Complex systems and early warning signals

Complex systems:

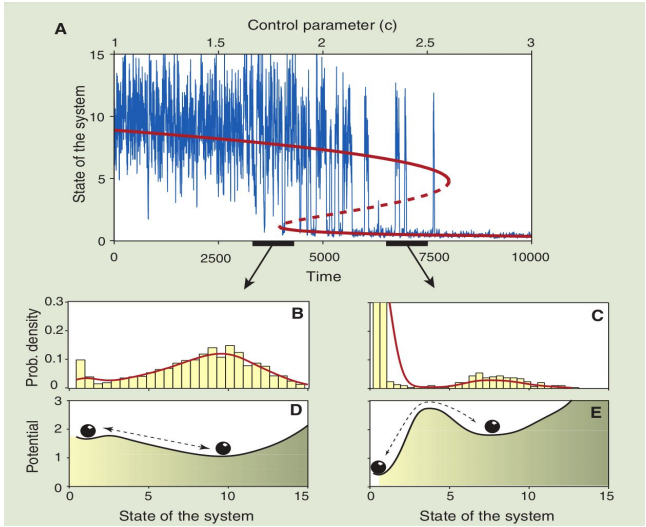
- Many (n→∞) “simple” agents
- Non-linear dynamics
- Can be heterogeneous

Critical transitions / tipping points / abrupt regime shifts:

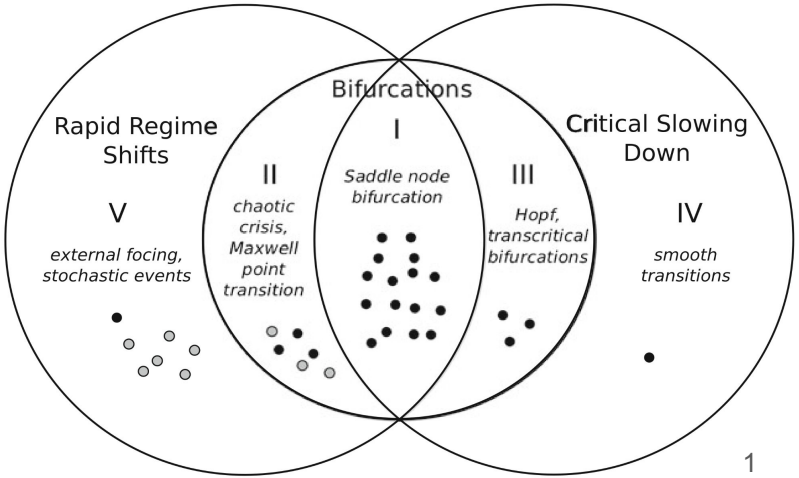
- **Brutal change of dynamics** of the system
- Is (sometimes) linked to **criticality / phase transitions** formalism
- Can one **predict** when / if they will arrive?

Early warning signals (EWS) of transitions:

- Some standard EWS in ecological systems (critical slowing down)
- In **what systems** are they applicable? Are there **other types of EWS?**
- Here: use **large-scale collaborative game** (with humans) to find **generalizable properties of EWS using machine learning**



Scheffer et al., *Science* 338 (2012)



Boettinger, Ross, Hastings, *Th. Ecol.* 6 (2013)

Use large-scale online games as testbed for complex systems ideas

Many real-life and experimental ecosystems are strenuous and **costly to monitor, measure, and control**.

“Gamified” experiments with human players can provide enormous amounts of data and very diverse experimental settings!

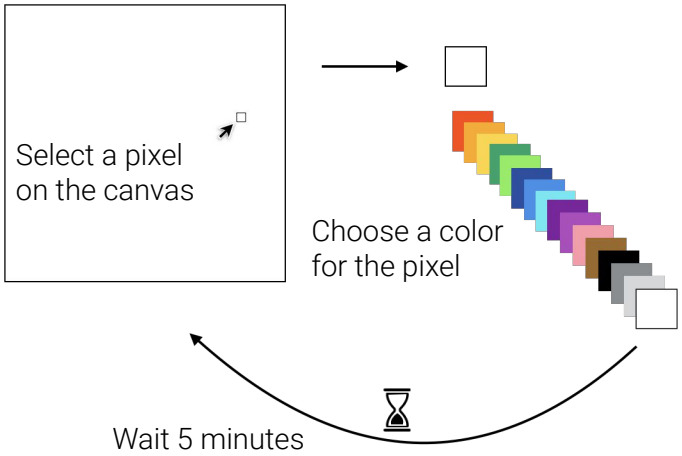
We aim to use the full data from a game-experiment on reddit to find **characteristics of early warning signals** and evidence of **emergent cooperation mechanisms**

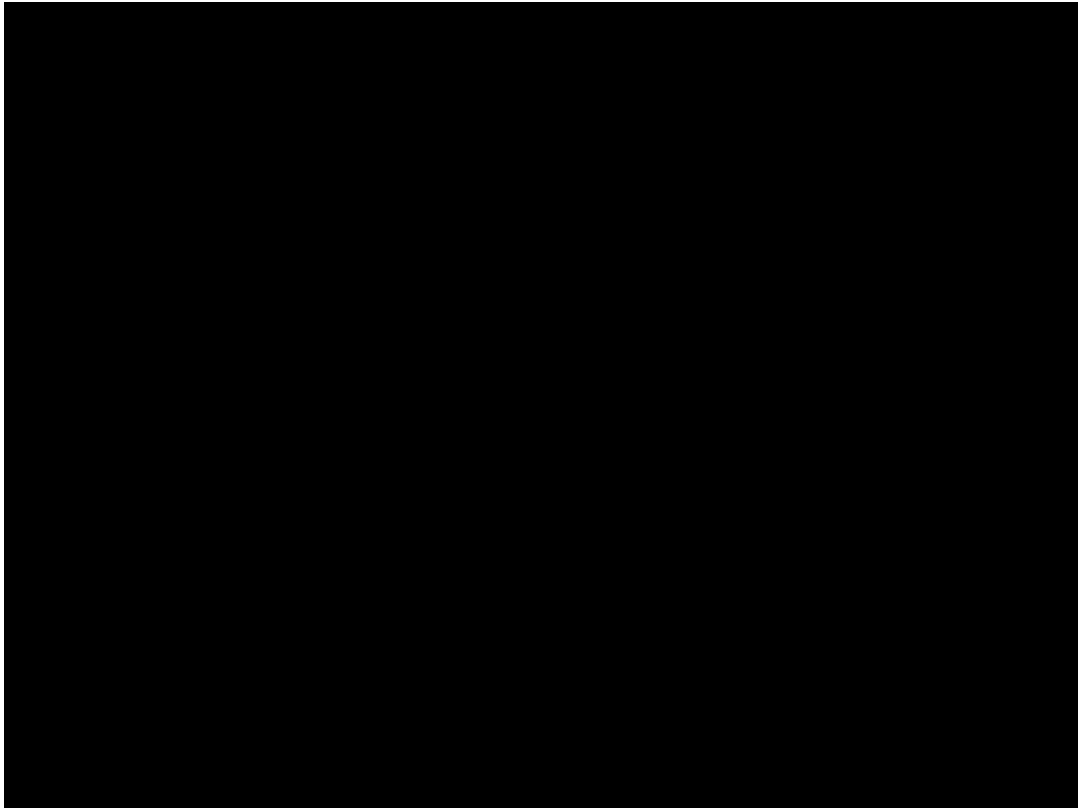
Long, Simson, Buxó-Lugo, Watson, Mehr. “How games can make behavioural science better.” *Nature* 613:433-436 (2023).

On April 1st, 2022, Reddit opened **r/place**: a blank canvas of pixels that users could change to various colors

However, there was a catch: each user can ***only change one pixel every five minutes***

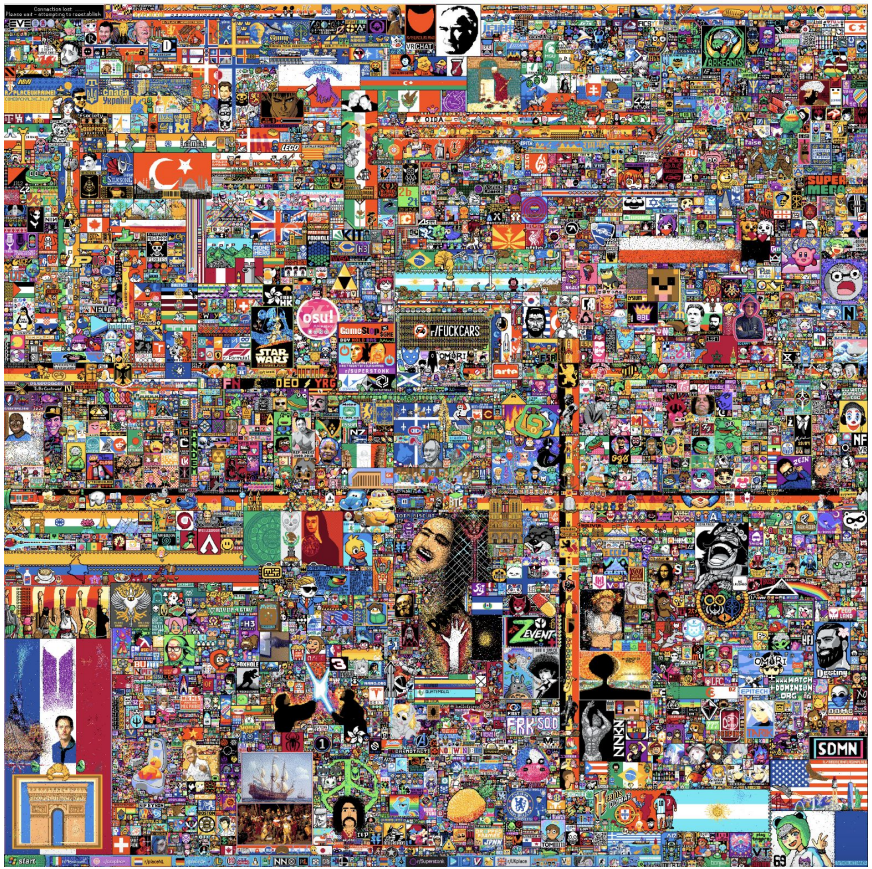
This rule meant that ***collaboration was essential*** to make and keep a composition on the canvas





Big data and rich dynamics for human collective behavior

- **160 million pixel changes**
- **10.6 million users**
- 3.5 days
- More than **10,000 “compositions”**, meaning groups of pixels forming a significant drawing

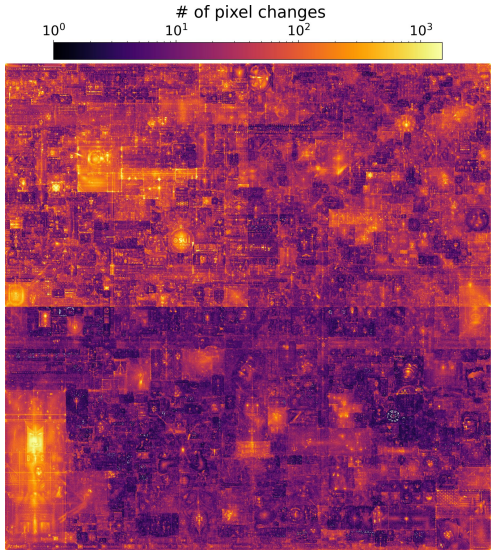


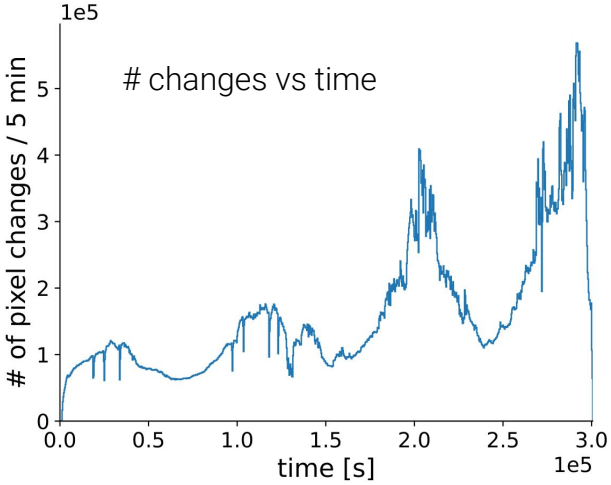
Great window into human collective behavior.
Allows to test ideas on:

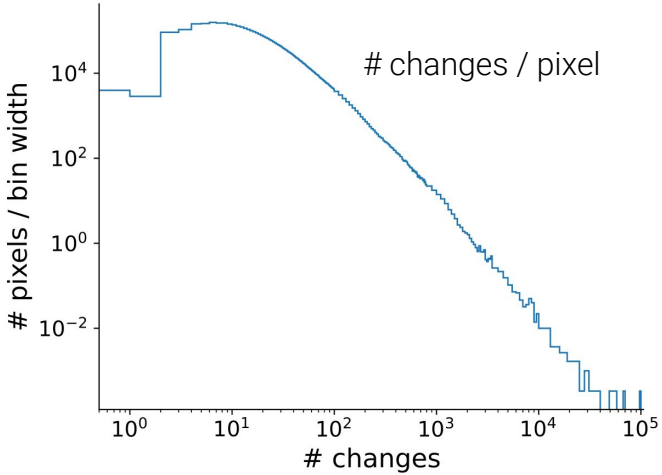
- **regime shifts + EWS**
- **emergent cooperation + structure of collaborations** (top-down vs bottom-up, stigmergy)
- **comparative** (heterogeneous) **subsystem dynamics**
- **…**

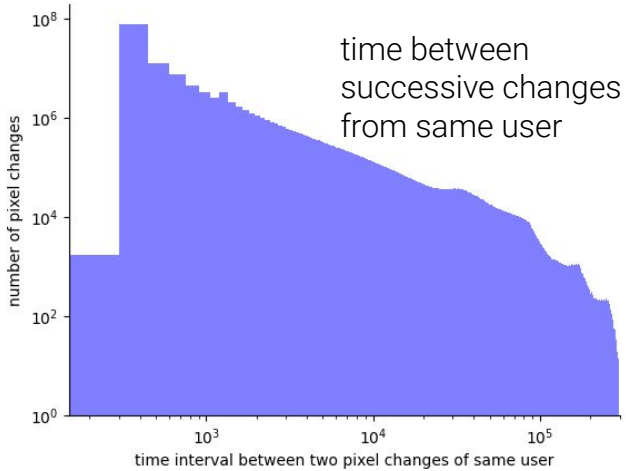
Some dynamics

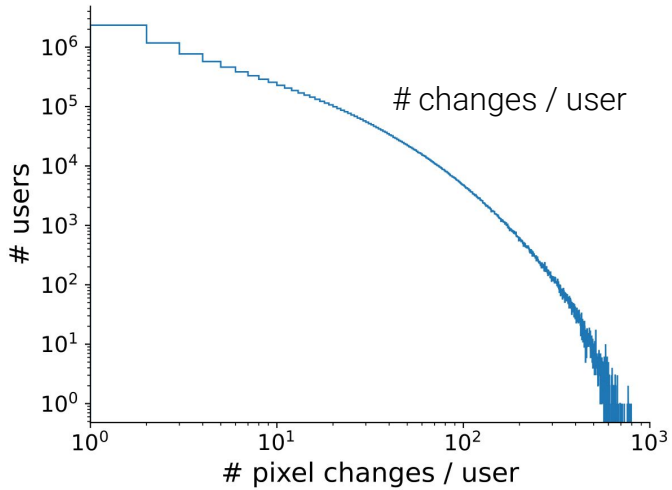
Heat map

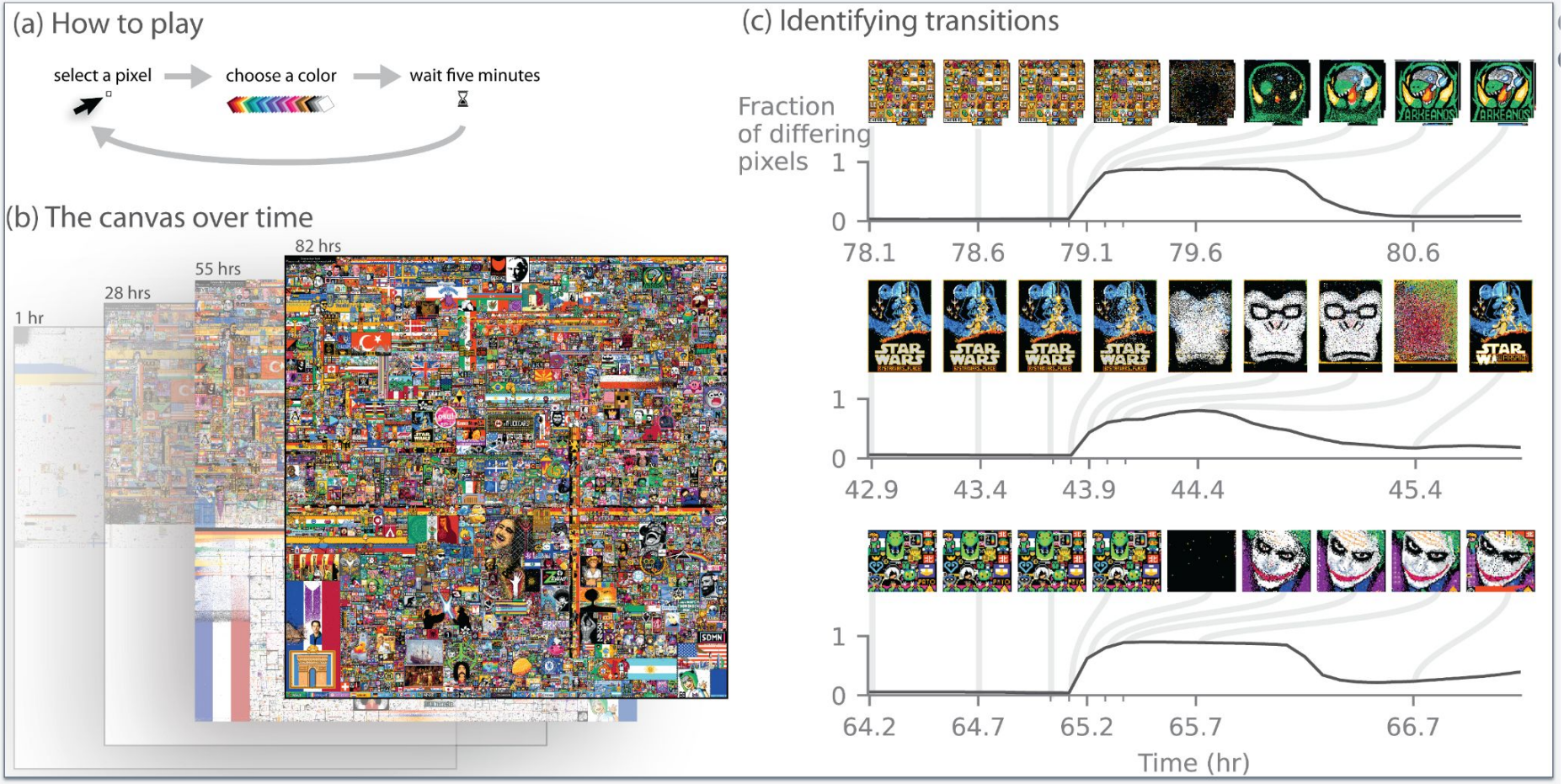











(a) How to play
select a pixel
choose a color
wait five minutes
(b) The canvas over time
1 hr
28 hrs
55 hrs
82 hrs
(c) Identifying transitions
Fraction of differing pixels
1
0
78.1
78.6
79.1
79.6
80.6
1
0
42.9
43.4
43.9
44.4
45.4
1
0
64.2
64.7
65.2
65.7
66.7
Time (hr)

Transitions take place within compositions when one group attacks the composition of another

Our goal is to:

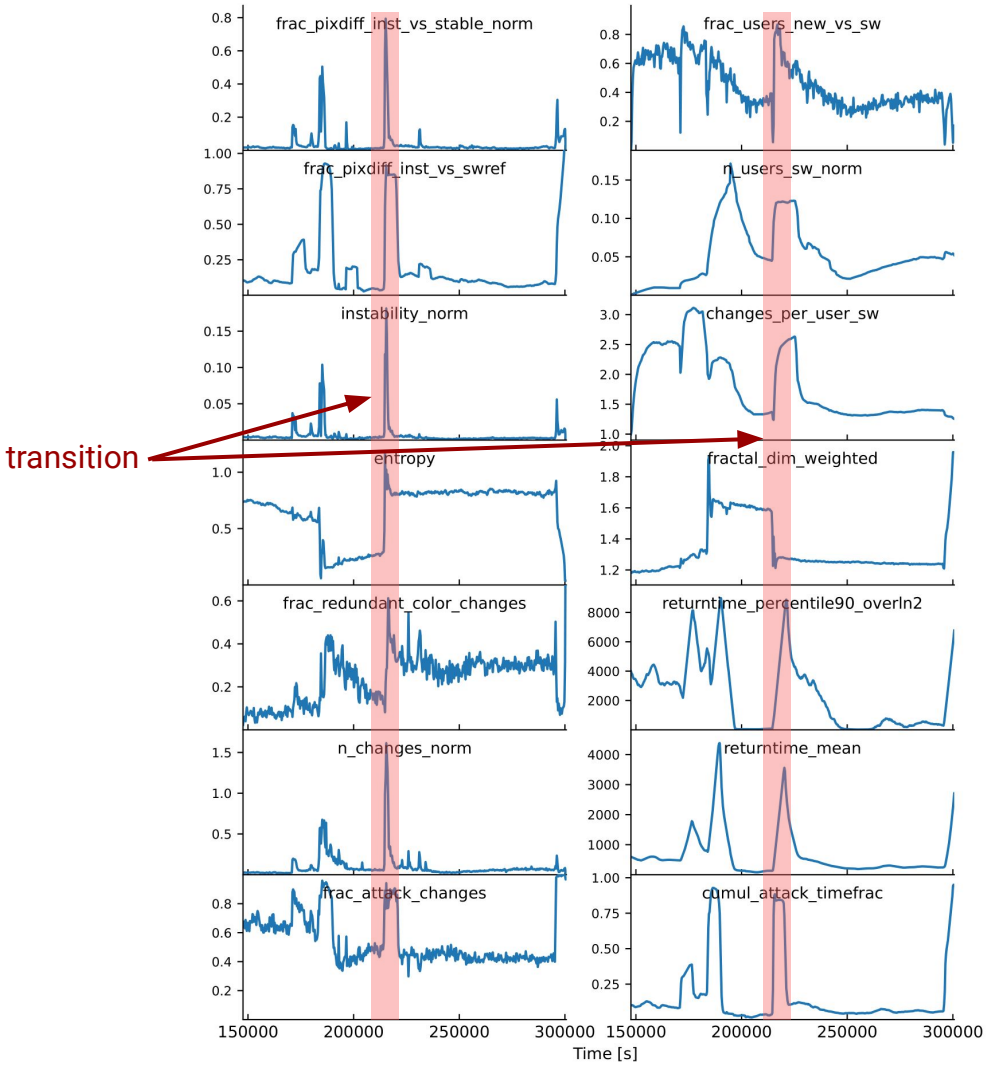
- Identify the transitions
- Predict **if/when they arrive** (early warning signals) with **good signal/noise** ratio
- Use **machine learning** to improve standard EWS indicators

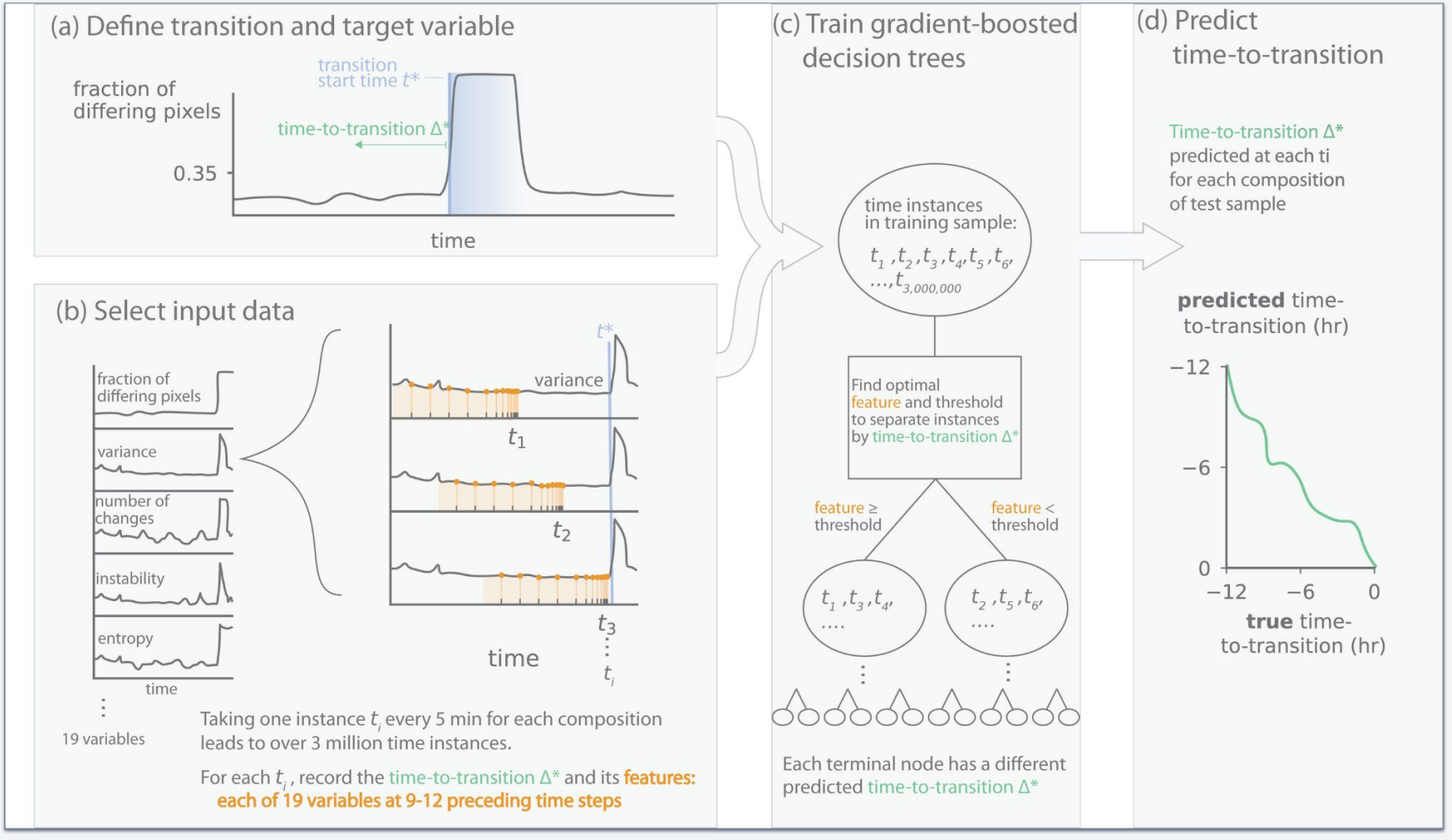
Ultimately, this could provide:

- **Generalizable insights on EWS for socio-ecological systems**
- Methods directly applicable to systems that have enough data

Time series for a single composition

Characteristic behavior of each variable near and at the transition!

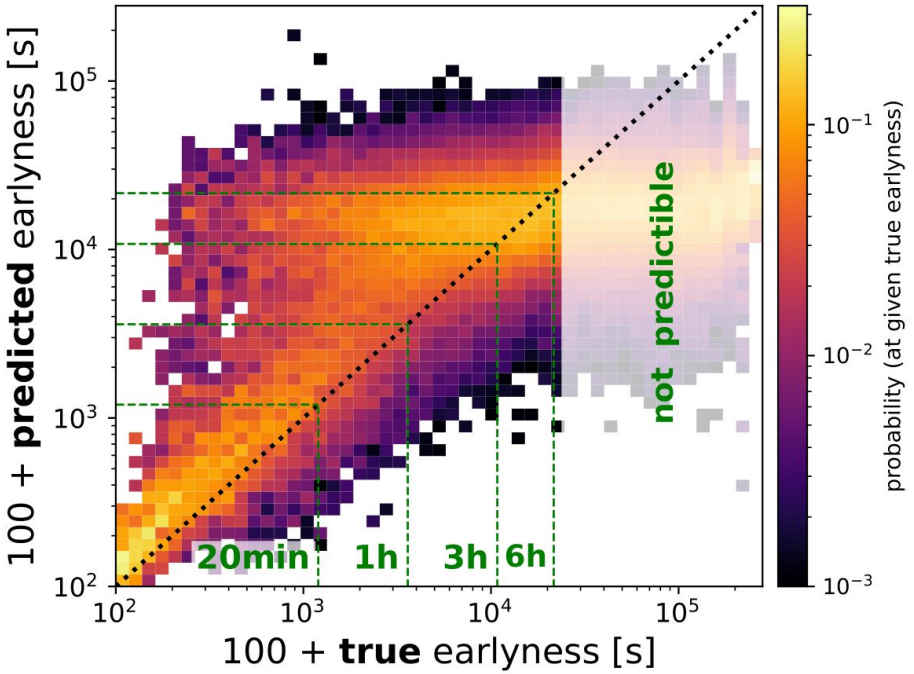


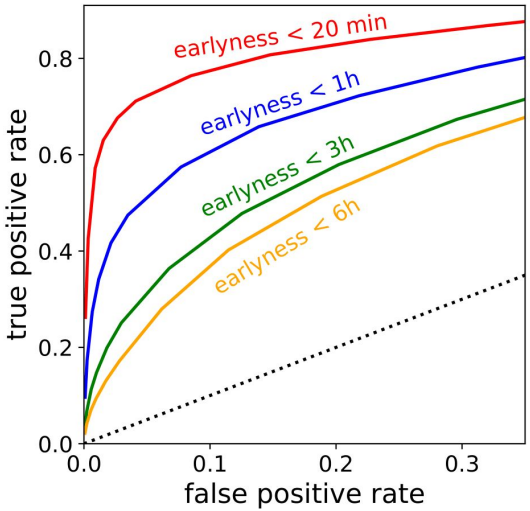

(a) Define transition and target variable
fraction of differing pixels
transition start time t*
time-to-transition Δ*
0.35
time
(b) Select input data
fraction of differing pixels
variance
number of changes
instability
entropy
time
19 variables
t*
variance
t1
t2
t3
ti
time
Taking one instance ti every 5 min for each composition leads to over 3 million time instances.
For each ti , record the time-to-transition Δ* and its features: each of 19 variables at 9-12 preceding time steps
(c) Train gradient-boosted decision trees
time instances in training sample:
t1 ,t2 ,t3 ,t4 ,t5 ,t6 , ...,t3,000,000
Find optimal feature and threshold to separate instances by time-to-transition Δ*
feature ≥ threshold
feature < threshold
t1 ,t3 ,t4 , ...
t2 ,t5 ,t6 , ...
Each terminal node has a different predicted time-to-transition Δ*
(d) Predict time-to-transition
Time-to-transition Δ* predicted at each ti for each composition of test sample
predicted time-to-transition (hr)
−12
−6
0
−12
−6
0
true time-to-transition (hr)

Learning about early warning signals

We obtain **predictive power for coming transitions, up to a few hours** before they arrive!

Bias towards high earlyness values?
Because everything above >6h is unpredictable…
In the future: classification first, then regression on the classification output





Convert result into **binary classification** where signal is “true earlyness < xx hours” and classifier is “predicted earlyness”

⇨ ROC curves, true and false positive rates, …

earlyness condition	**true positive** rate	**false positive** rate
< 20 min	**50%**	**0.6%**
< 1 hour	**50%**	**4.6%**
< 6 hours	**50%**	**18%**

Predict **half of “earlyness < 20 minutes”** events with **only 0.6% false positives**!

Interpretability?