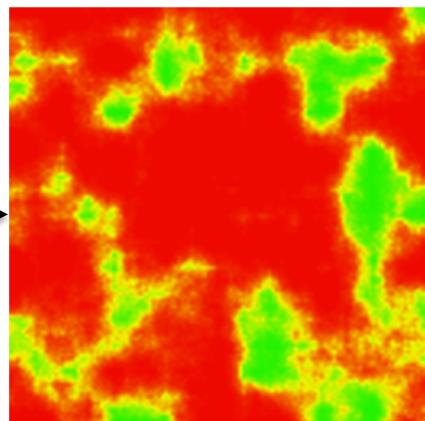
Represents a challenging and more general class of MDPs

- High Dimensional States
- Large State Space
- Integrates Several Simulators

**Simulators****Optimizer****Rewards****Policy** $P_0 \bullet$

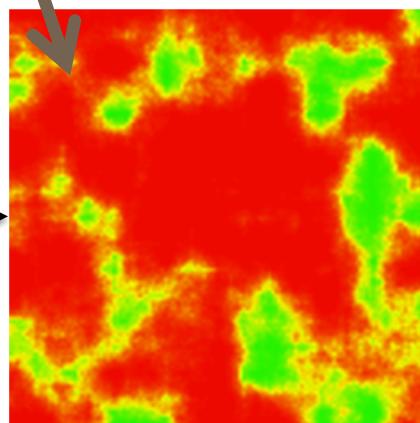
Start with Today's Landscape

$P_0$  

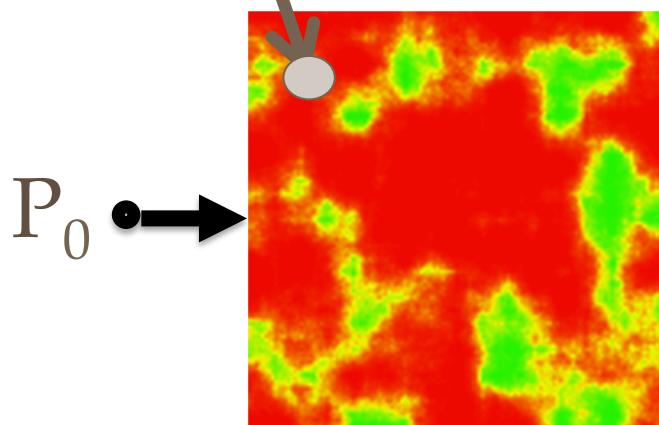


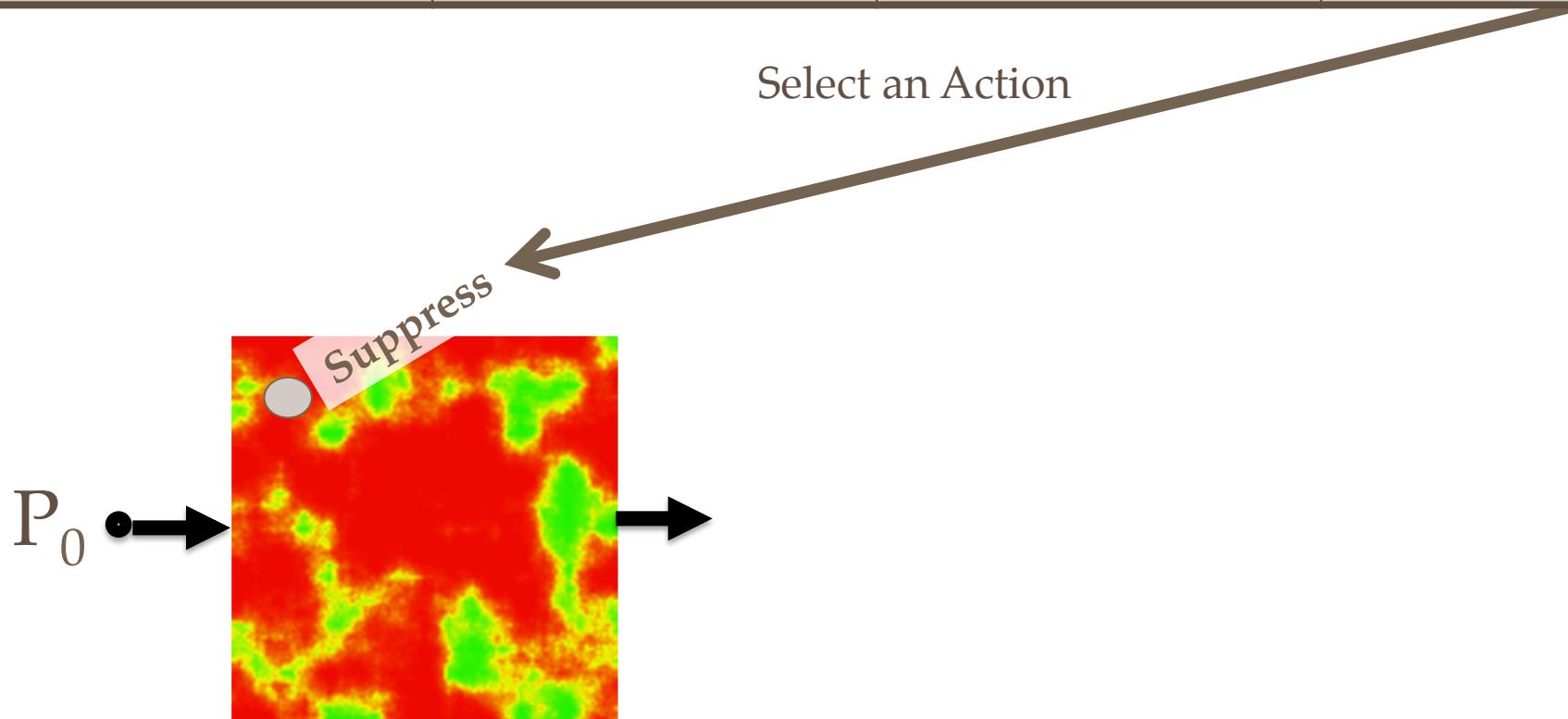
Generate an ignition and weather

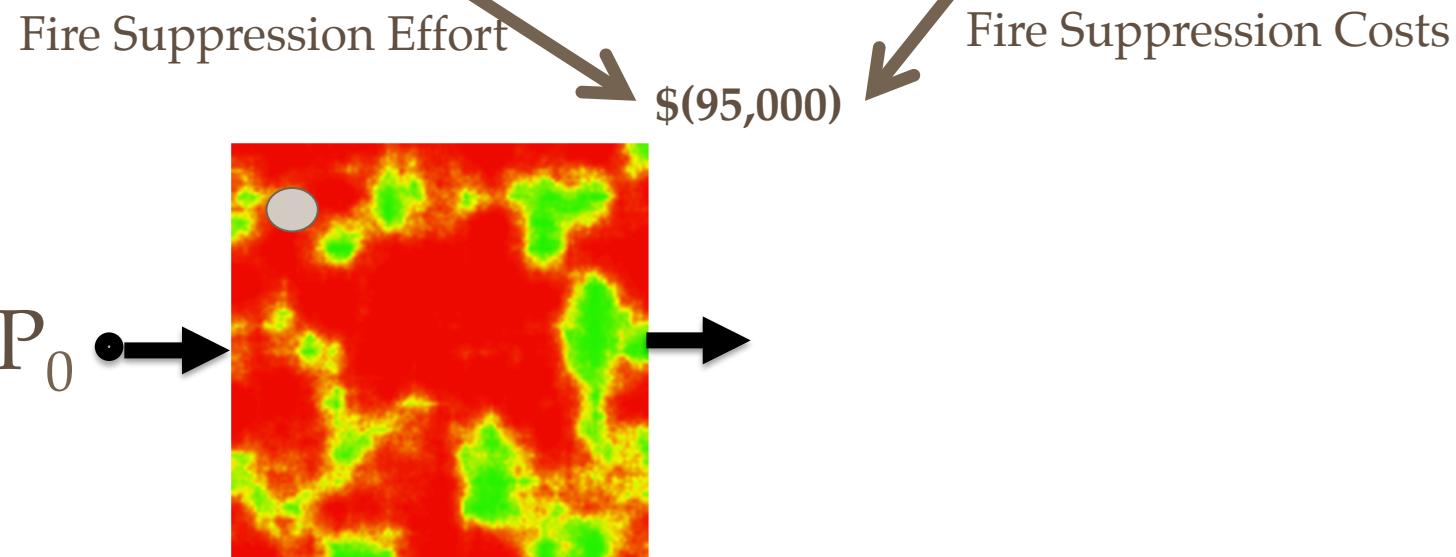
$P_0$  • →



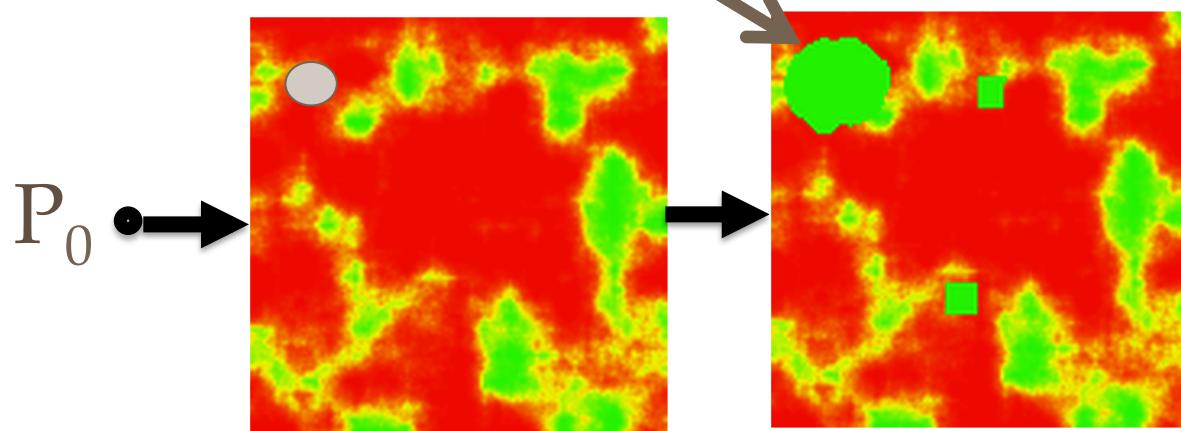
Generate an ignition and weather

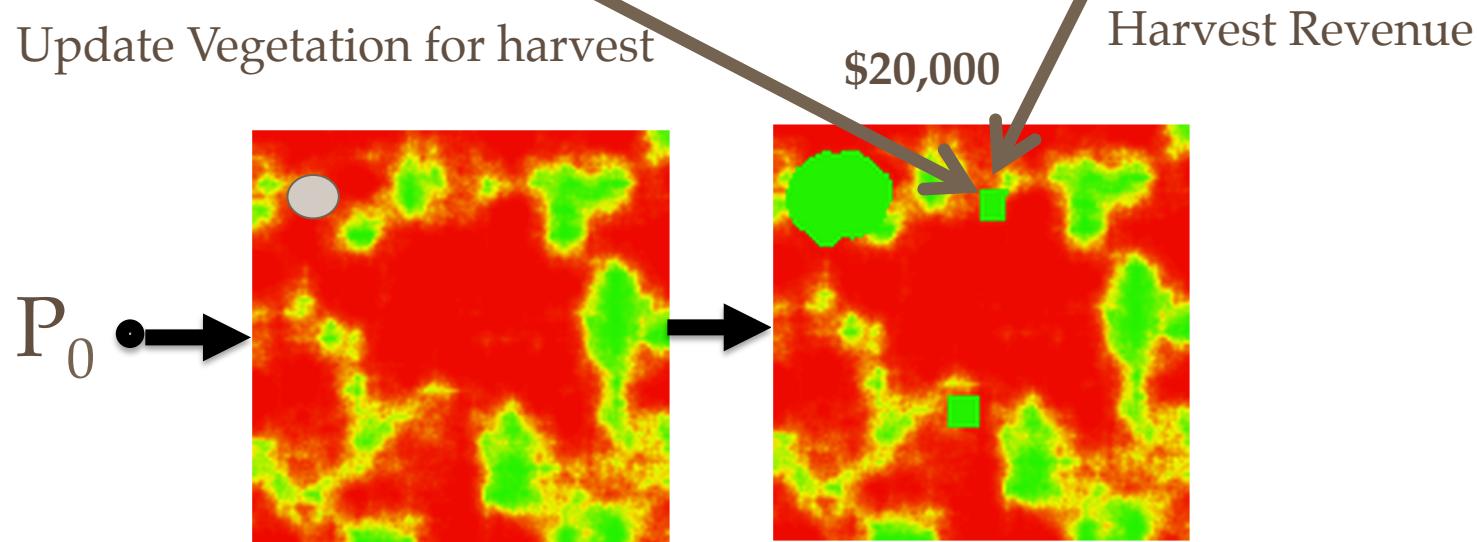




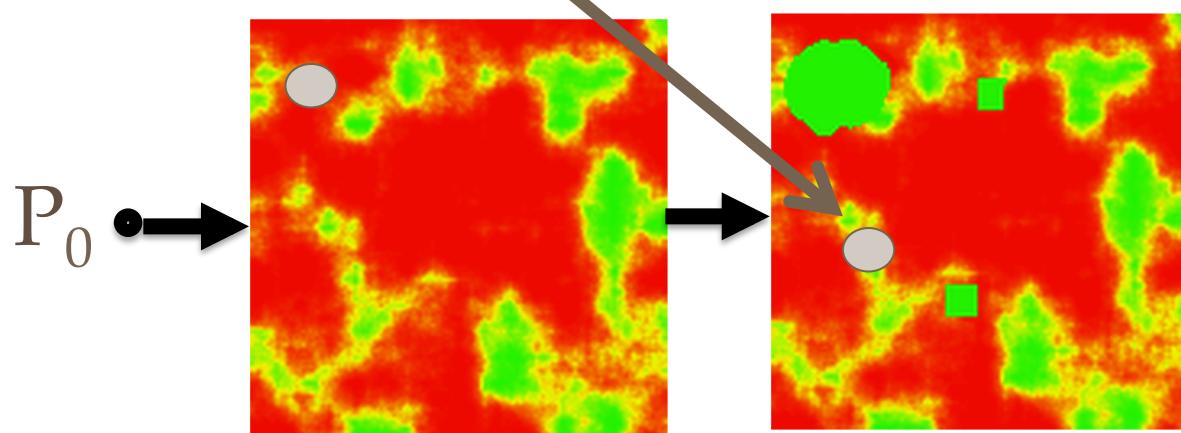
**Simulators****Optimizer****Rewards****Policy**

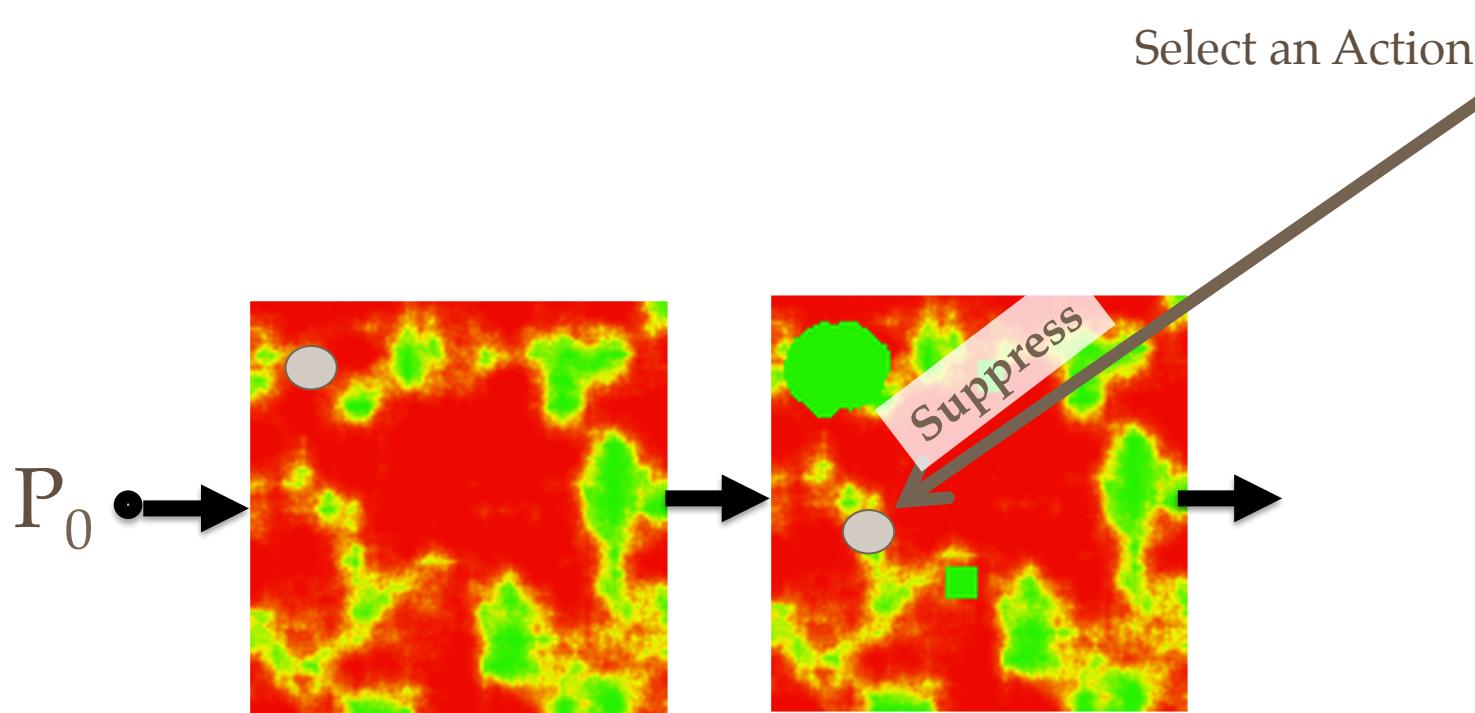
Update Vegetation for Wildfire



**Simulators****Optimizer****Rewards****Policy**

Generate an ignition and weather



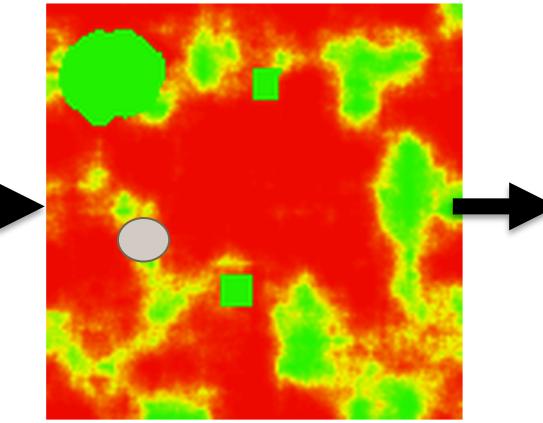
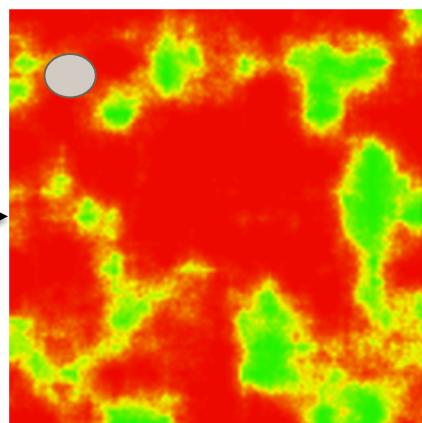


**Simulators****Optimizer****Rewards****Policy**

Fire Suppression Effort

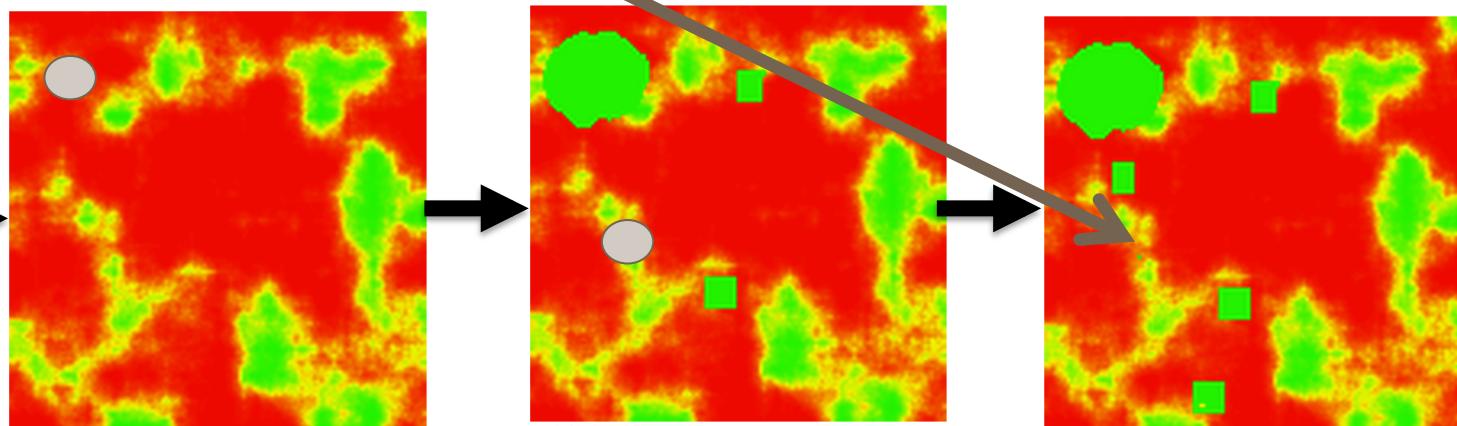
Fire Suppression Costs

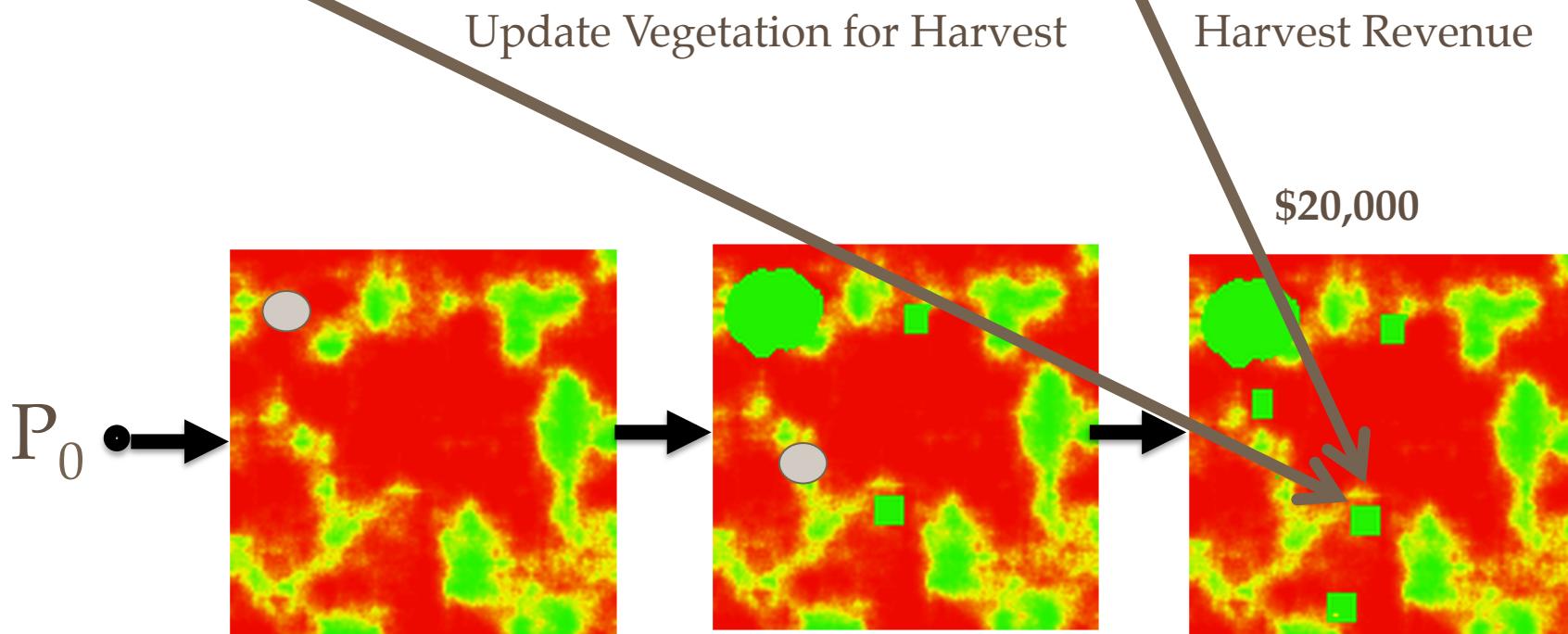
\$-(15,000)

 $P_0$  • →

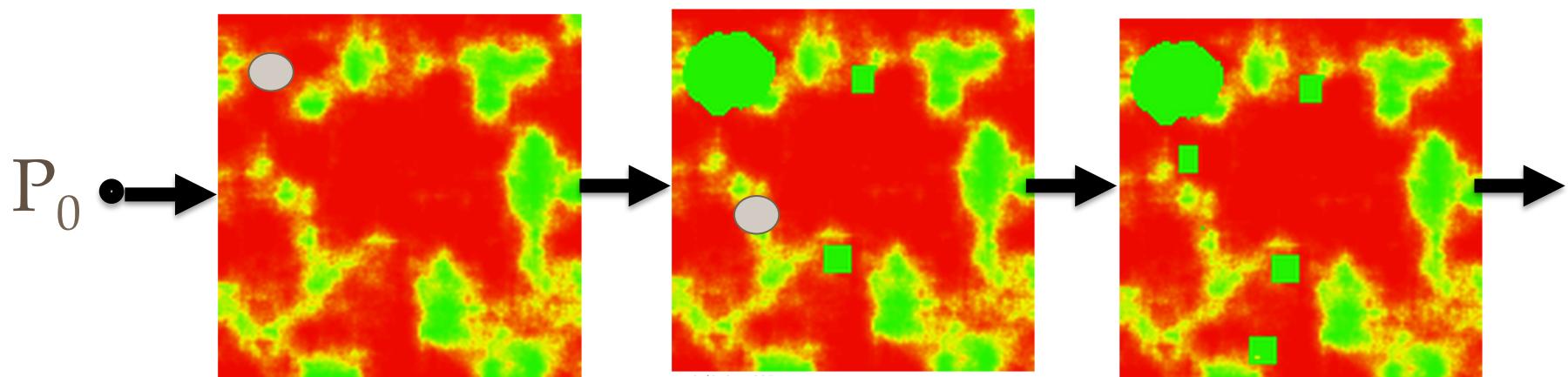
Update Vegetation for Wildfire

$P_0$  • →

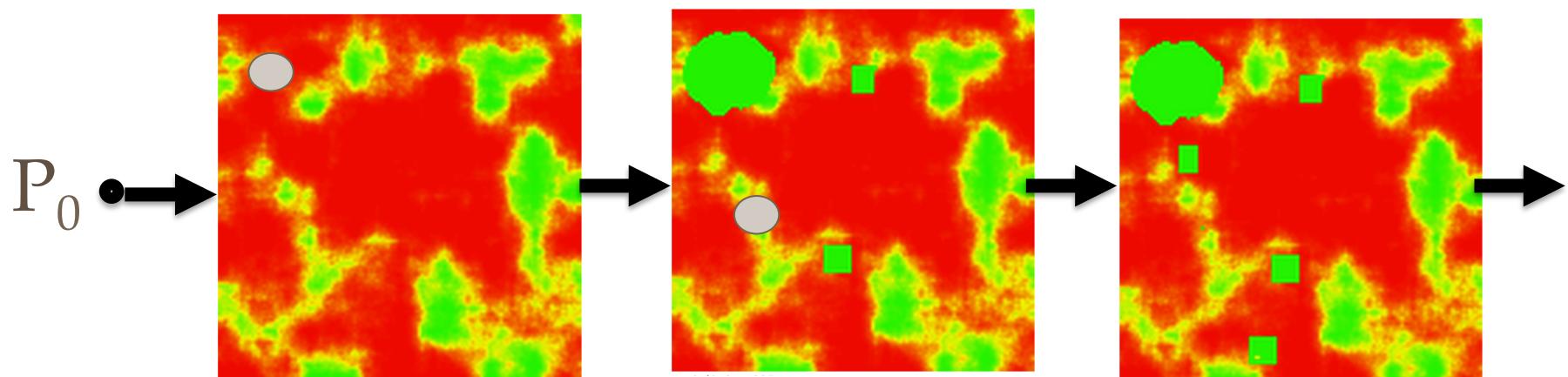


**Simulators****Optimizer****Rewards****Policy**

(Continue Until Reaching the Horizon)

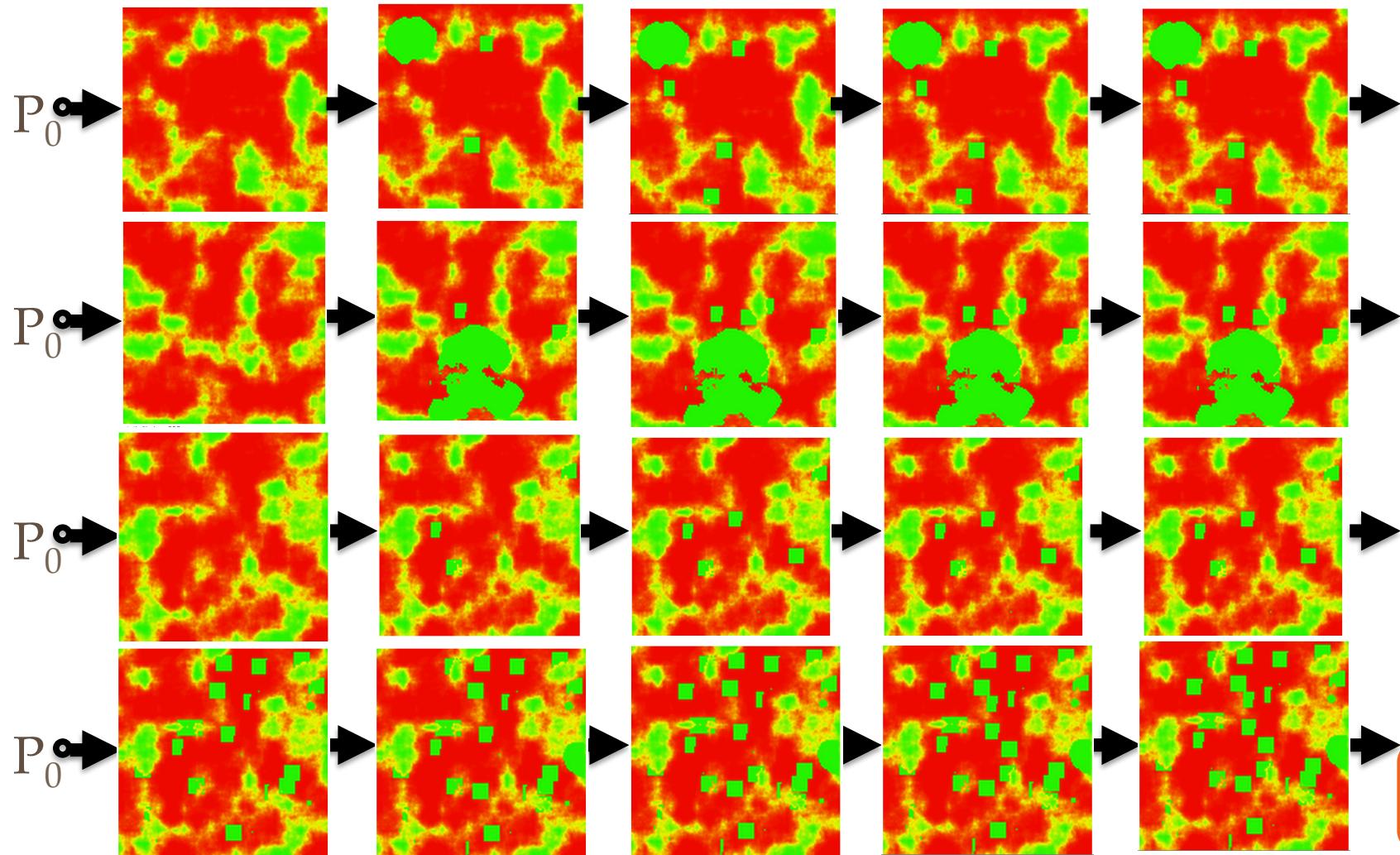


## A High Dimensional Probabilistic Time Series

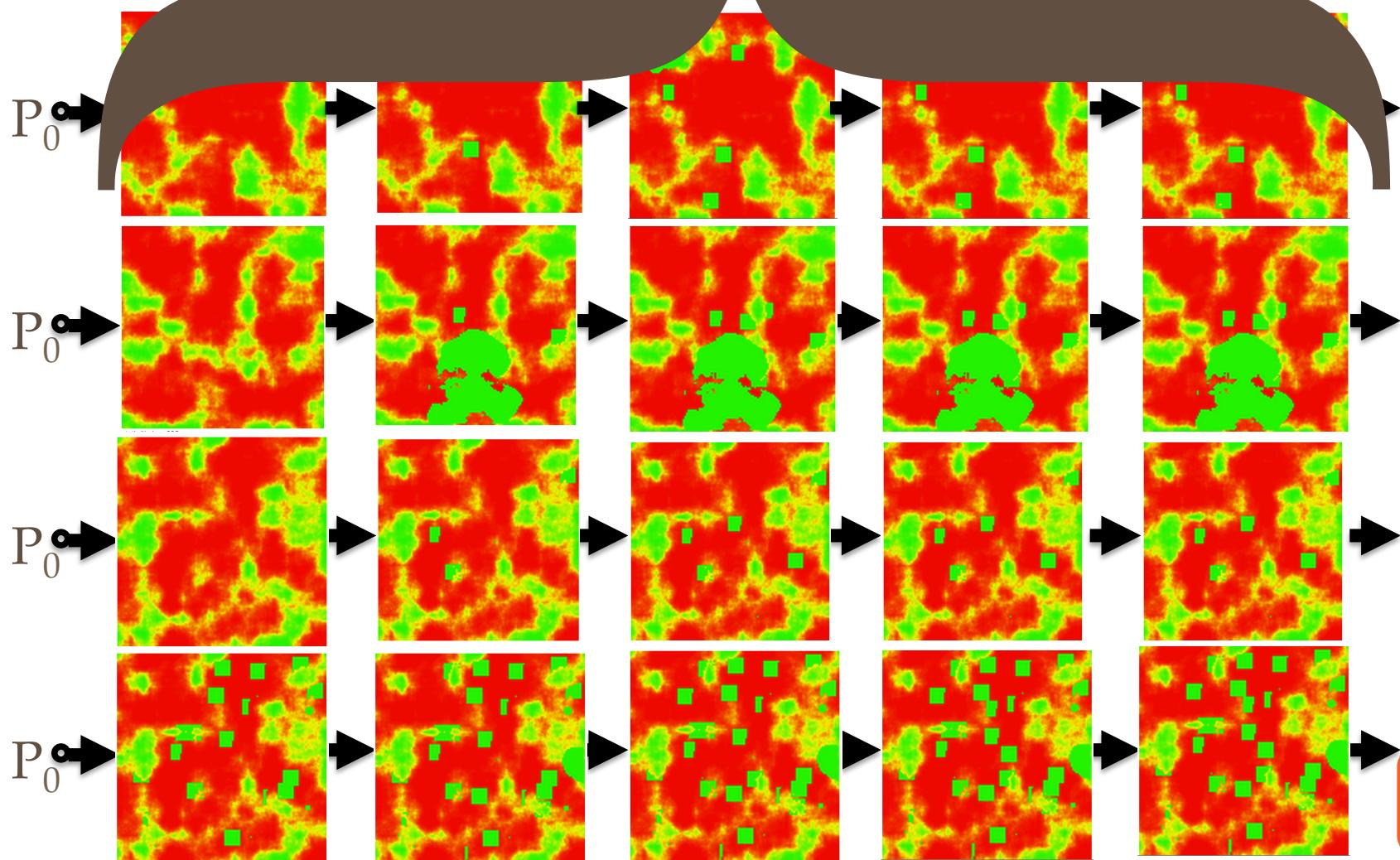


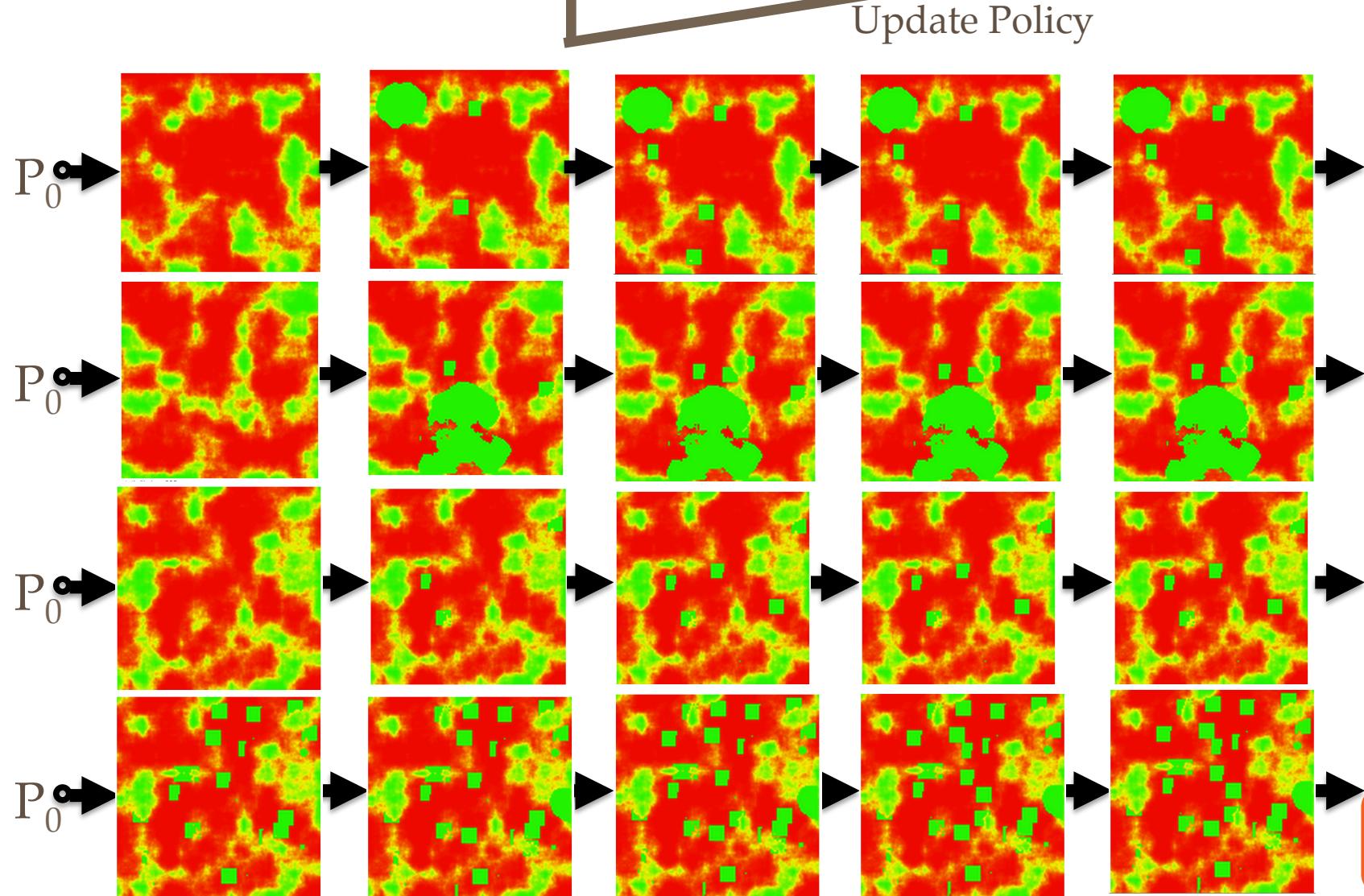
...And this is just one of many!

## Monte Carlo Rollouts

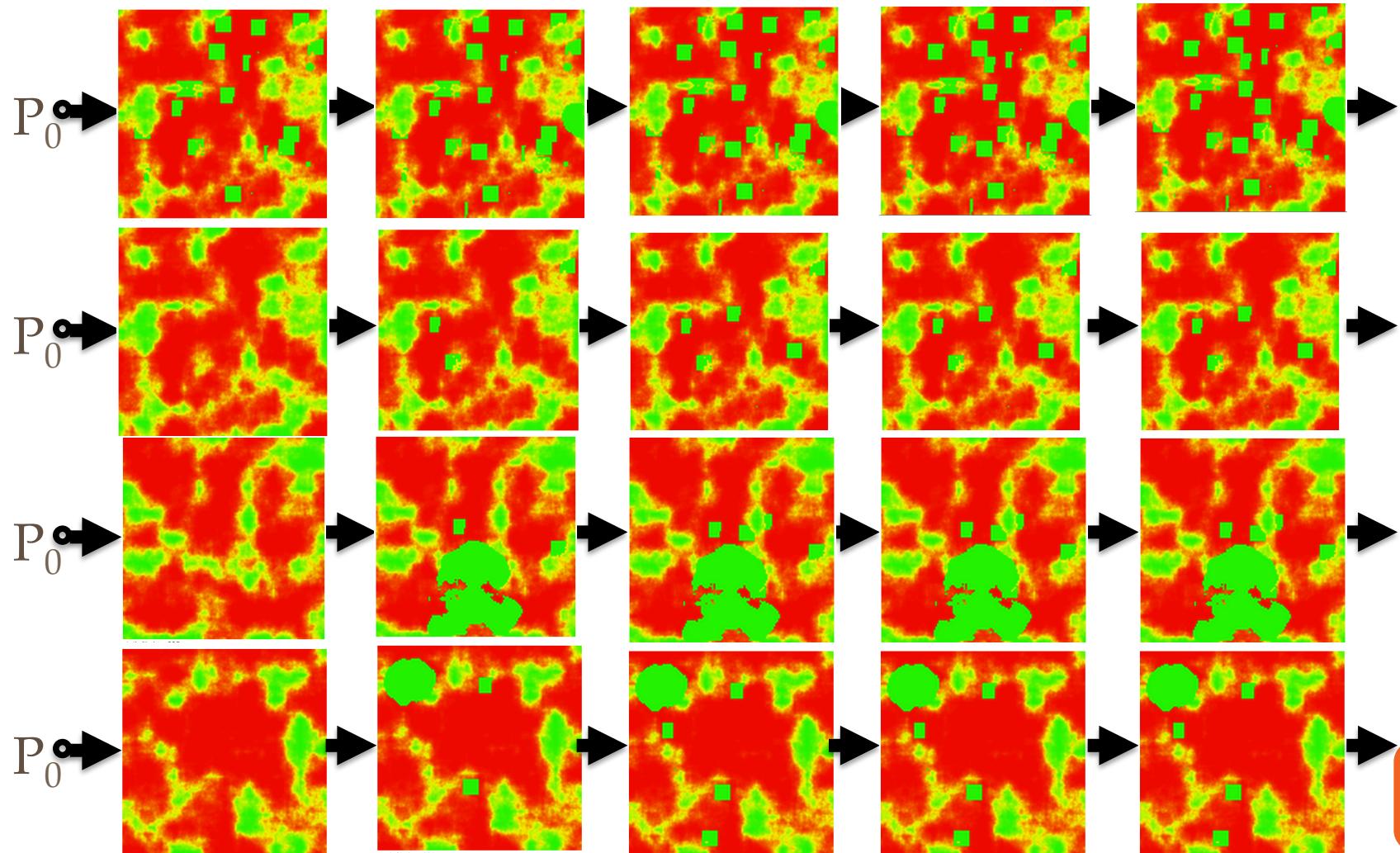


All visited states influence optimizer





# The Rollout Distribution Changes!



## MDP Testing Challenges

- Bugs are **probabilistically** expressed in a **high dimensional temporal dataset**.
- The **dataset changes** with changes to parameters.
- The **optimizer sees more of the state and policy space** than the user.

Testing requires  
exploring rollouts and  
parameters

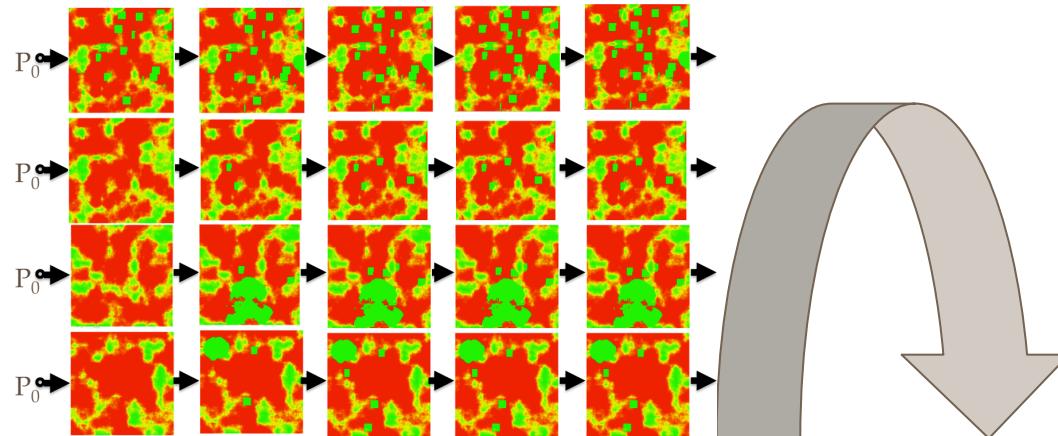
# MDP Debugging and Fault Isolation

- Deactivate/modify components to isolate fault
  - e.g. Balance reward magnitude and frequency

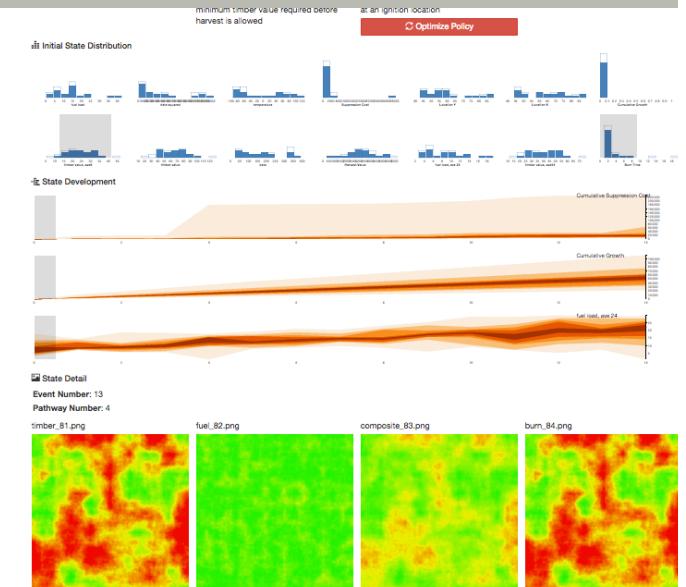
**Debug MDP  
specification and  
integration with  
parameter changes**

# Testing and Debugging Process

## 1. Generate Rollouts



## 2. Visualize the data



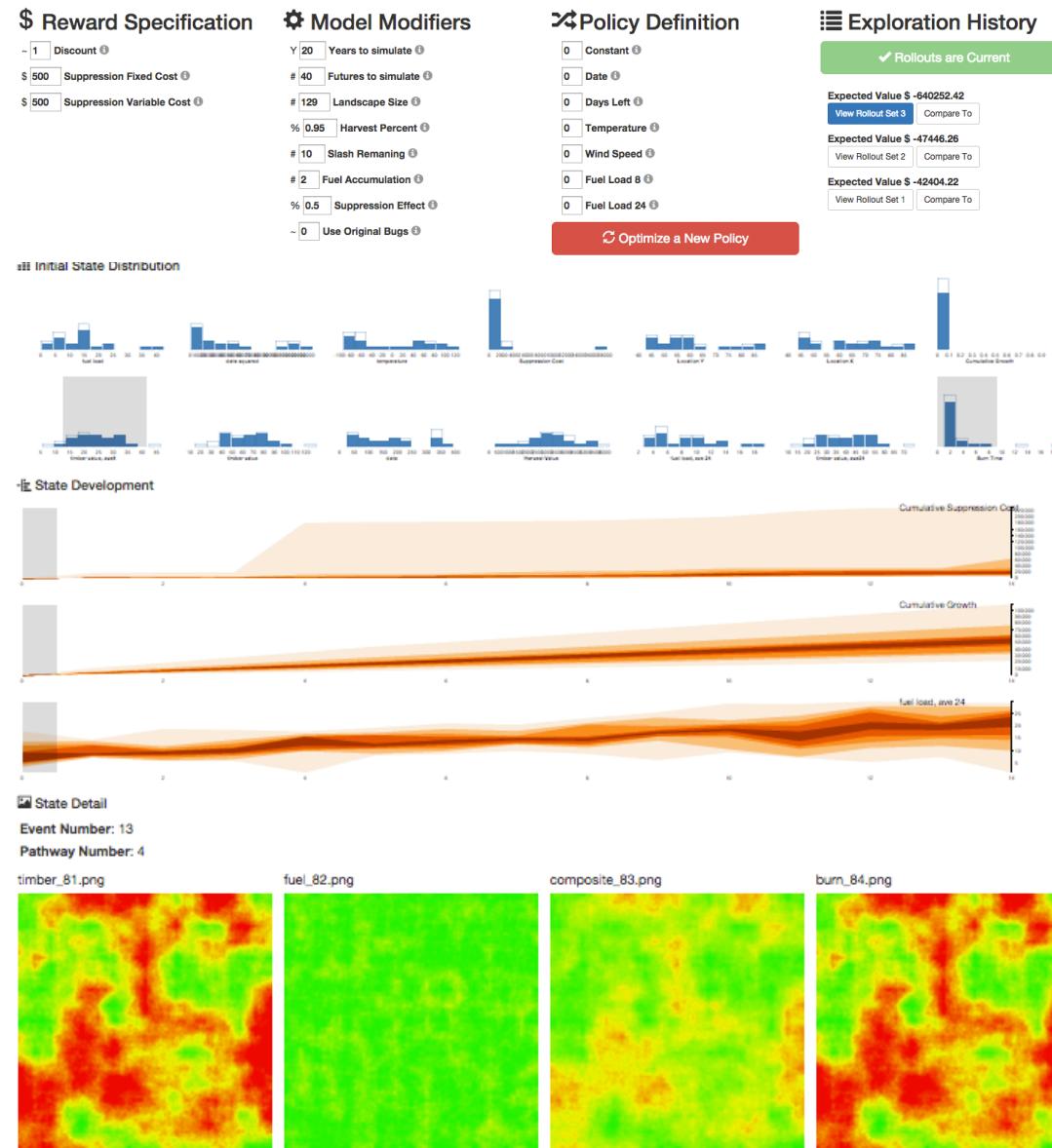
## 3. Change Parameters

The screenshot shows a software interface for changing parameters. It includes sections for "Reward Specification", "Model Modifiers", "Policy Definition", and "Exploration History". The "Policy Definition" section contains a large list of parameters with input fields. A prominent red button at the bottom right says "Optimize a New Policy".

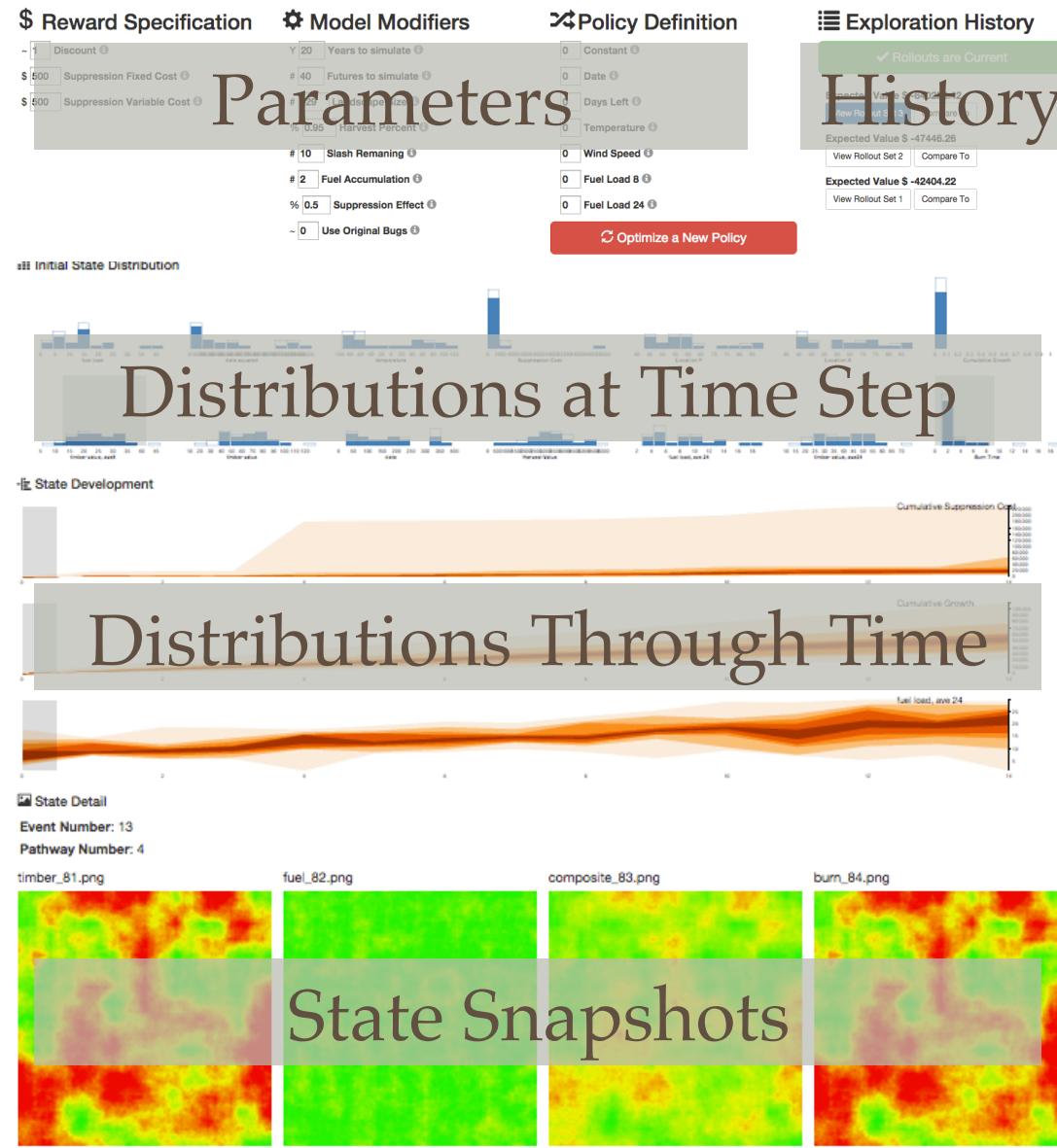
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# Introducing MDPvis



# What are the elements of the MDPvis design?



# Parameter Areas

## \$ Reward Specification

~ 1 Discount ⓘ  
\$ 500 Suppression Fixed Cost ⓘ  
\$ 500 Suppression Variable Cost ⓘ

## ⚙️ Model Modifiers

Y 20 Years to simulate ⓘ  
# 40 Futures to simulate ⓘ  
# 129 Landscape Size ⓘ  
% 0.95 Harvest Percent ⓘ  
# 10 Slash Remaining ⓘ  
# 2 Fuel Accumulation ⓘ  
% 0.5 Suppression Effect ⓘ  
~ 0 Use Original Bugs ⓘ

## 📌 Policy Definition

0 Constant ⓘ  
0 Date ⓘ  
0 Days Left ⓘ  
0 Temperature ⓘ  
0 Wind Speed ⓘ  
0 Fuel Load 8 ⓘ  
0 Fuel Load 24 ⓘ

## ☰ Exploration History

✓ Rollouts are Current

Expected Value S -640252.42

[View Rollout Set 3](#) Compare To

Expected Value S -47446.26

[View Rollout Set 2](#) Compare To

Expected Value S -42404.22

[View Rollout Set 1](#) Compare To

⟳ Optimize a New Policy

# History Area

## \$ Reward Specification

~ 1 Discount  
\$ 500 Suppression Fixed Cost  
\$ 500 Suppression Variable Cost

## ⚙️ Model Modifiers

Y 20 Years to simulate  
# 40 Futures to simulate  
# 129 Landscape Size  
% 0.95 Harvest Percent  
# 10 Slash Remaining  
# 2 Fuel Accumulation  
% 0.5 Suppression Effect  
~ 0 Use Original Bugs

## 📌 Policy Definition

0 Constant  
0 Date  
0 Days Left  
0 Temperature  
0 Wind Speed  
0 Fuel Load 8  
0 Fuel Load 24

⟳ Optimize a New Policy

## ☰ Exploration History

✓ Rollouts are Current

Expected Value \$ -640252.42

[View Rollout Set 3](#) [Compare To](#)

Expected Value \$ -47446.26

[View Rollout Set 2](#) [Compare To](#)

Expected Value \$ -42404.22

[View Rollout Set 1](#) [Compare To](#)

-1 Discount: The per-year discount  
 \$500 Suppression Fixed Cost: cost per day of suppression  
 \$500 Suppression Variable Cost: cost per hectare of suppression  
 % 0.9% Harvest Percent: timber harvest of annual increment  
 \$50 Minimum Timber Value: the minimum timber value required before harvest is allowed

Y 15 Years to simulate: how far to look into the future  
 - 25 Futures to simulate: how many stochastic futures to generate

0 Days Left: for each day left in the year  
 0 Temperature: for air temperature at the time of an ignition

0 Wind Speed: for wind speed at the time of an ignition

0 Timber Value: for the timber value at an ignition location

0 Rollouts are Current

Expected Value \$ 18354.79

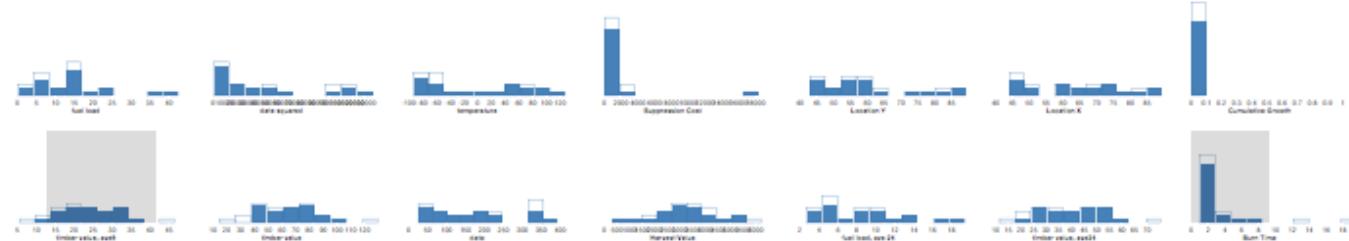
[View Rollout Set 2 Compare To](#)

Expected Value \$ -10385.19

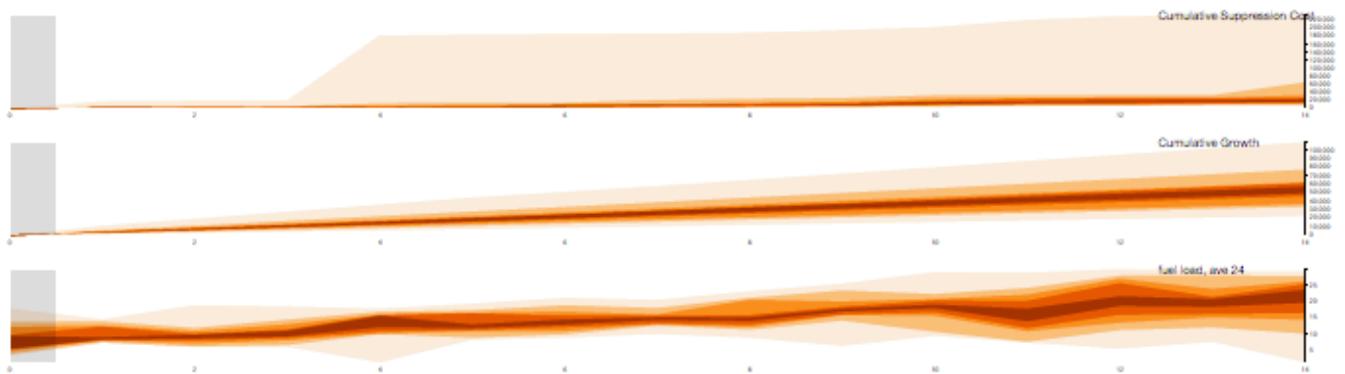
[View Rollout Set 1 Compare To](#)

# Visualization Areas

## Initial State Distribution



## State Development

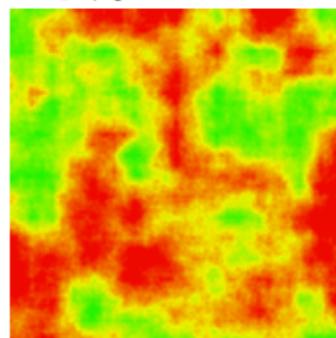


## State Detail

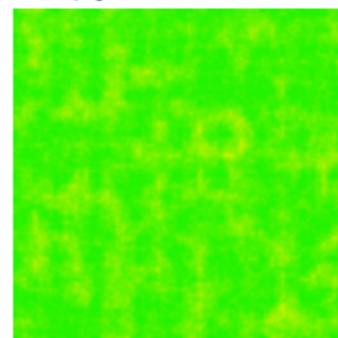
Event Number: 13

Pathway Number: 4

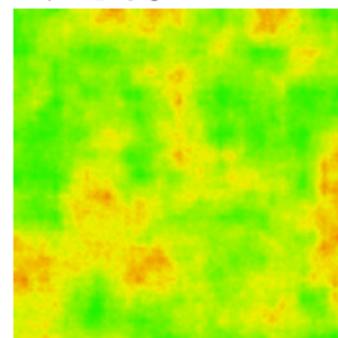
timber\_81.png



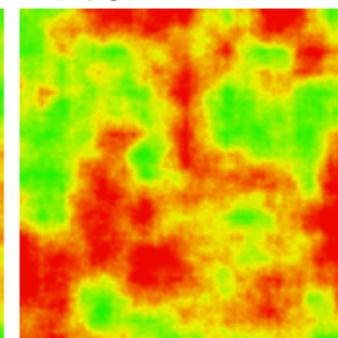
fuel\_82.png



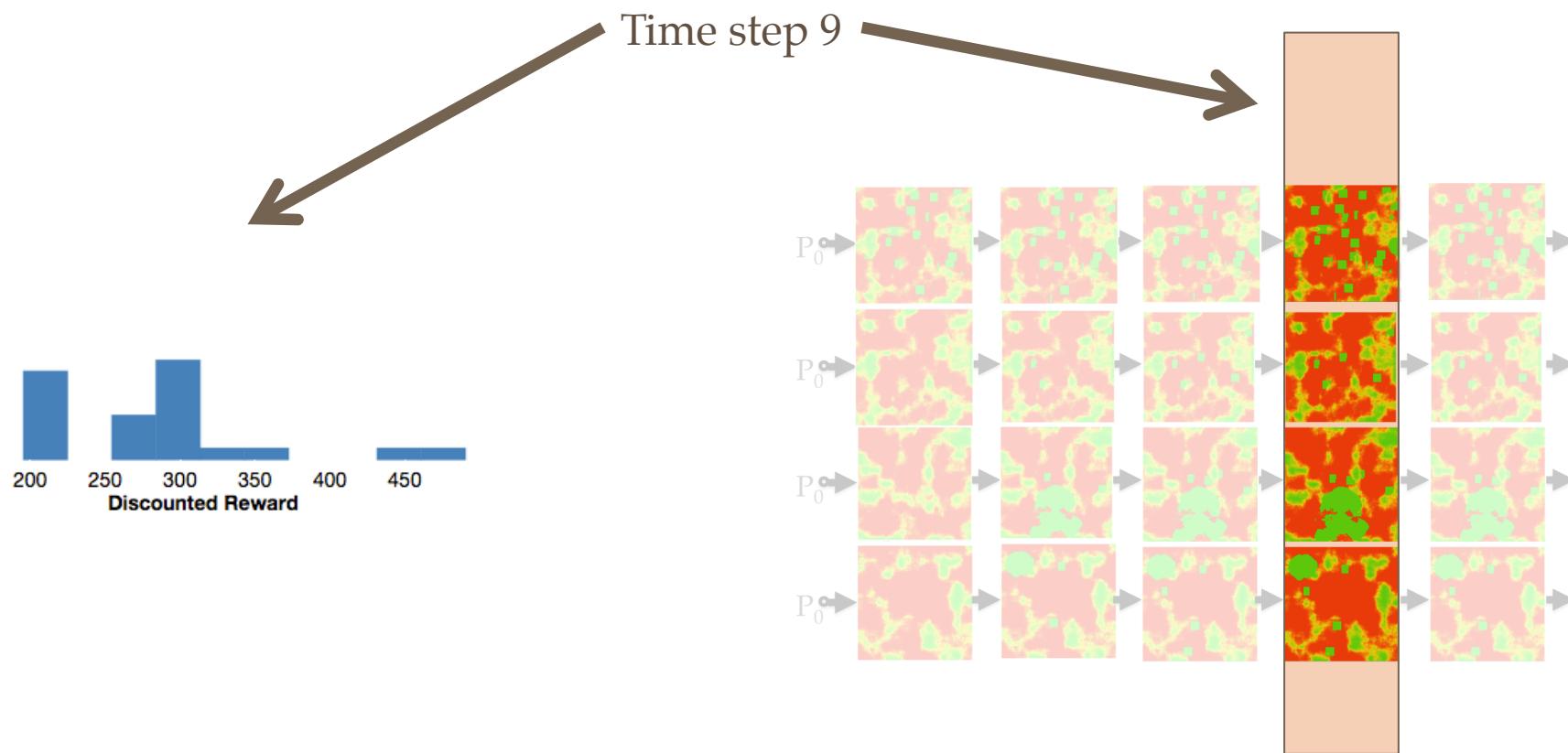
composite\_83.png



burn\_84.png



# State Variable Distributions for a Fixed Time Step



# State Variable Distributions for a Fixed Time Step



$\pi_1$ : Let-Burn



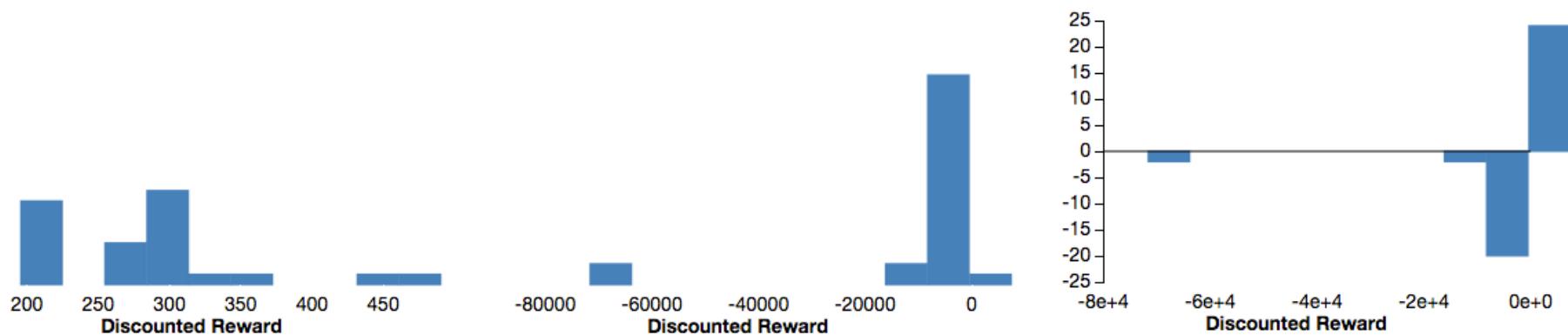
$\pi_2$ : Suppress-All



Comparison

$\pi_1 - \pi_2$

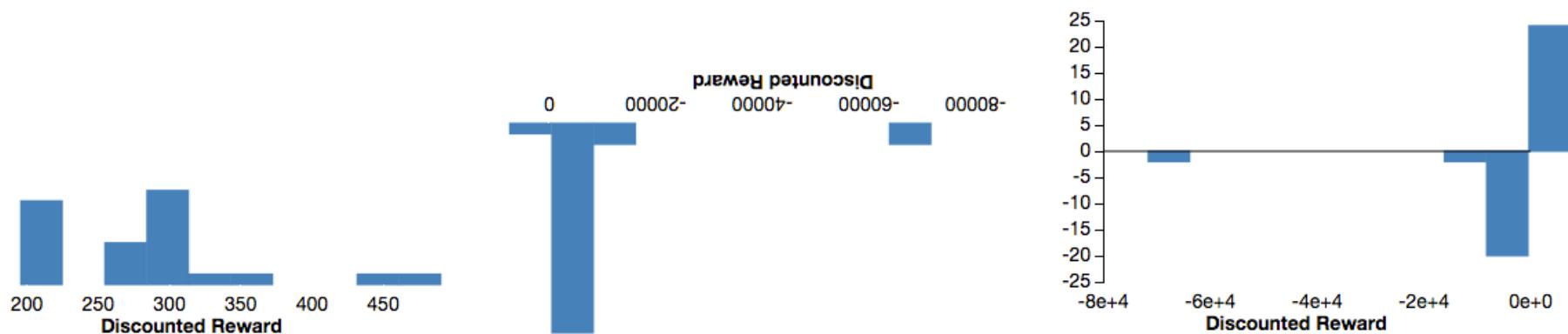
# State Variable Distributions for a Fixed Time Step



## Comparison

$$\pi_1 - \pi_2$$

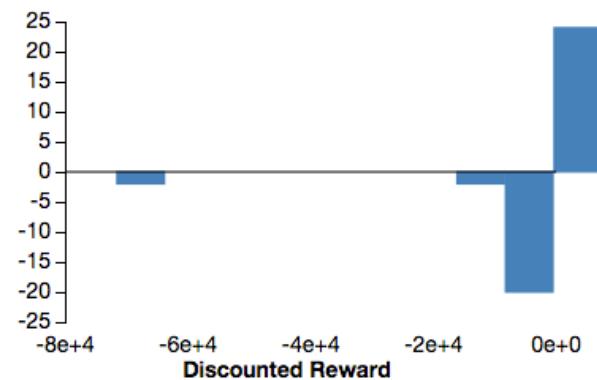
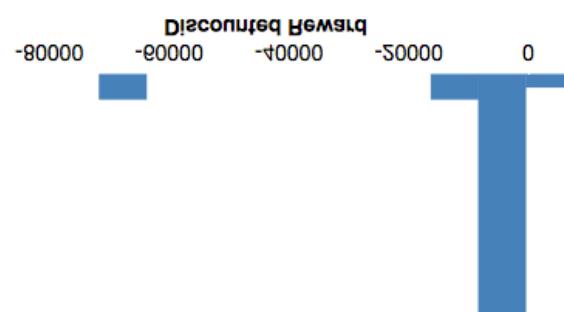
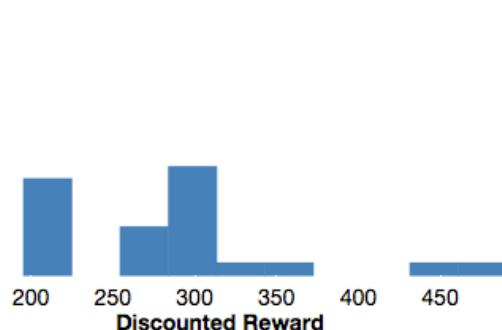
# State Variable Distributions for a Fixed Time Step



## Comparison

$$\pi_1 - \pi_2$$

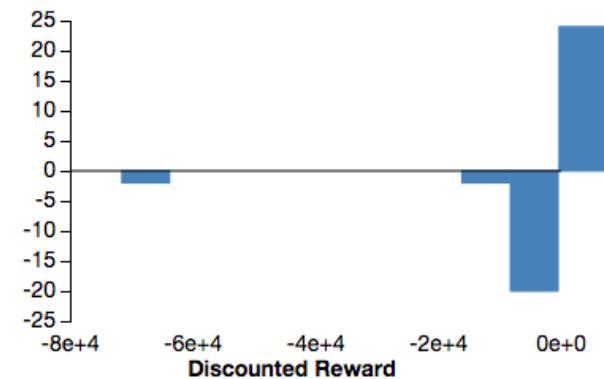
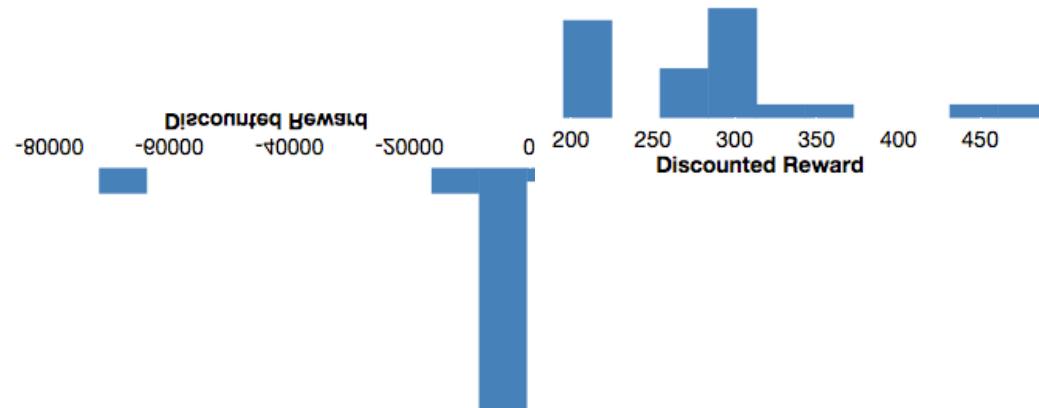
# State Variable Distributions for a Fixed Time Step



## Comparison

$$\pi_1 - \pi_2$$

# State Variable Distributions for a Fixed Time Step



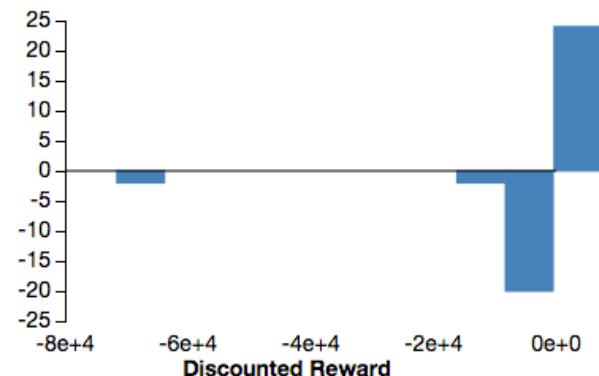
## Comparison

$$\pi_1 - \pi_2$$

# State Variable Distributions for a Fixed Time Step



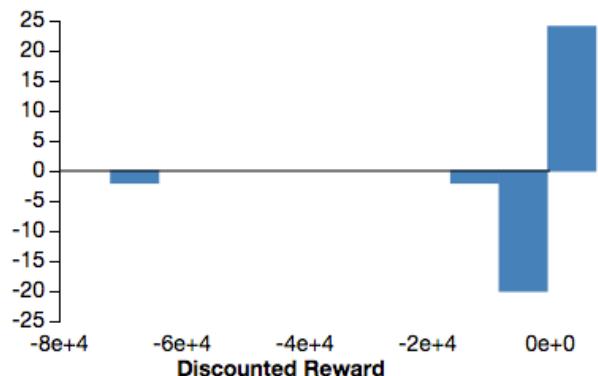
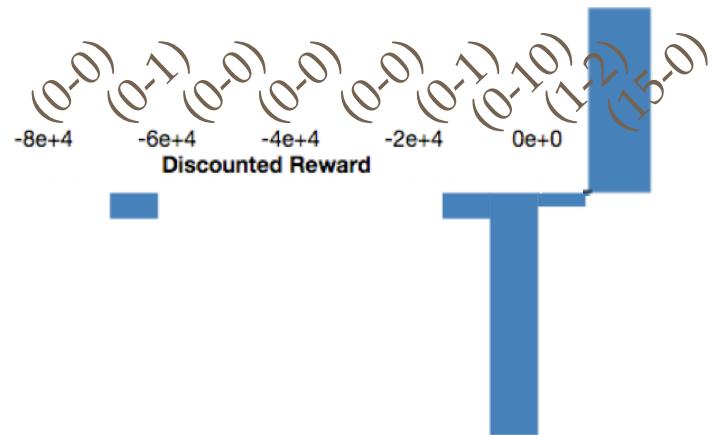
Rescale



Comparison

$$\pi_1 - \pi_2$$

## State Variable Distributions for a Fixed Time Step

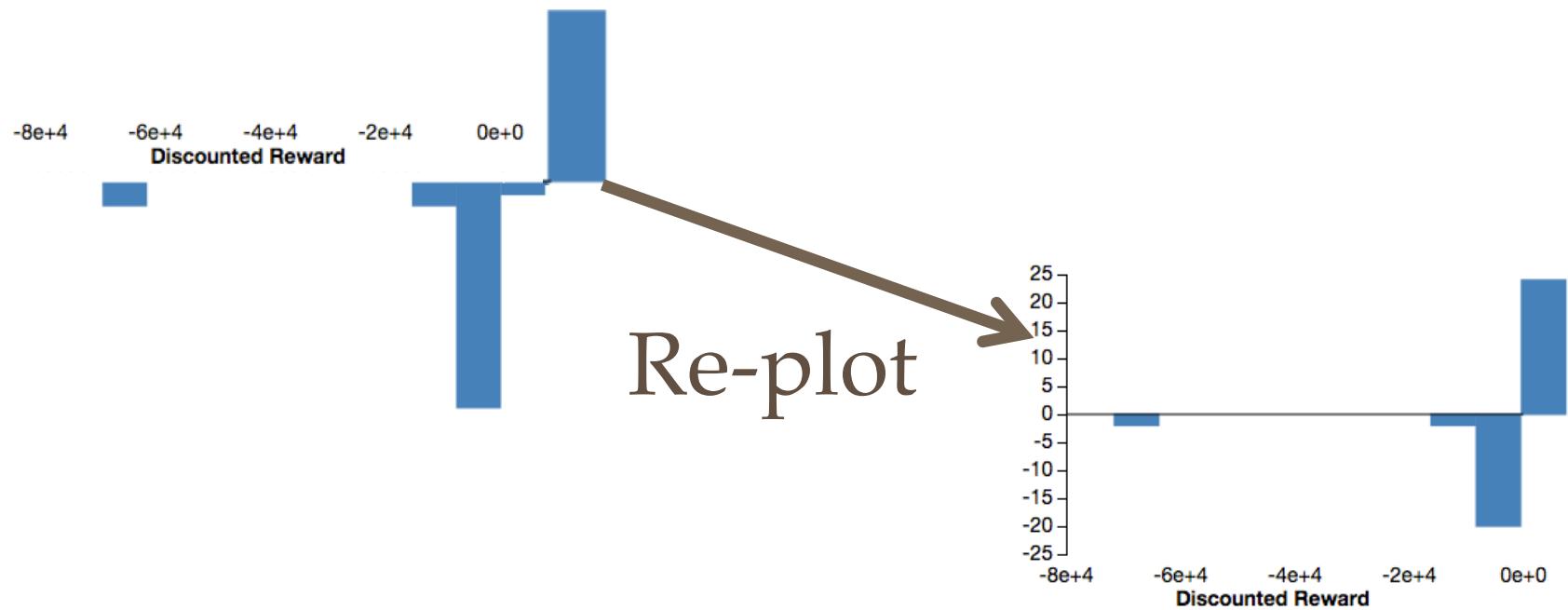


Take Difference in Counts

Comparison

$$\pi_1 - \pi_2$$

# State Variable Distributions for a Fixed Time Step



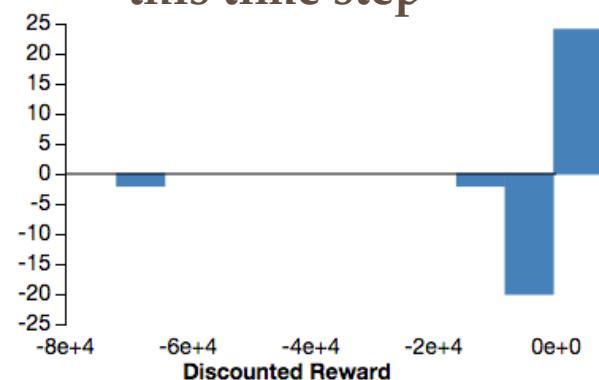
Comparison

$$\pi_1 - \pi_2$$

# State Variable Distributions for a Fixed Time Step



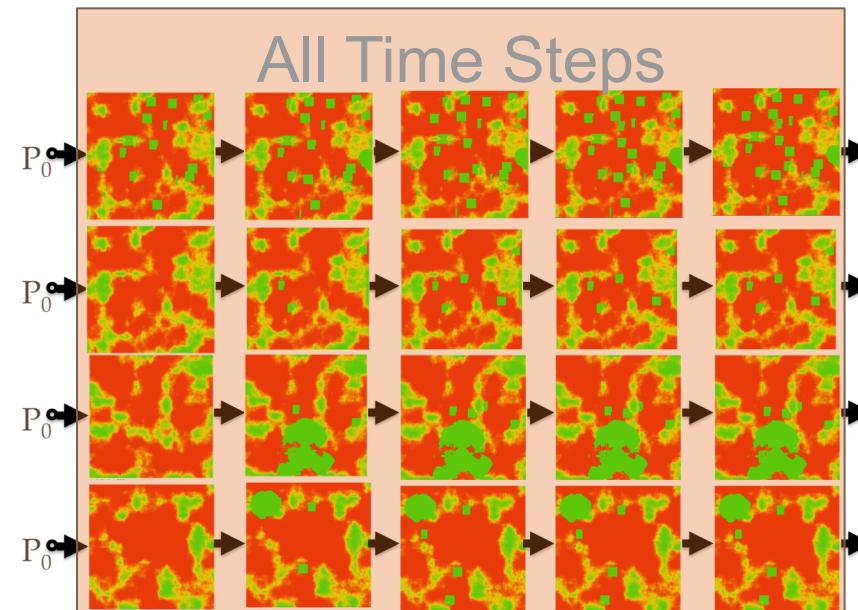
Let-Burn  
Dominates  
Suppress-All in  
this time step



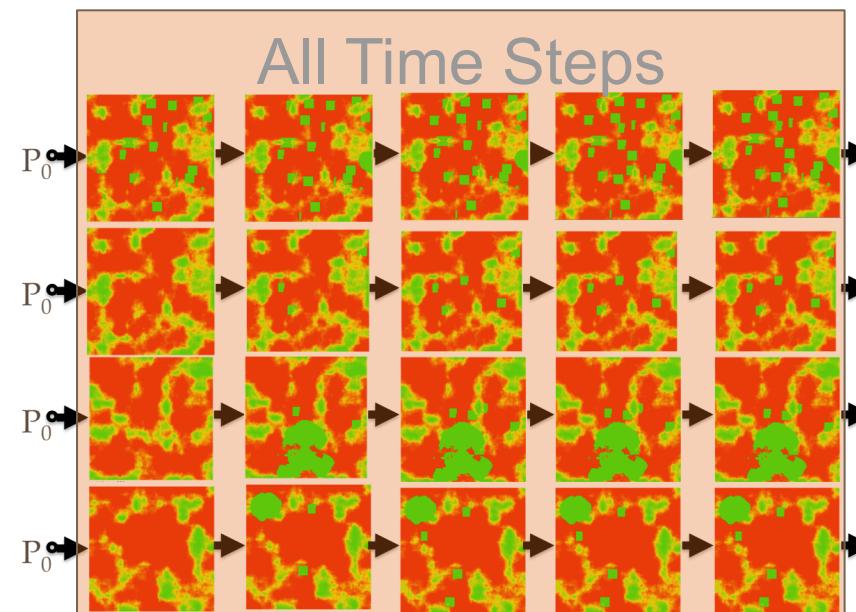
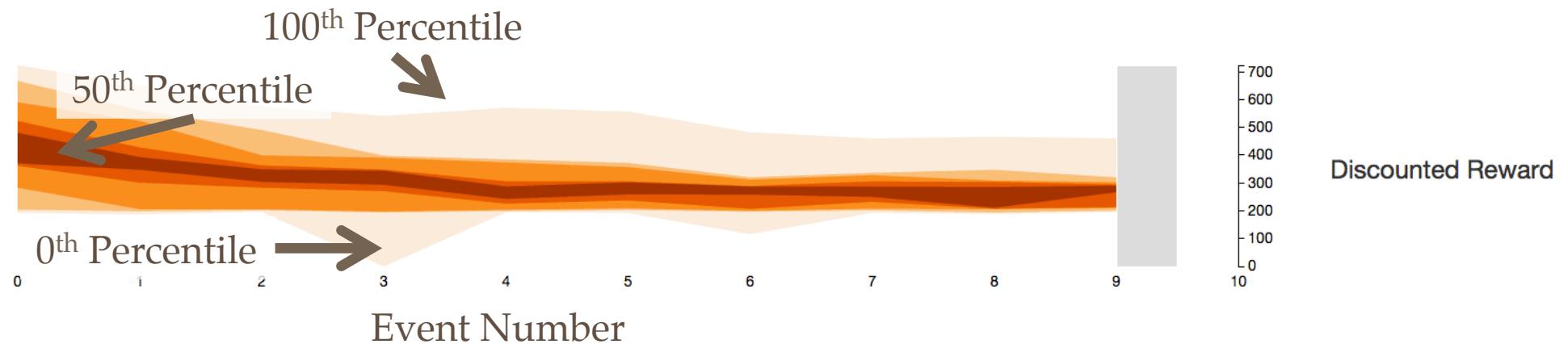
## Comparison

$$\pi_1 - \pi_2$$

# State Variable Distributions through Time

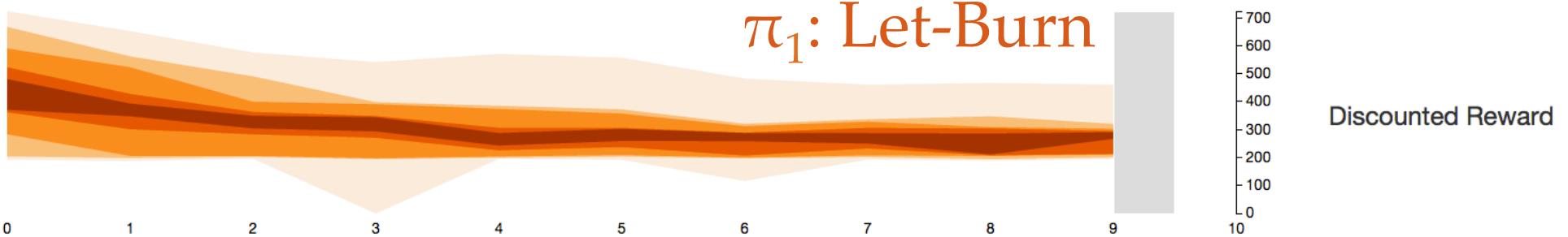


# State Variable Distributions through Time

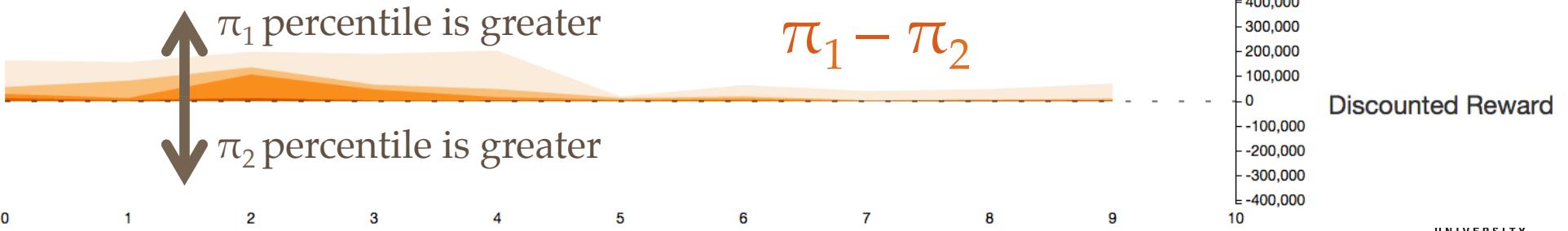


45

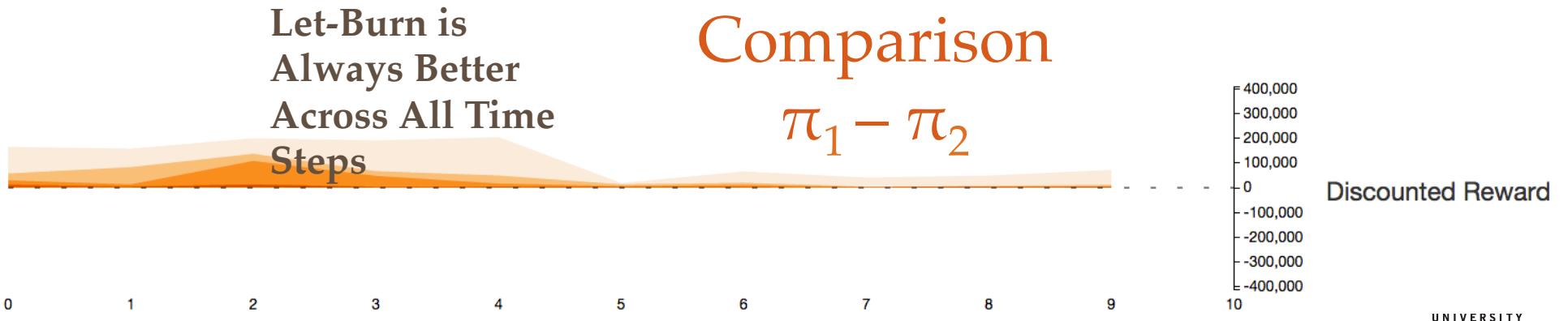
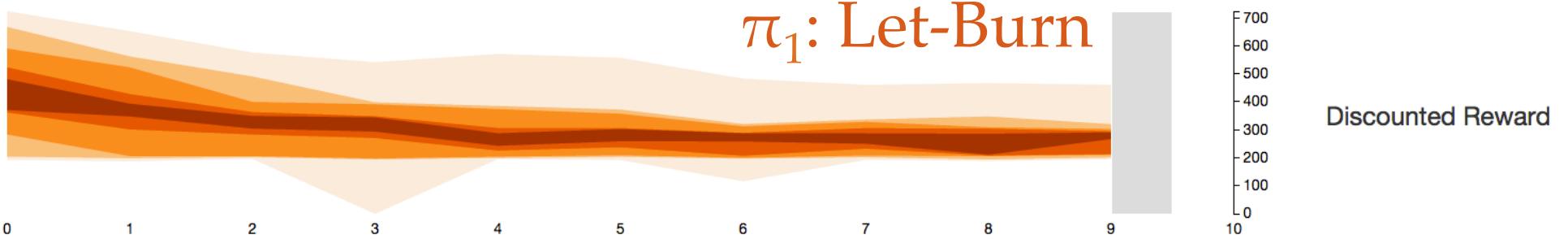
# State Variable Distributions through Time



## Comparison

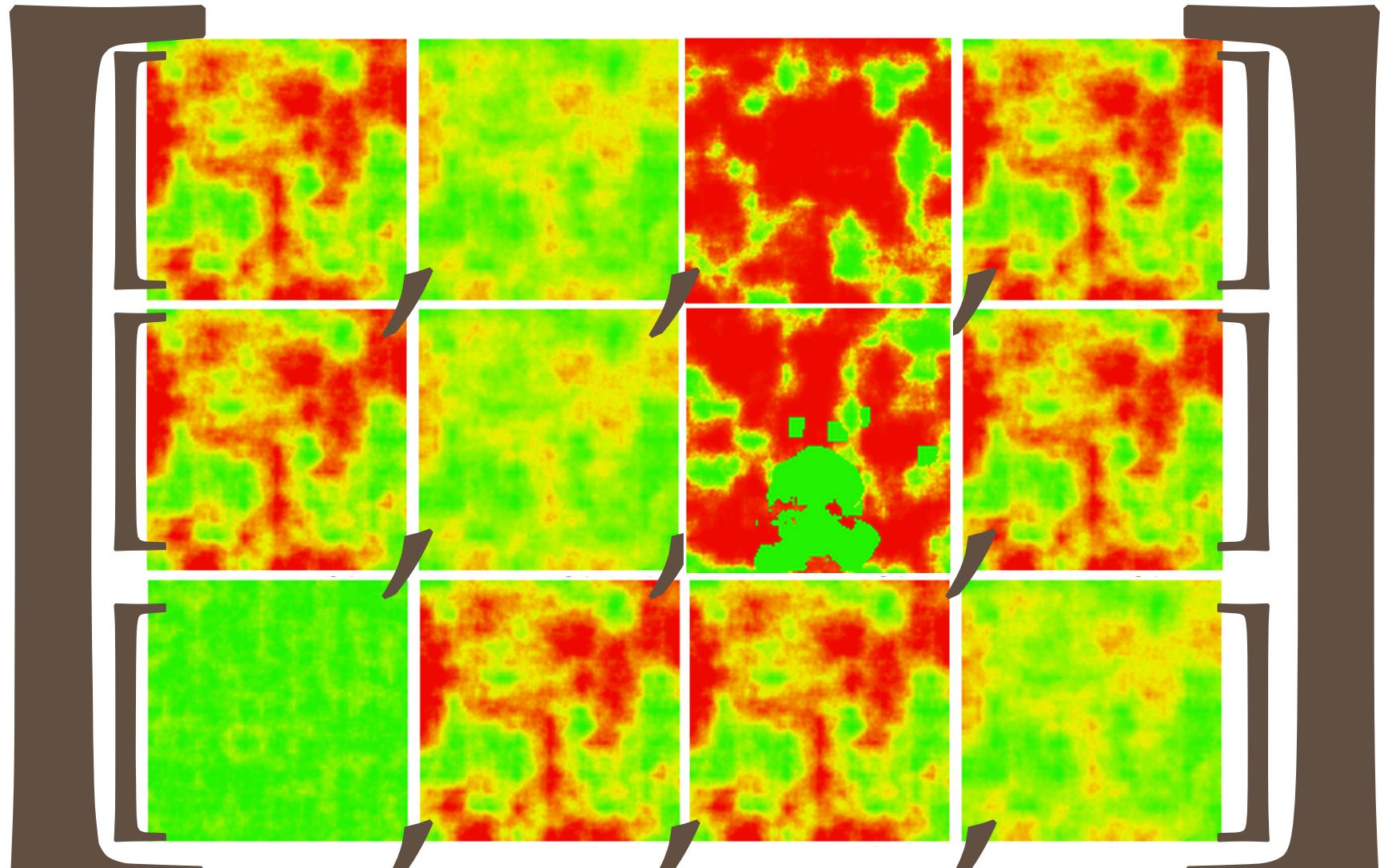


# State Variable Distributions through Time



## State details

Allow MDP Simulator to Generate State Visualizations



# Parameter Space Analysis (PSA)

*“[PSA] is the systematic variation of model input parameters, generating outputs for each combination of parameters, and investigating the relation between parameter settings and corresponding outputs.”*

Categories  
Sensitivity  
Optimization  
Outliers  
Partition  
Uncertainty  
Fitting

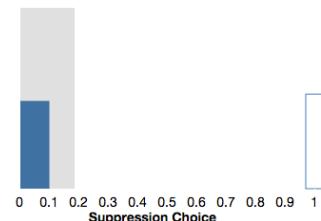
Sensitivity · Optimization · Outliers · Partition · Uncertainty · Fitting

*Is the policy Sensitive to the state?*

## Interaction

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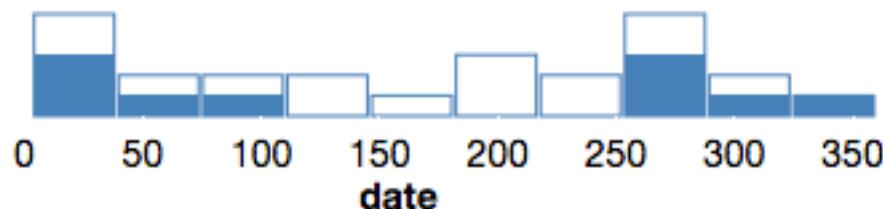
1. Brush suppression choice to select Let-Burn



## Expectation

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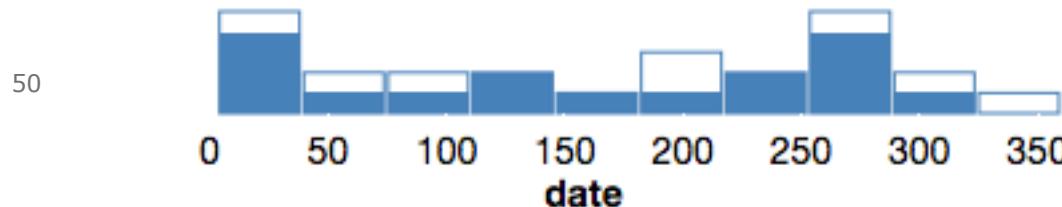
2. Date is a determinant of suppression choice



## Buggy Result

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3. Date does not determine suppression choice



Sensitivity · Optimization · Outliers · Partition · Uncertainty · Fitting

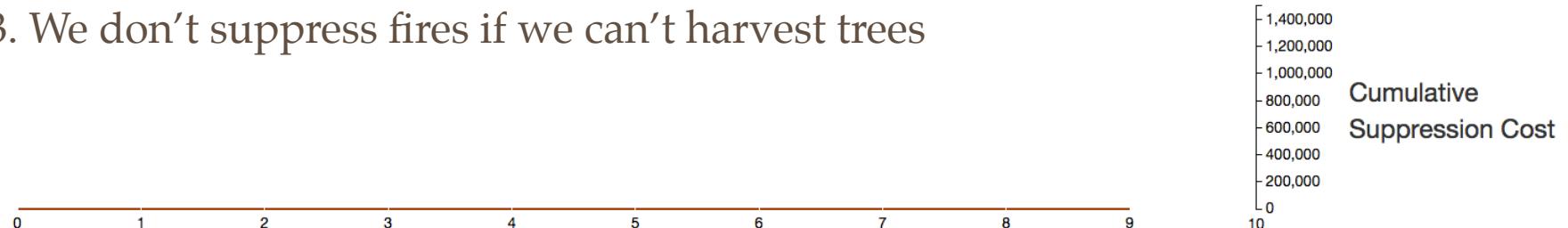
*Is the optimization sensitive to the reward signal?*

## Interaction

1. Zero-out harvest rewards %  Harvest Percent ⓘ
2. Re-optimize and generate rollouts ⟳ Optimize a New Policy

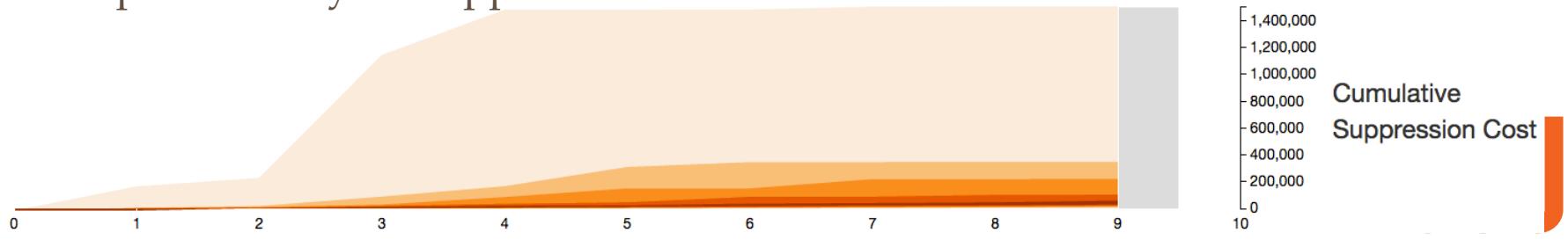
## Expectation

3. We don't suppress fires if we can't harvest trees



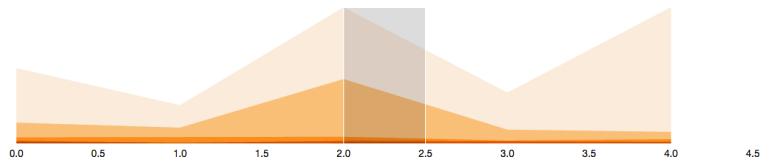
## Buggy Result

4. We spend money on suppression

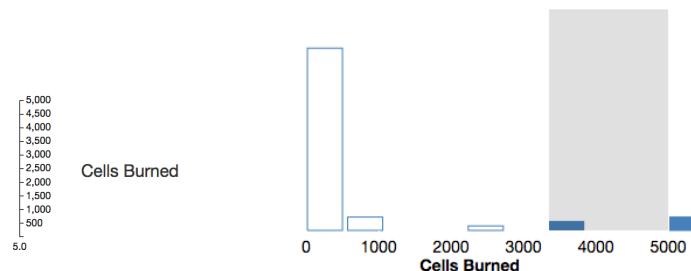


*Are the largest fires realistic?***Interaction**

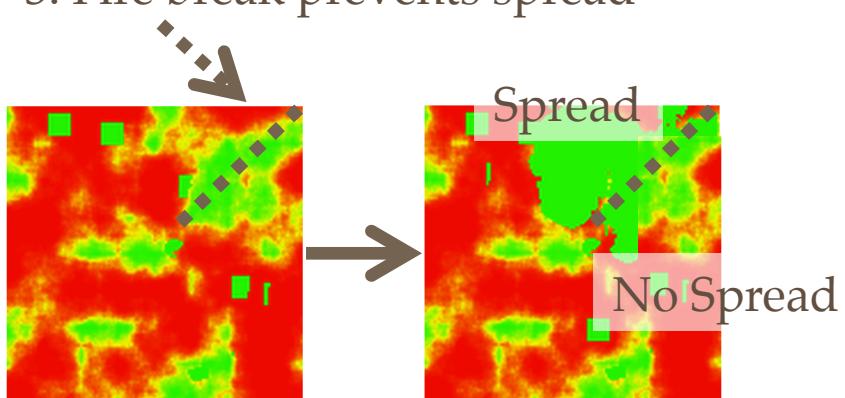
1. Change the year to the one with the largest fire



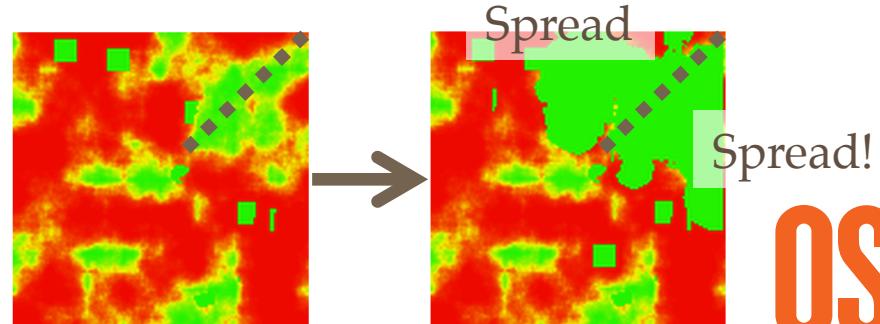
2. Brush histogram to view largest fires

**Expectation**

3. Fire break prevents spread

**Buggy Result**

4. Fire break doesn't prevent spread



Sensitivity · Optimization · Outliers · Partition · Uncertainty · Fitting

*Do policies partition the state space?*

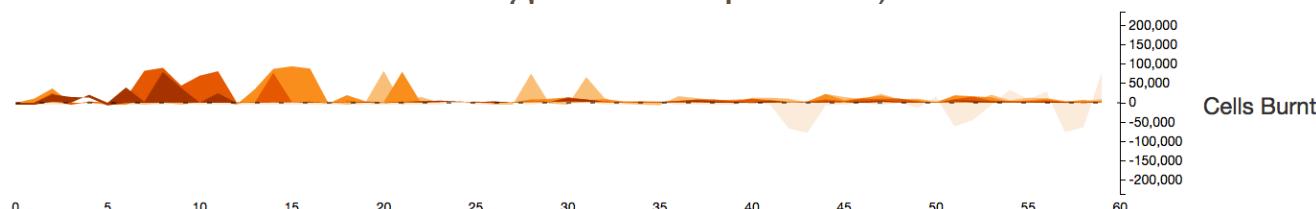
## Interaction

1. Generate suppress-all rollouts
2. Generate let-burn-all rollouts
3. Click the “compare rollouts” button



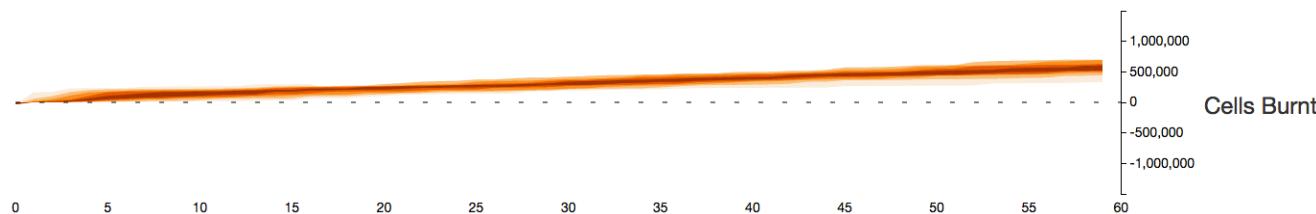
## Expectation

4. Let-burn-all fires will be larger in the present, and smaller in the future



## Buggy Result

5. Let-burn-all fires are the same in the present, and larger in the future



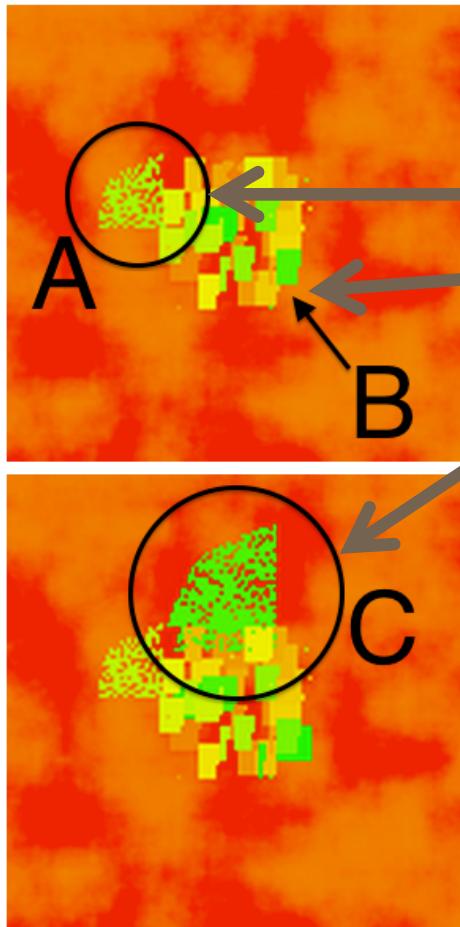
## Use Case Study of MDPvis

We tested a new wildfire policy domain

- Visualization Developer: 1 Ph.D. Student in Computer Science
- New Fire Domain Developer: 1 Ph.D. Student in Forestry
- Wildfire Optimization Expert: 1 faculty research assistant

We found numerous bugs

## Evaluation of MDPvis



**Viewed Largest Fires in Rollouts**

Second Largest Fire

Harvest Areas

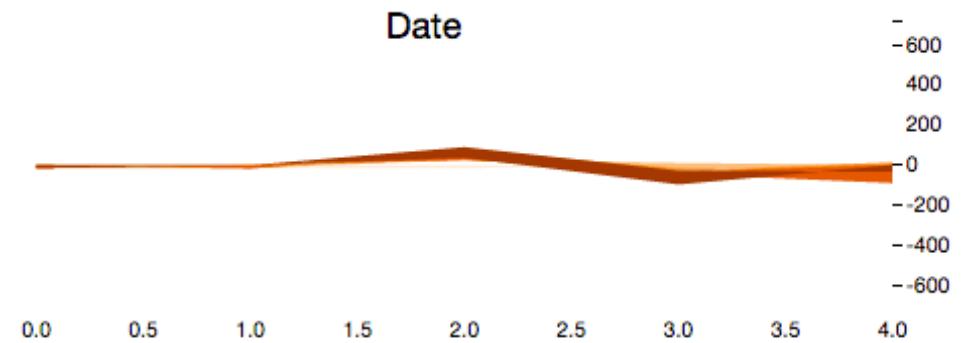
Largest Fire

Fires are not spreading east!

Hidden except in most extreme fire by harvests

# Evaluation of MDPvis

1. **Compare:** Same model with different policies
2. **Expect:** Same ignition date in both rollout sets.
3. **Actual:** Policies change the weather.



## Conclusion

# Summary

We need visualization IDEs for MDPs!

## Interactive Demo

# MDPVis.github.io

\* Not robust to many *simultaneous* requests



# Thanks

- **Reviewers:** <you know who you are>
- **Advisor:** Thomas Dietterich
- **Research Group:** Ronald Metoyer, Claire Montgomery, Rachel Houtman, Mark Crowley, Hailey Buckingham
- **Funder:** National Science Foundation



# MDPVis.github.io

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

End.

# Questions?



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End.

# Come to the Full Demo!



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*How consistent is the policy for small changes to the model?*

## Interaction

1. Optimize and generate rollouts
2. Add air tankers to the model
3. Optimize and generate rollouts
4. Click the “Compare Rollouts” button

 Optimize a New Policy



**Model Modifiers**

% 0.5 Suppression Effect 

 Optimize a New Policy

Expected Value \$ -570788.61

 View Rollout Set 5

Compare To

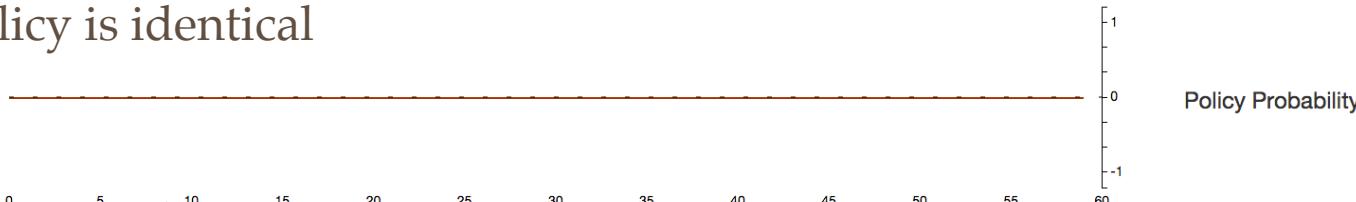
Expected Value \$ 9129.08

 View Rollout Set 4

Compare To

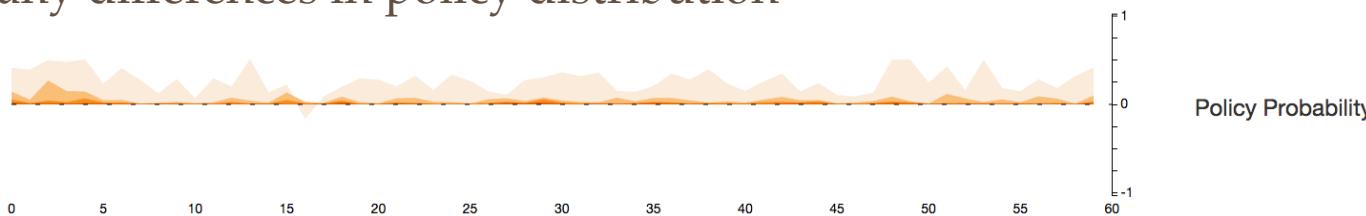
## Expectation

5. Policy is identical



## Buggy Result

6. Many differences in policy distribution



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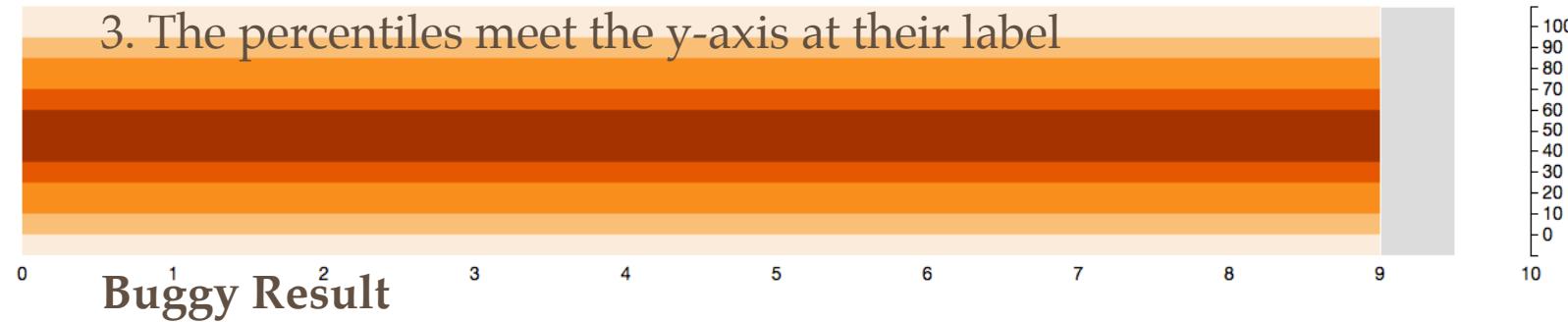
*Does the growth rate match the historical dataset?*

### Pre-Process

1. Add a variable for the growth percentile within the historic data

### Expectation

3. The percentiles meet the y-axis at their label



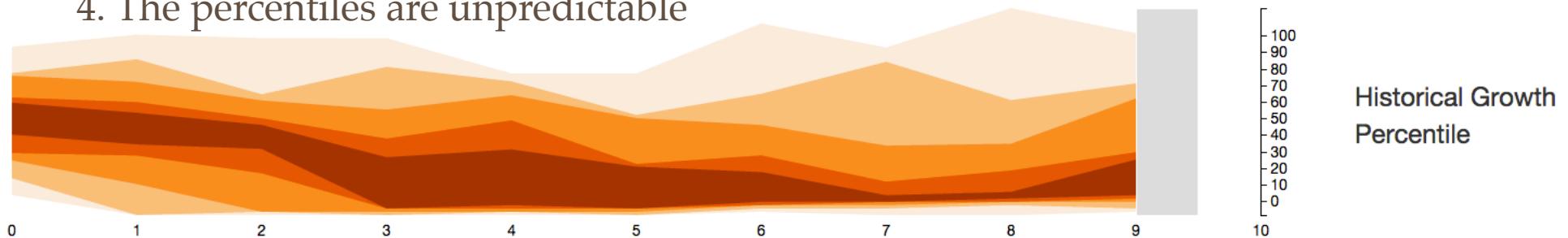
### Interaction

2. Assign the policy to the historical policy (suppress all)

#### Policy Definition

999	Constant
0	Date
0	Fuel Load
0	Fuel Load 8

4. The percentiles are unpredictable



## Let's Construct a Simple MDP: "Pixel Forest"

