Resilience in social-ecological systems: identifying stable and unstable equilibria with agent-based models

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Mountain socio-ecological systems

Main factors

Settlement development

Encroachment

Climate change

Land use change since 1700

Forest

Pasture

Settlement

(Kotlarski et al., 2012, Climate Change)

(Brunner and Grêt-Regamey, GEC, 2016)
Mountain socio-ecological systems

Level 1: global scenarios

Level 2: shocks

Level 3: policy strategies

(Brunner and Grêt-Regamey, Environmental Science and Policy, 2016.)
Resilience of socio-ecological systems

Regional scale

Local scale

(Grêt-Regamey et al., Nature Sustainability, 2019.)
The importance of equilibria in systems

All systems are characterised by “push” and “pull” factors:

Ecology/demography: Birth vs. death
Economy: Production vs. consumption
Agriculture/Forestry: Growth vs. harvest
Environment: Evaporation vs. precipitation

Equilibrium: push rate = pull rate

(Van Strien, ., Huber, S. H., Andereis, M., Grêt-Regamey, A. in review, Ecology and Society)
The importance of equilibria in systems

![Graph showing the relationship between system state (number of trees) and annual change (trees/year). The graph includes lines for harvest, natural growth, and an equilibrium point.](image-url)
The importance of equilibria in systems

The graph shows the relationship between the annual change in the number of trees and the system state (number of trees). The graph includes two lines:

- The red line represents the harvest rate.
- The blue line represents the natural growth rate.

The green dot indicates a stable equilibrium point where the harvest and natural growth rates are in balance. The graph also includes arrows indicating the direction of change as the system state increases or decreases.
The importance of equilibria in systems
The importance of equilibria in systems

The graph illustrates the relationship between the system state (number of trees) and the annual change (trees/ year). The graph shows two lines: one for harvest and another for natural growth. The point marked as unstable equilibrium indicates a critical point where small changes can lead to significant shifts in the system.
The importance of equilibria in systems

- Unstable equilibrium
- Stable equilibrium

The graph shows the relationship between annual change in the number of trees and the system state. The red line represents harvest, the green line represents natural growth, and the black arrows indicate the system state (number of trees). The graph highlights unstable and stable equilibria points.
The importance of equilibria in systems

Assume the natural growth function is reacting to climate change (i.e. external system stressor)
The importance of equilibria

Bifurcation diagram (meta-model of system)

The importance of equilibria in systems

Bifurcation diagram (meta-model of system)
The importance of equilibria in systems

Bifurcation diagram (meta-model of system)

- Catastrophic bifurcations
- Critical transitions
- Tipping points
The importance of equilibria in systems

Science, 2012

Anticipating Critical Transitions

Marten Scheffer1,2, Stephen R. Carpenter3, Timothy M. Lenton4, Jordi Bascompte5, William Brock5, Vasiliis Dakos4, Victor Brovkin5, Stephen R. Carpenter1, Vasilis Dakos4, Hermann Held6, Egbert H. van Nes4, Max Rietkerk7 & George Sugihara8

Tipping points in complex systems may imply risks of unbalanced collapse, but also opportunities for positive change. Our capacity to navigate such risks and opportunities can be boosted by combining emerging insights from interconnected fields of research. One line of work is focusing on the role of equilibria in systems. Equilibria can provide fundamental architectural features that may cause ecological networks, financial markets, and other complex systems to have tipping points. Another field of research is uncovering emerging fields of research. This section highlights several examples of how equilibria can help us understand the dynamics of complex systems.

PNAS, 2008

Slowing down as an early warning signal for abrupt climate change

Vasilis Dakos4, Marten Scheffer1, Egbert H. van Nes4, Victor Brovkin5, Vladimir Petoukhov7 & Hermann Held6

In the Earth's history, periods of relatively stable climate have often been interrupted by abrupt changes to contrasting states. One explanation for such events of abrupt climate change is that the Earth system reached a critical tipping point. However, this remains hard to prove for events in the recent past. Here, we present a generic model that allows us to test for a generic early warning signal for abrupt climate change. Although most existing climate models are not able to capture these early warning signals, recent developments in the field of climate dynamics may provide a way forward.

Nature, 2009

Early-warning signals for critical transitions

Marten Scheffer1, Jordi Bascompte5, William A. Brock3, Victor Brovkin5, Stephen R. Carpenter4, Vasilis Dakos4, Hermann Held6, Egbert H. van Nes4, Max Rietkerk7 & George Sugihara8

Complex dynamical systems, ranging from ecosystems to financial markets and the climate, can have tipping points at which a sudden shift to a contrasting dynamical regime may occur. Although predicting such critical points before they are reached is extremely difficult, work in different scientific fields is now suggesting the existence of generic early-warning signals that may indicate for a wide class of systems if a critical threshold is approaching.
Identifying stable and unstable equilibria with agent-based models

**Model**: ALUAM-AB, which simulates land-use changes in mountain landscapes based on land-use decisions of individual farmers under a range of socio-economic, political and ecological constraints.

**System state**: area of intensive and extensive agriculture.

**External system stressors**: Prices for agricultural produce, subsidy policies, or climate (showing results for agricultural direct payments).

**Simulations**: 350 model runs with different initial land-use configurations and different values of direct payments for 10-year periods. Other input settings were randomised as much as possible.

**Analysis of simulation output**: Assess the rate and direction of change in intensive and extensive agriculture with linear regression.
Identifying stable and unstable equilibria with agent-based models

Direction-field plots

A

B

Area intensive agriculture (ha)

Area extensive agriculture (ha)

Multiplication factor direct payments

Multiplication factor direct payments

0 1 2 3 4 5 6

0 1 2 3 4 5 6
Identifying stable and unstable equilibria with agent-based models

Stability landscapes
Identifying stable and unstable equilibria with agent-based models

Bifurcation diagrams making use of support-vector machine classification

A

Initial area intensive agriculture (ha)

6000

5000

4000

3000

2000

1000

0

Multiplication factor direct payments

0.0

0.5

1.0

1.5

2.0

B

Initial area extensive agriculture (ha)

4000

3000

2000

1000

0

Multiplication factor direct payments

0.0

0.5

1.0

1.5

2.0

Simulations
- Area increasing
- Area decreasing
- No change

SVM classification
- Positive growth class
- Negative growth class

Equilibria
- Stable equilibrium
- Unstable equilibrium
Identifying stable and unstable equilibria with agent-based models

Minimum amount of direct payments necessary for extensification to take place

\[\text{Simulations}
\begin{itemize}
\item Area increasing
\item Area decreasing
\item No change
\end{itemize}
\]

\[\text{SVM classification}
\begin{itemize}
\item Positive growth class
\item Negative growth class
\end{itemize}
\]

\[\text{Equilibria}
\begin{itemize}
\item Stable equilibrium
\item Unstable equilibrium
\end{itemize}\]
Identifying stable and unstable equilibria with agent-based models

In a system with 2500 ha of intensive agriculture, increasing the current direct payments with 50% (1.0 = current level) will cause the area of intensive to shrink.
**Identifying stable and unstable equilibria with agent-based models**

The intensive agriculture will always decrease in a system with < 1200 ha and direct payments > 0.4.