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

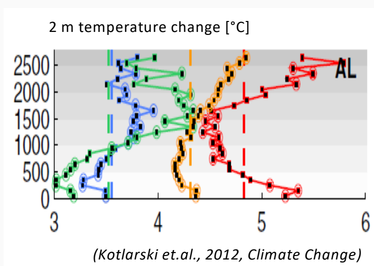
Maarten J. van Strien, Sibyl H. Huber, John M. Anderies, Adrienne Grêt-Regamey

Mountain socio-ecological systems

Main factors

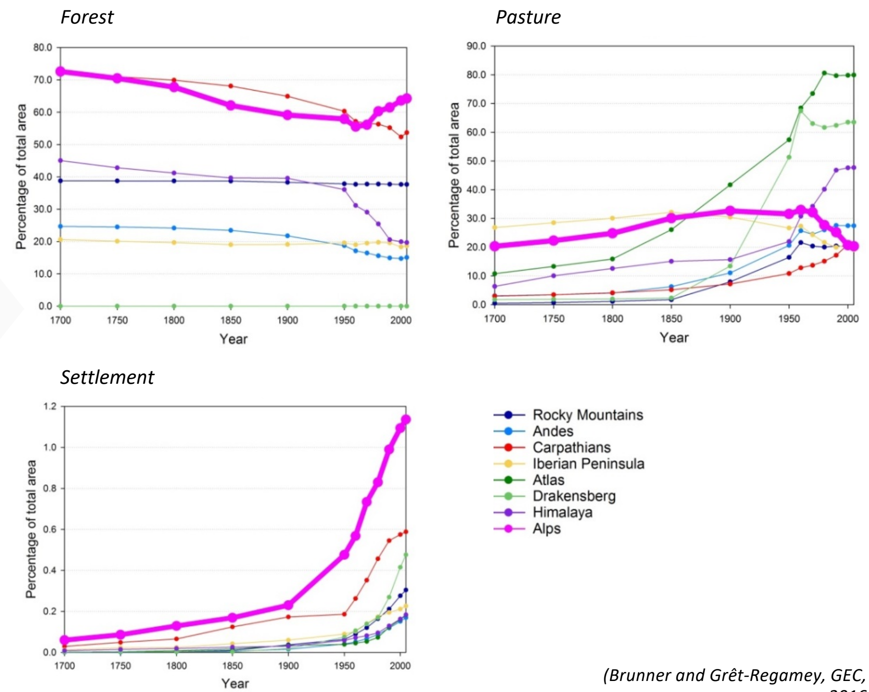
Settlement development

Encroachment



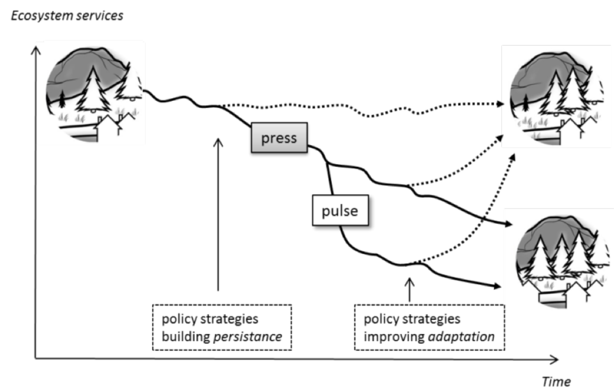
Climate change

Land use change since 1700



(Brunner and Grêt-Regamey, GEC, 2016)

Mountain socio-ecological systems

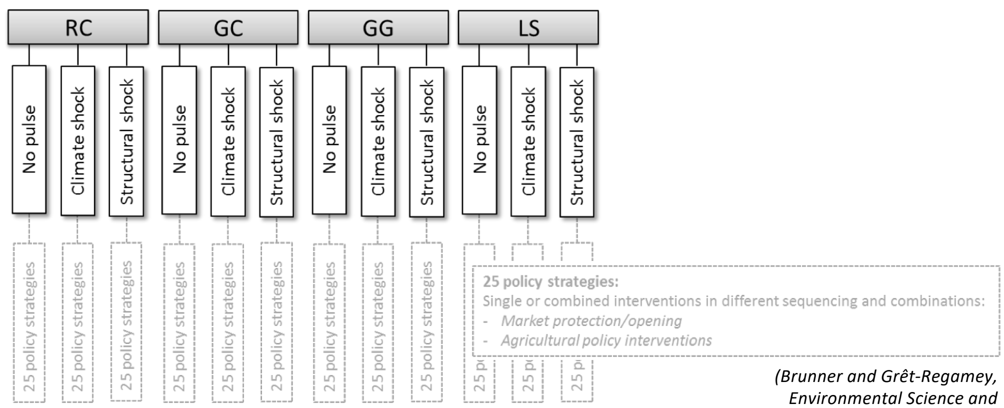


Valais

Level 1: global scenarios

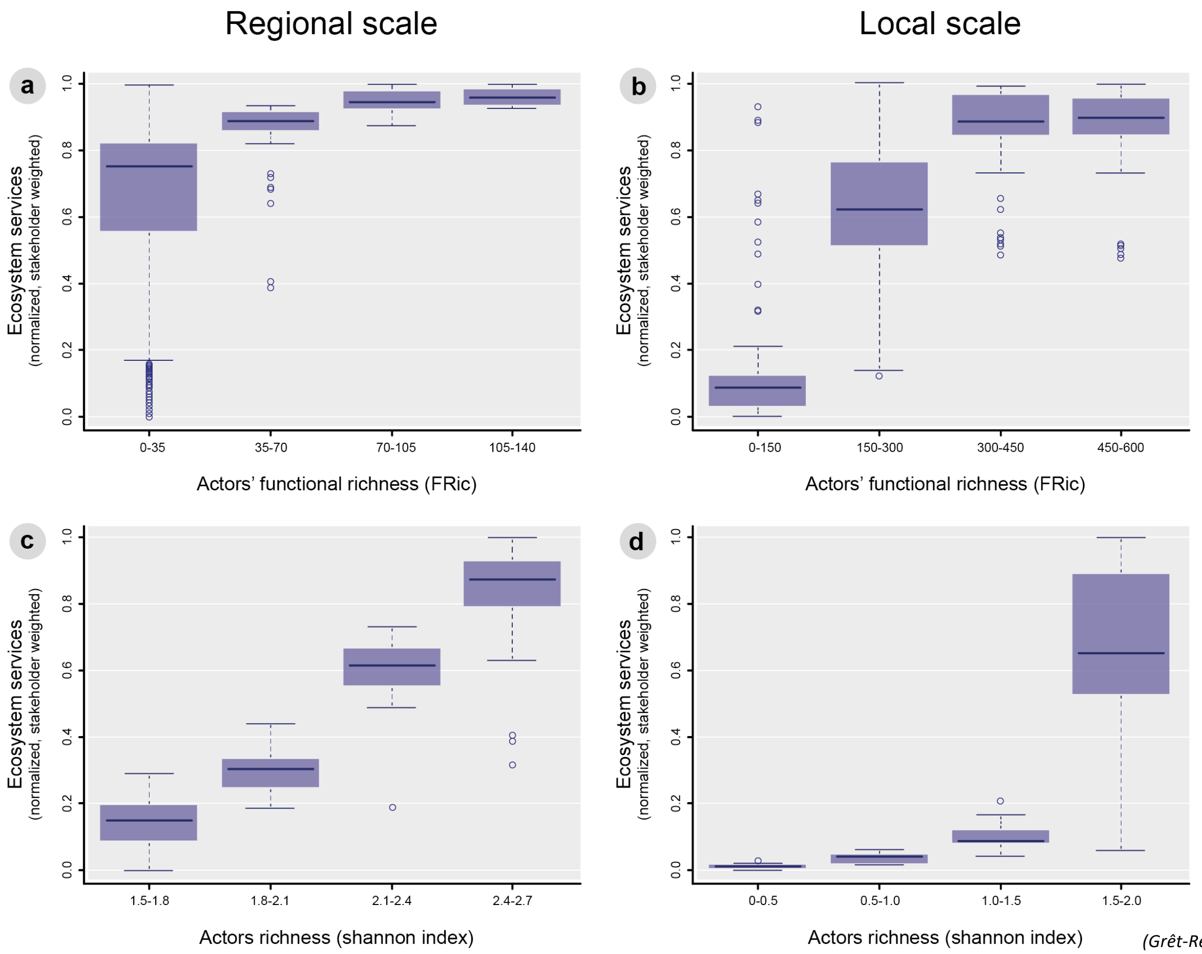
Level 2: shocks

Level 3: policy strategies



(Brunner and Grêt-Regamey, Environmental Science and Policy, 2016.)

Resilience of socio-ecological systems



(Grêt-Regamey et al., Nature Sustainability, 2019.)

The importance of equilibria in systems

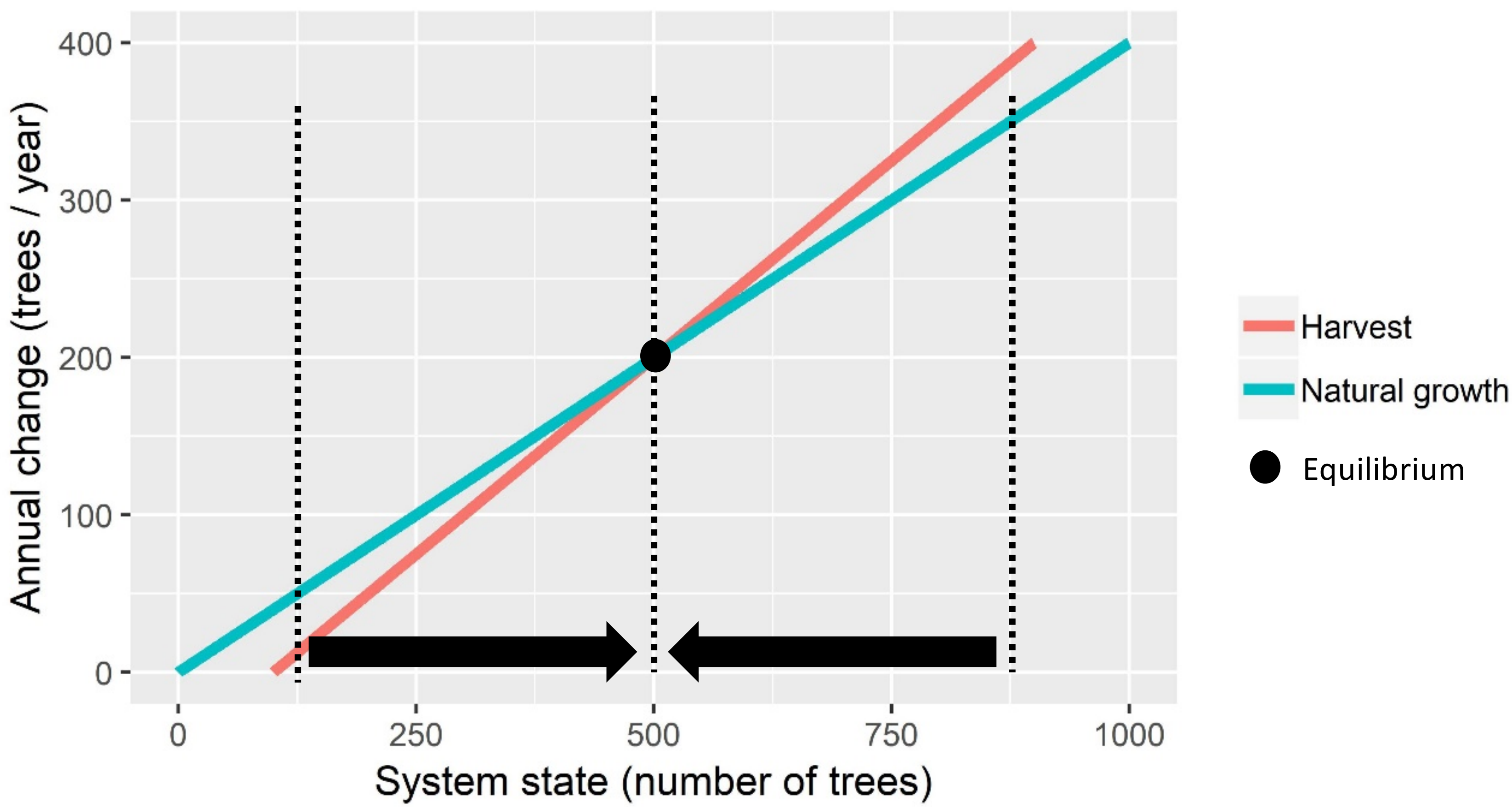
All systems are characterised by “push” and “pull” factors:

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

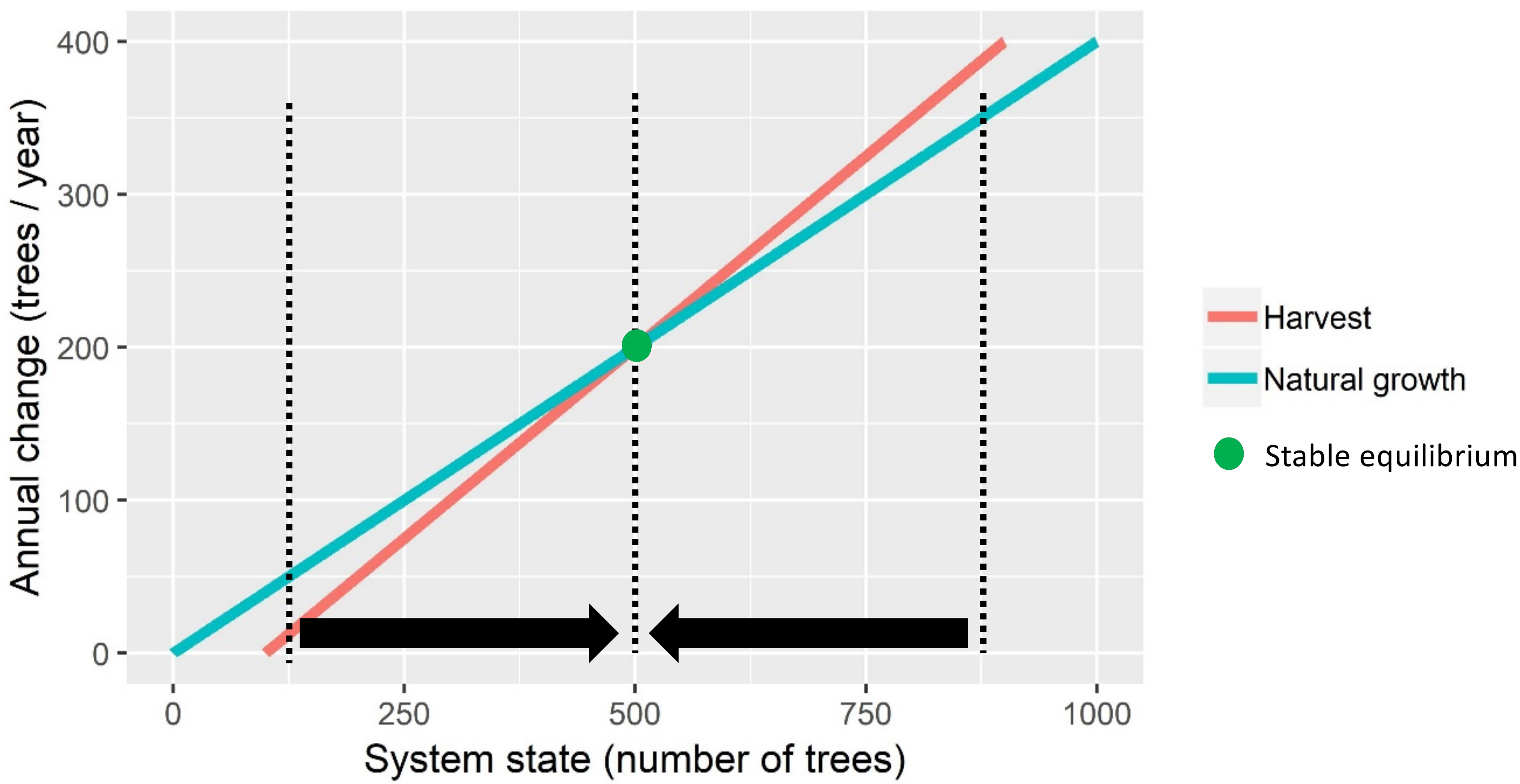
Equilibrium: push rate = pull rate

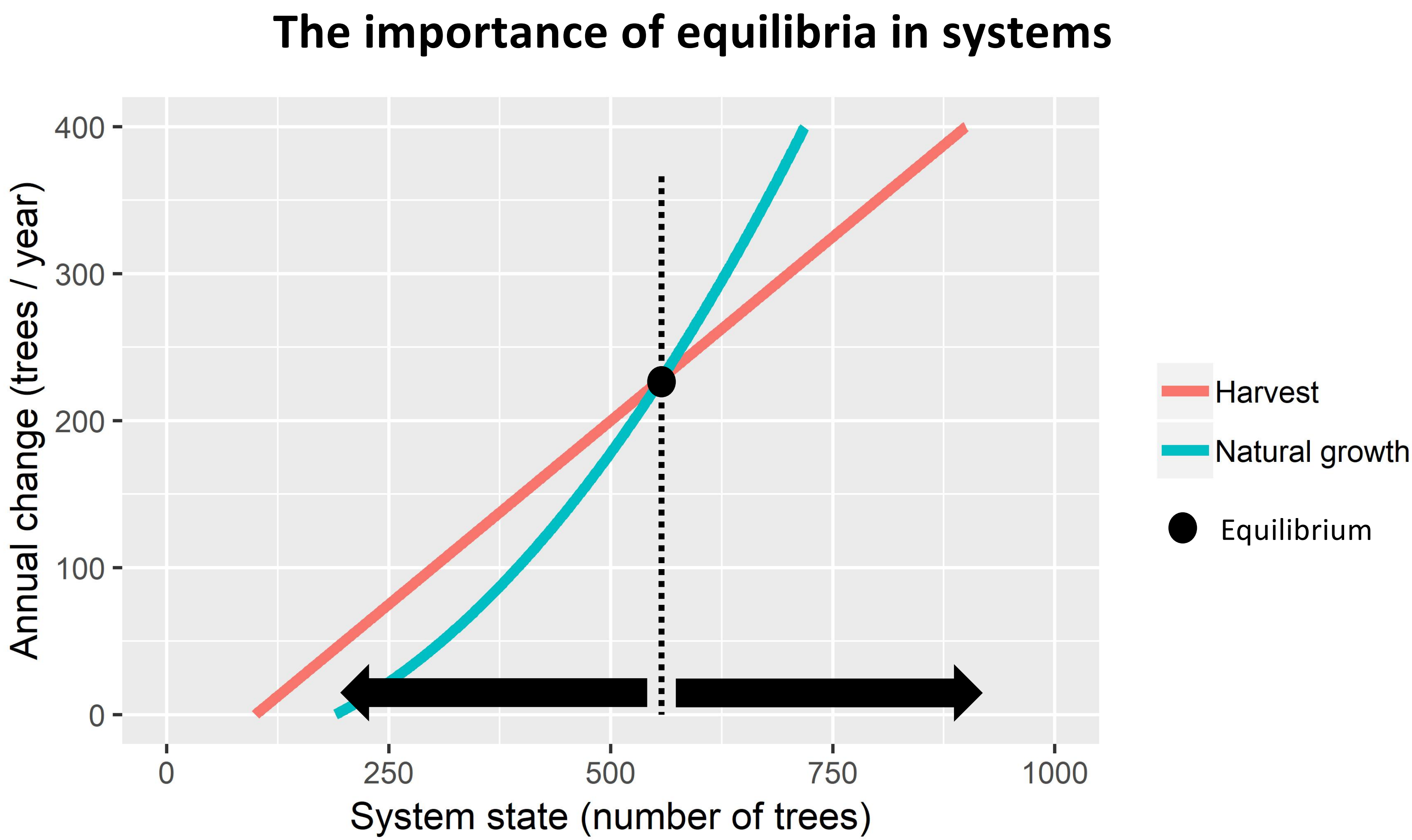
(Van Strien, ., Huber, S. H., Andereis, M., Grêt-Regamey, A. in review , Ecology and Society)

The importance of equilibria in systems

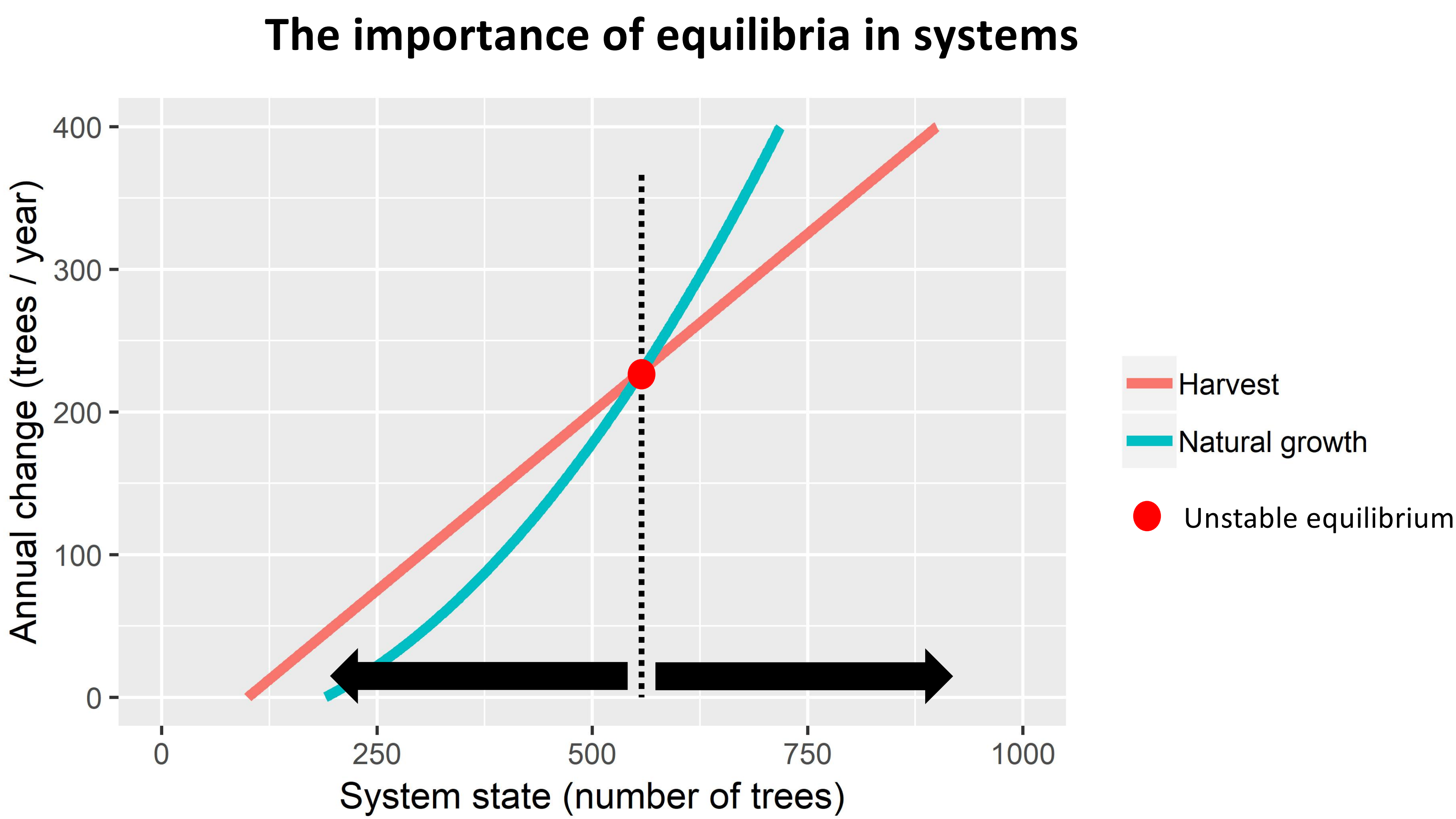


The importance of equilibria in systems

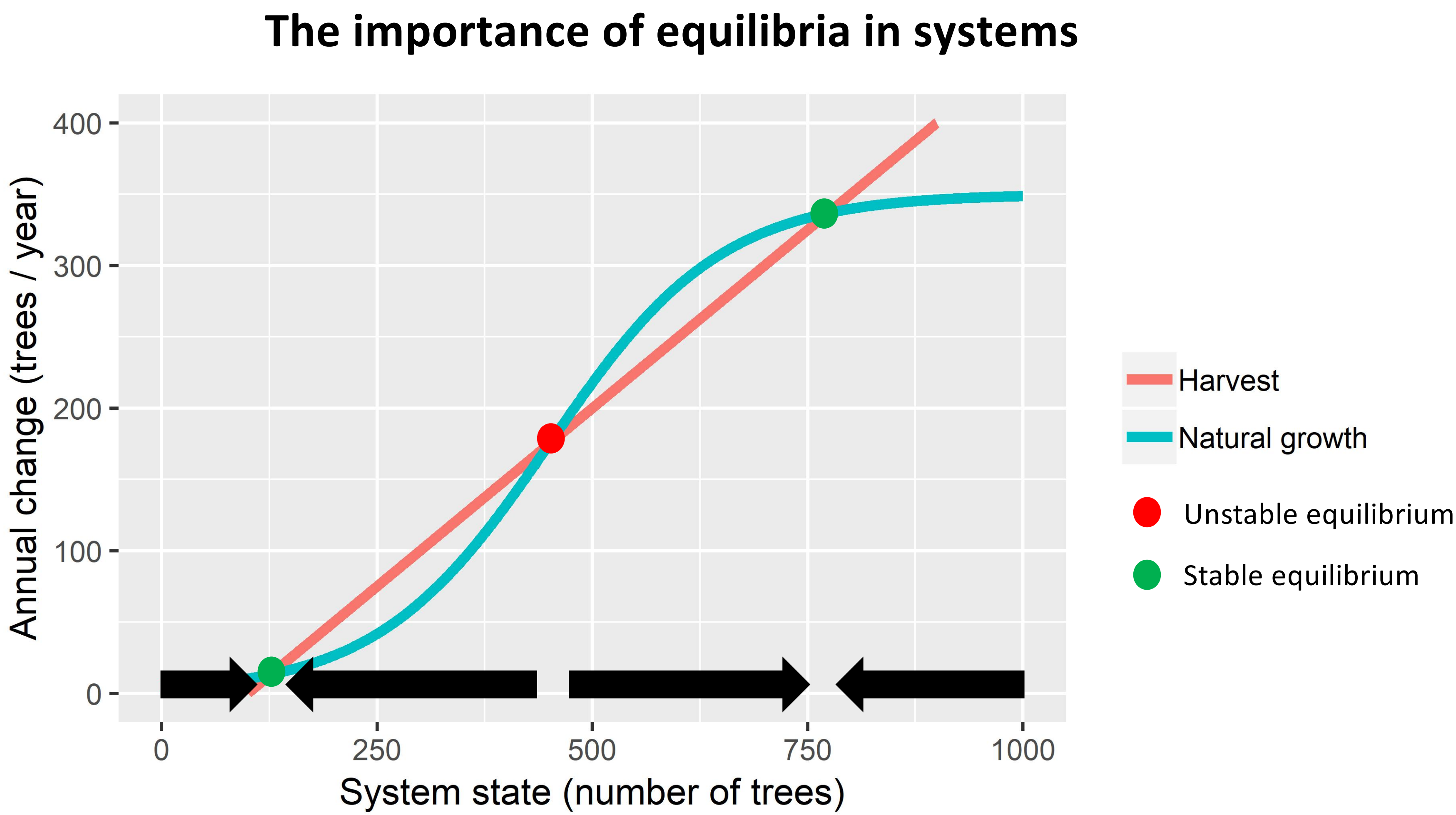




The importance of equilibria in systems
Annual change (trees / year)
400
300
200
100
0
0
250
500
750
1000
System state (number of trees)
Harvest
Natural growth
Equilibrium



The importance of equilibria in systems
400
300
200
100
0
0
250
500
750
1000
Annual change (trees / year)
System state (number of trees)
Harvest
Natural growth
Unstable equilibrium


The importance of equilibria in systems
400
300
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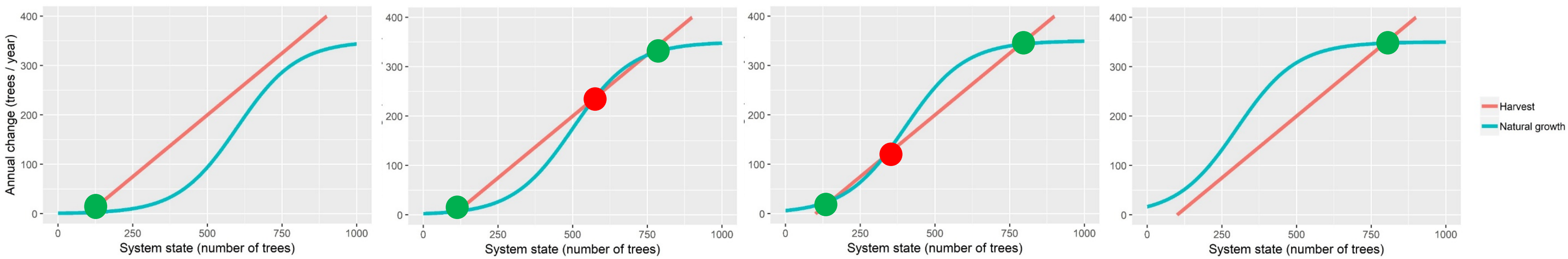
100
0
Annual change (trees / year)
0
250
500
750
1000
System state (number of trees)
Harvest
Natural growth
Unstable equilibrium
Stable equilibrium

The importance of equilibria in systems

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

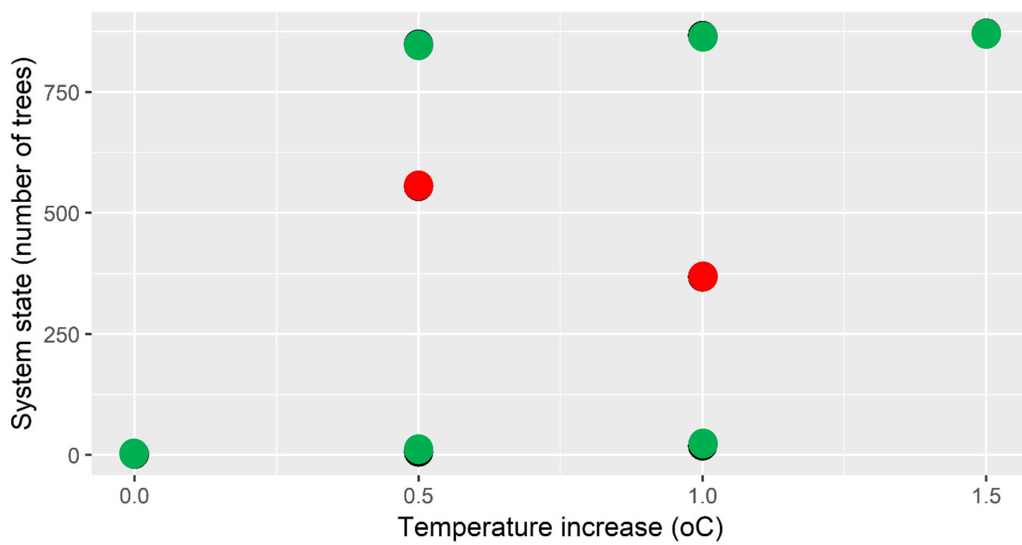


Current temperature

+0.5 °C

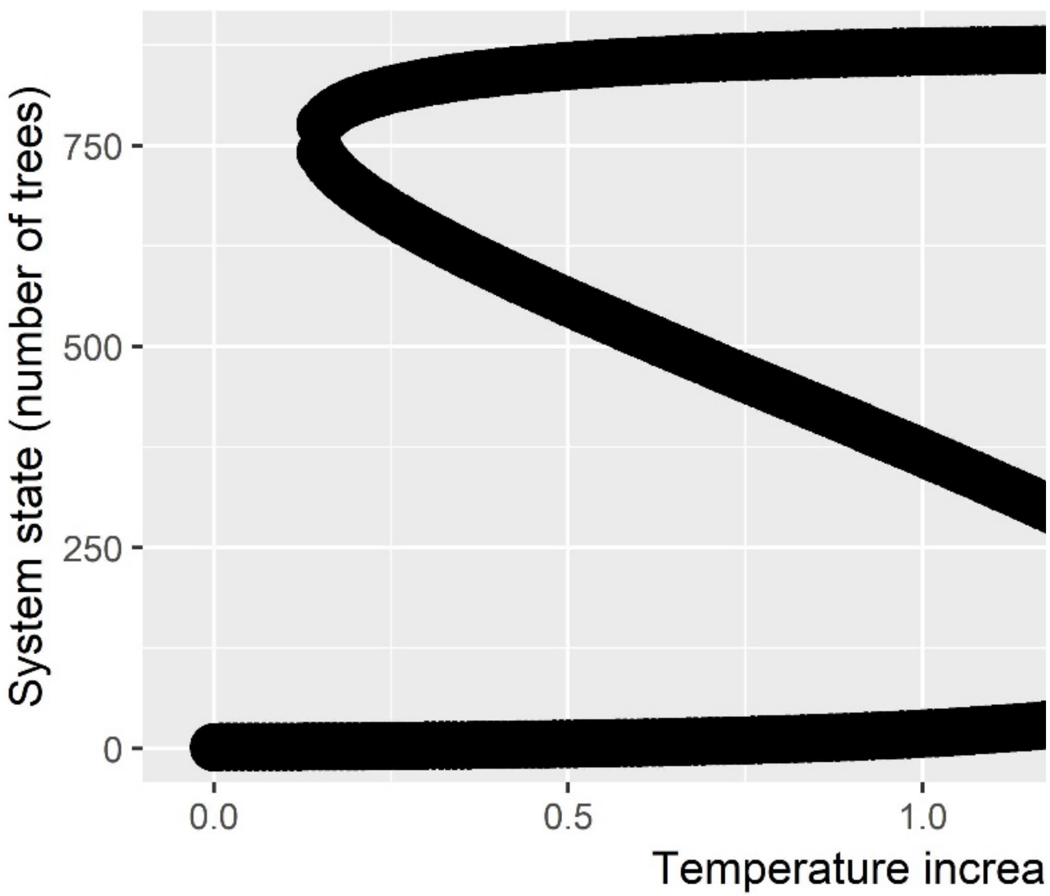
+1.0 °C

+1.5 °C

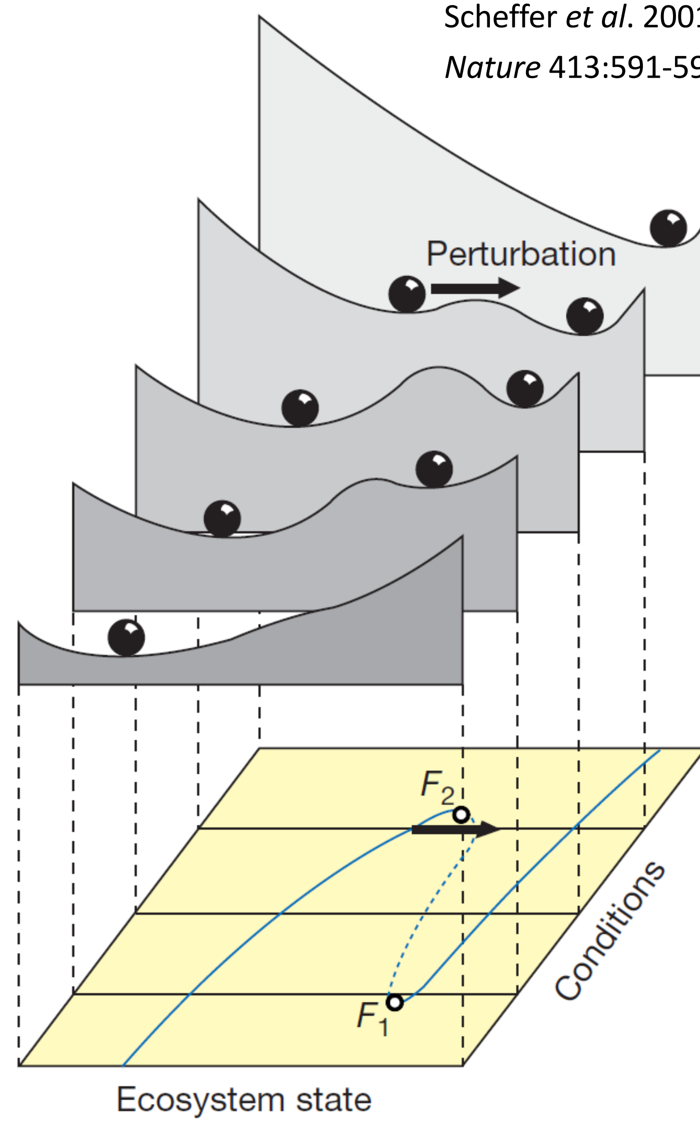


The importance of equilibri

Bifurcation diagram (meta-moc

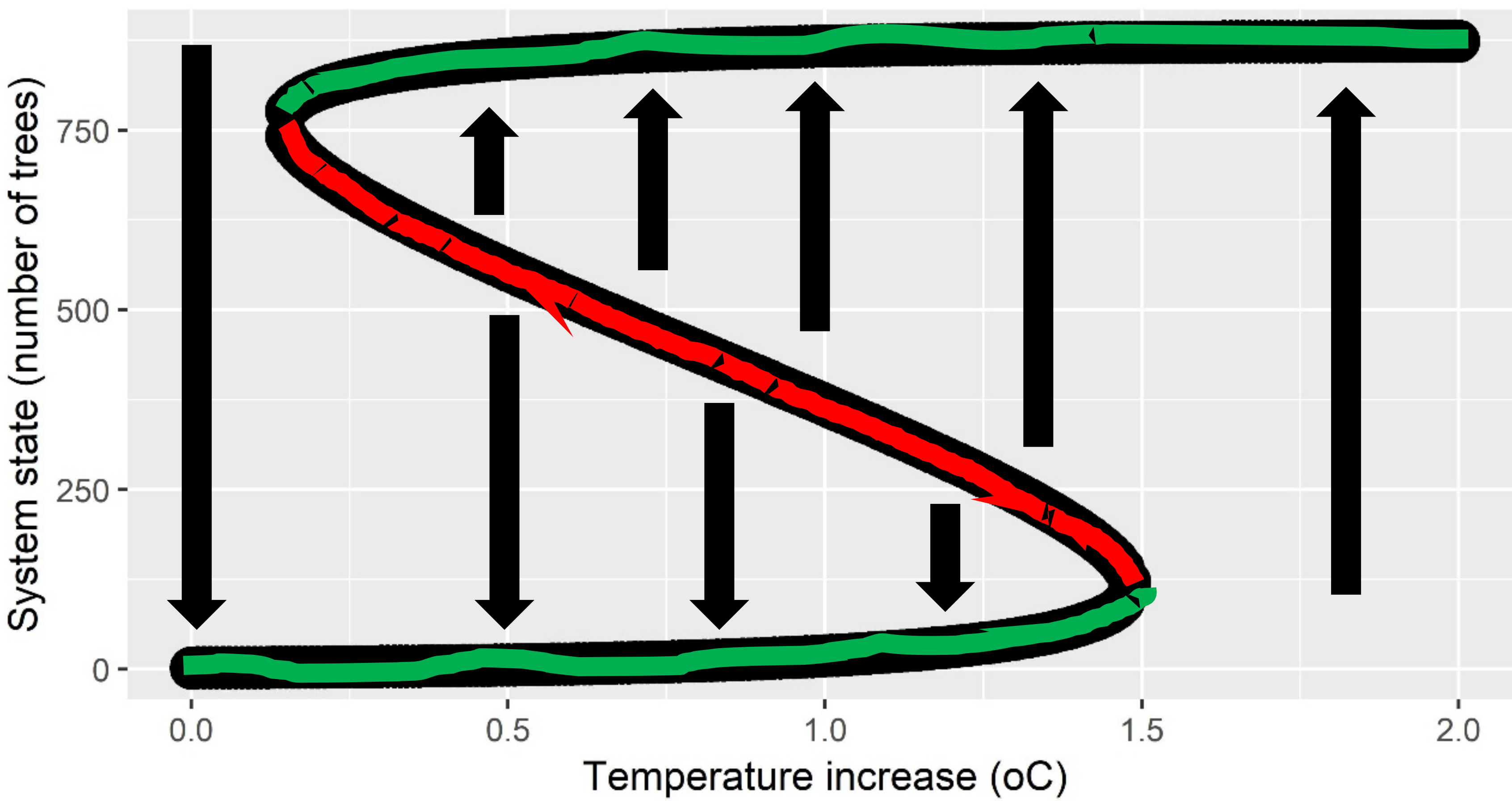


Scheffer *et al*. 2001.
Nature 413:591-596.



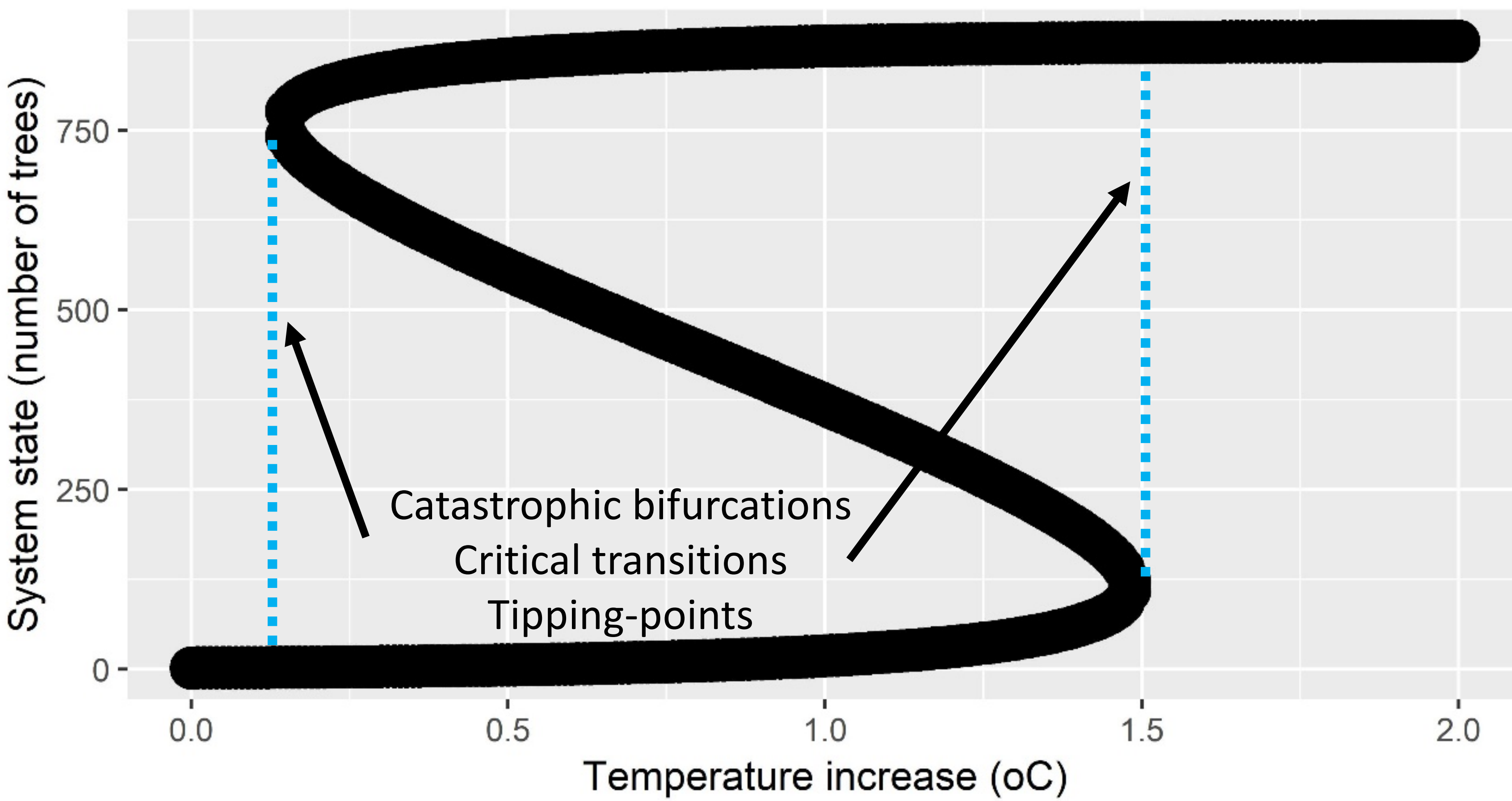
The importance of equilibria in systems

Bifurcation diagram (meta-model of system)



The importance of equilibria in systems

Bifurcation diagram (meta-model of system)



The importance of equilibria in systems

Science, 2012

Anticipating Critical Transitions

Marten Scheffer,[1,2*] Stephen R. Carpenter,[3] Timothy M. Lenton,[4] Jordi Bascompte,[5] William Brock,[6] Vasilis Dakos,[1,5] Johan van de Koppel,[7,8] Ingrid A. van de Leemput,[1] Simon A. Levin,[9] Egbert H. van Nes,[1] Mercedes Pascual,[10,11] John Vandermeer[10]

Tipping points in complex systems may imply risks of unwanted collapse, but also opportunities for positive change. Our capacity to navigate such risks and opportunities can be boosted by combining emerging insights from two unconnected fields of research. One line of work is revealing fundamental architectural features that may cause ecological networks, financial markets, and other complex systems to have tipping points. Another field of research is uncovering generic empirical indicators of the proximity to such critical thresholds. Although sudden shifts in complex systems will inevitably continue to surprise us, work at the crossroads of these emerging fields offers new approaches for anticipating critical transitions.

PNAS, 2008

Slowing down as an early warning signal for abrupt climate change

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Edited by Stephen R. Carpenter, University of Wisconsin, Madison, WI, and approved July 16, 2008 (received for review March 11, 2008)

In the Earth's history, periods of relatively stable climate have often been interrupted by sharp transitions to a contrasting state. One explanation for such events of abrupt change is that they happened when the earth system reached a critical tipping point. However, this remains hard to prove for events in the remote past, and it is even more difficult to predict if and when we might reach a tipping point for abrupt climate change in the future. Here, we

remain rather hypothetical because they are difficult to test. Even if the proposed mechanisms seem plausible, our capacity to model these systems accurately is too limited to conclude with reasonable certainty that tipping points are involved. This is particularly worrisome in view of the possibility of hitting on a tipping point as current climate change proceeds. Although most climate scientists would acknowledge that possibility, we are

Nature, 2009

Early-warning signals for critical transitions

Marten Scheffer[1], Jordi Bascompte[2], William A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1], Hermann Held[6], Egbert H. van Nes[1], Max Rietkerk[7] & George Sugihara[8]

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.

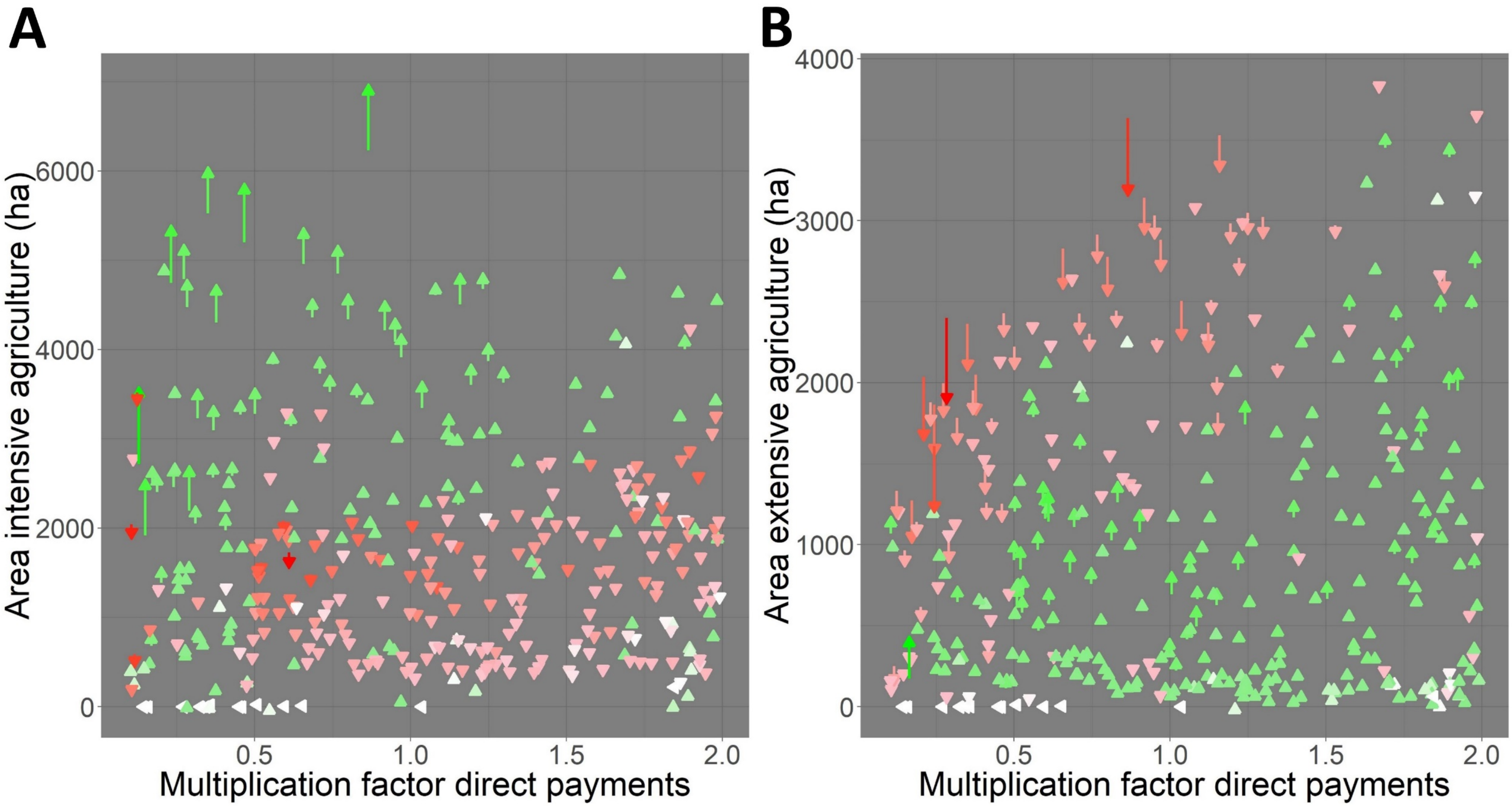
External system stressors: Prices for agricultural produce, subsidy policies, or climate (showing results for agricultural direct payments).

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.

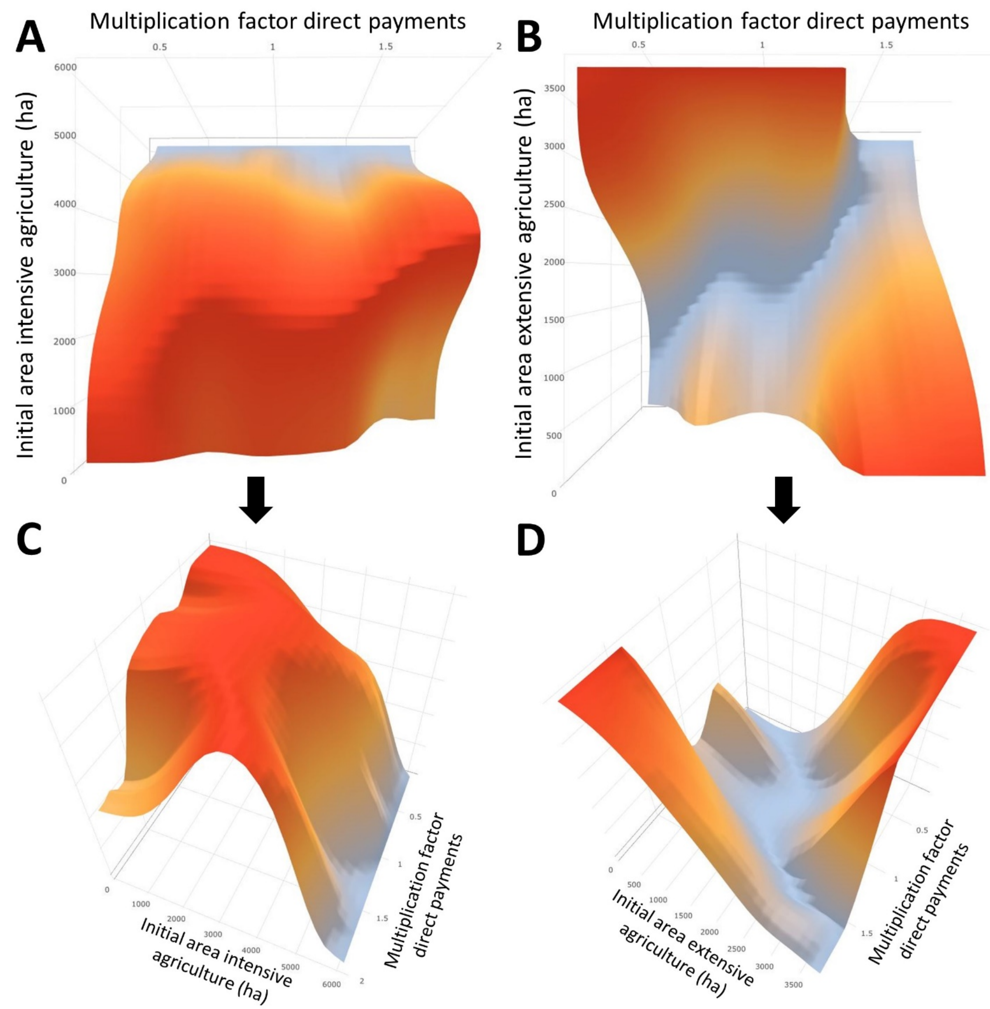
Identifying stable and unstable equilibria with agent-based models

Direction-field plots



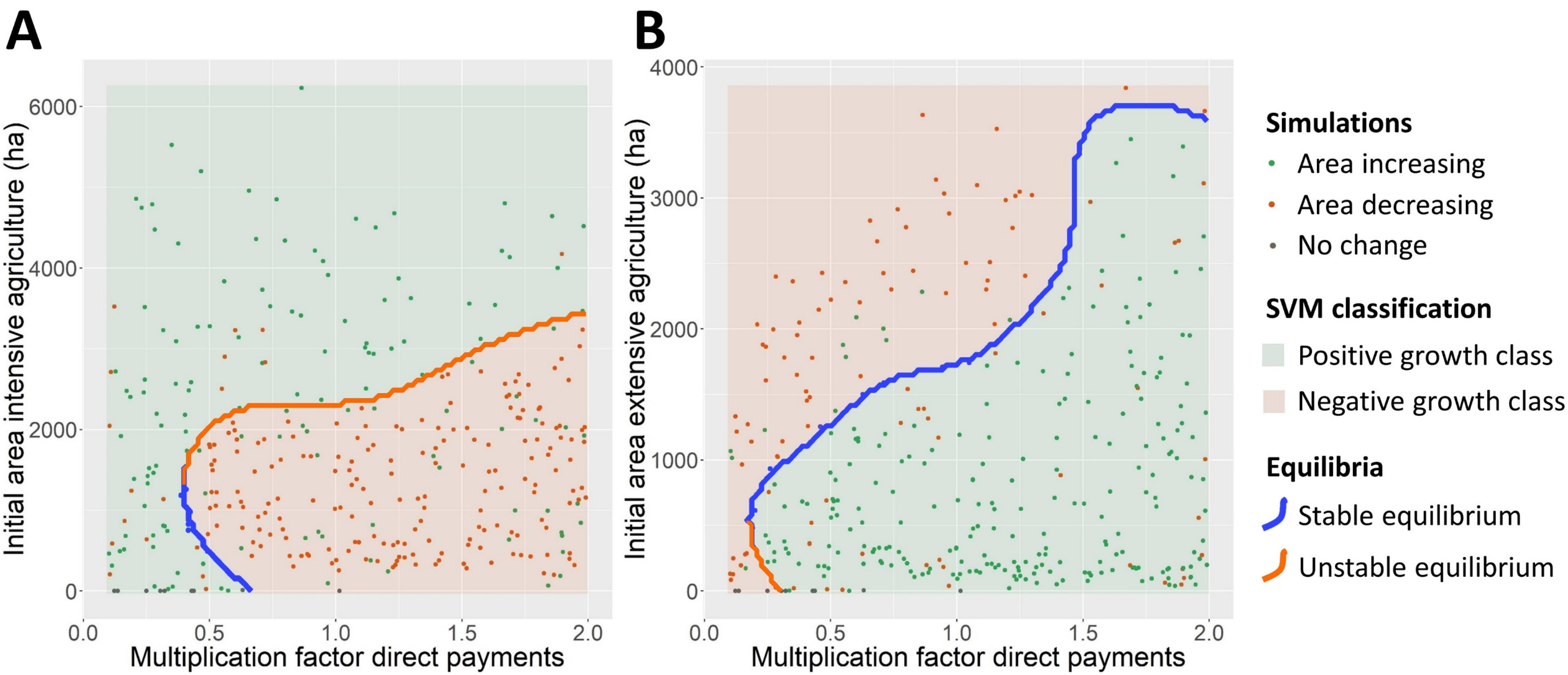
Identifying stable and unstable equilibria with agent-based models

Stability landscapes



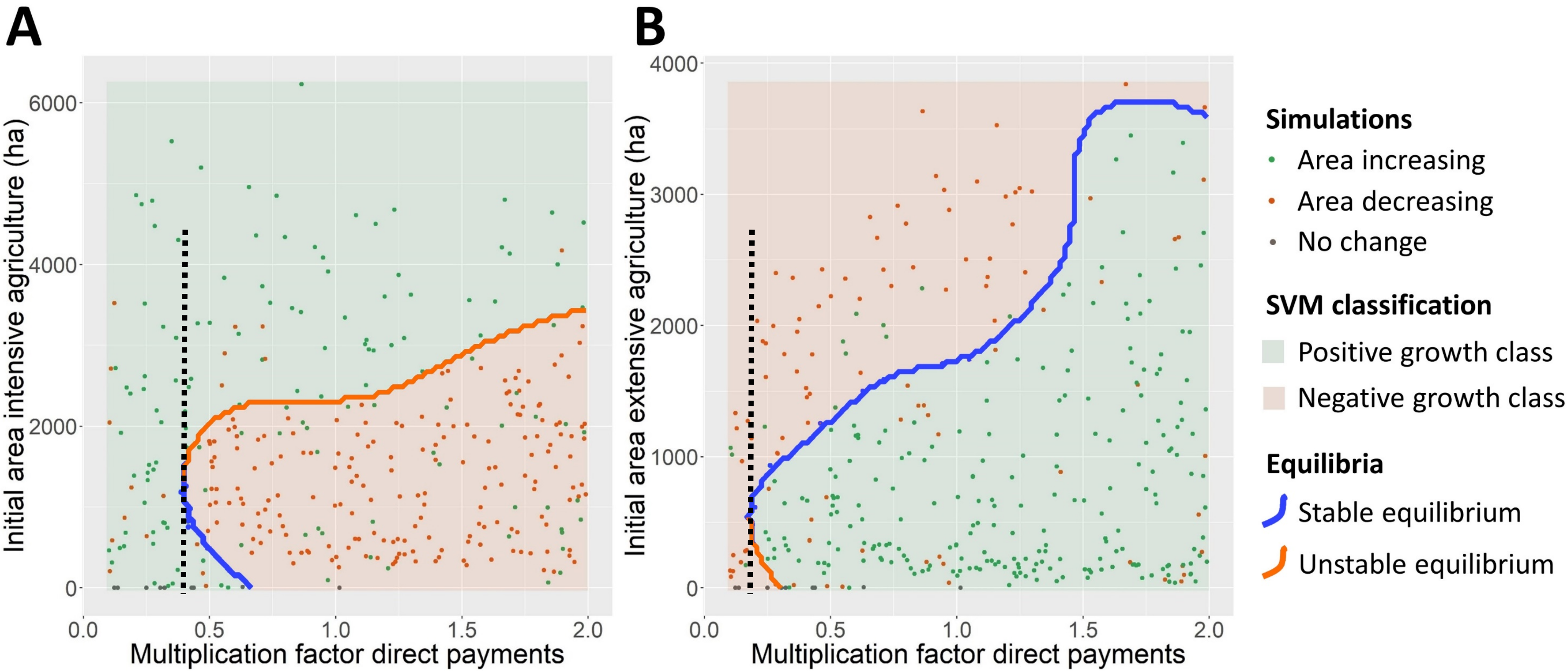
Identifying stable and unstable equilibria with agent-based models

Bifurcation diagrams making use of support-vector machine classification



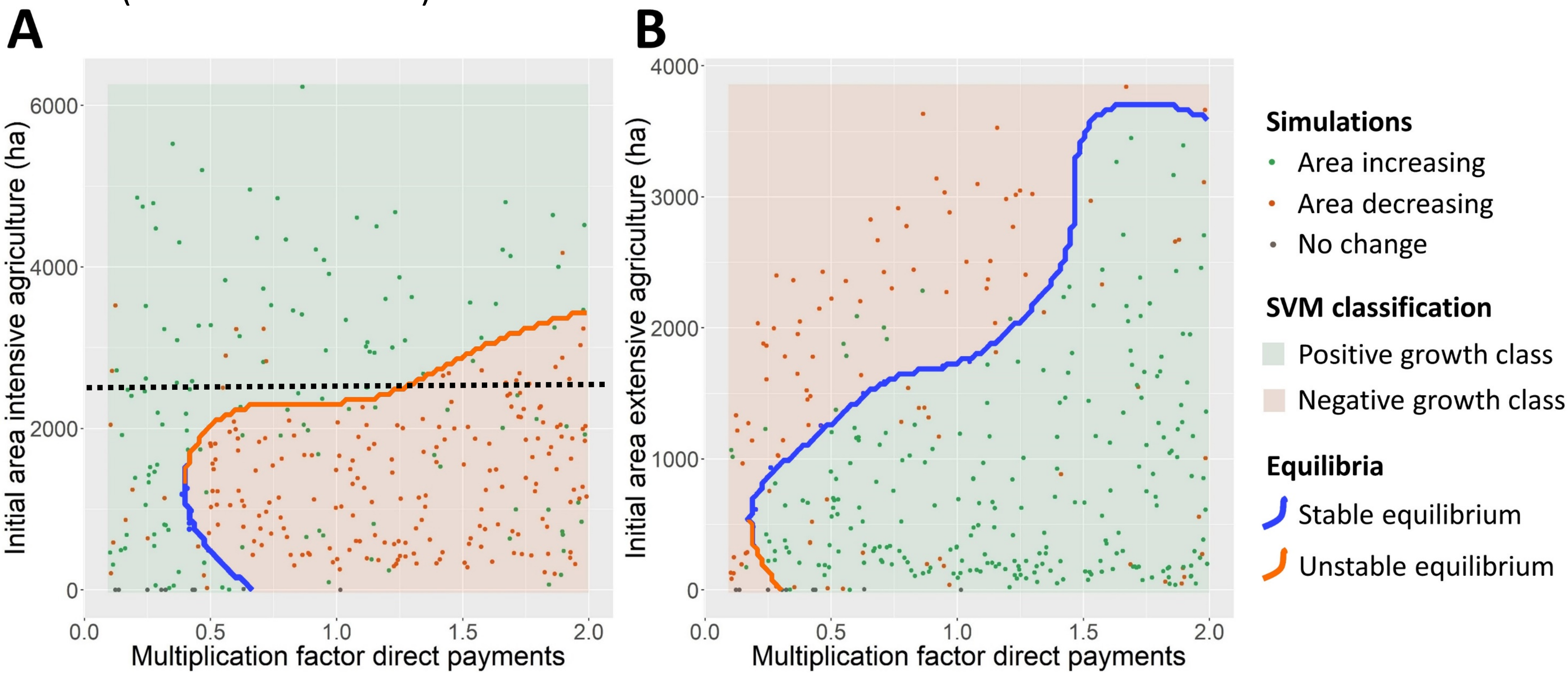
Identifying stable and unstable equilibria with agent-based models

Minimum amount of direct payments necessary for extensification to take place



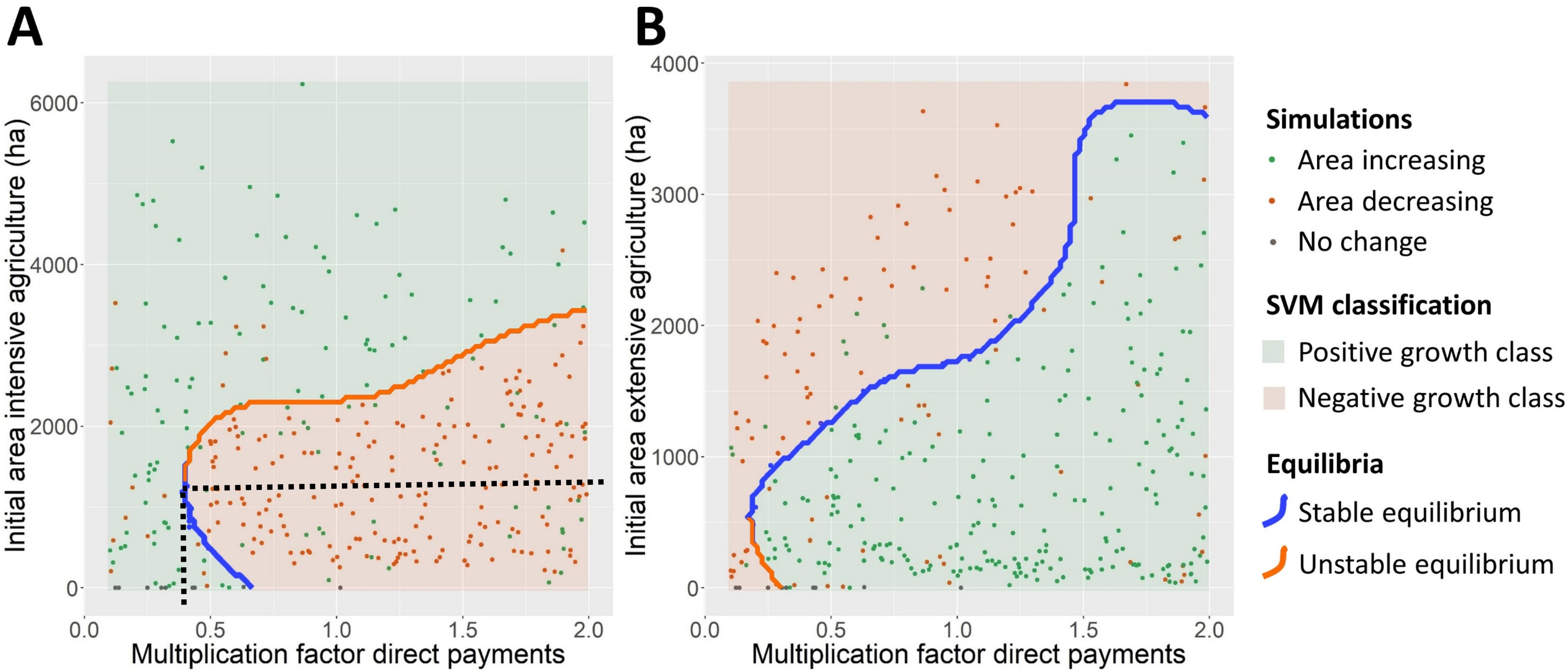
Identifying stable and unstable equilibria with agent-based models

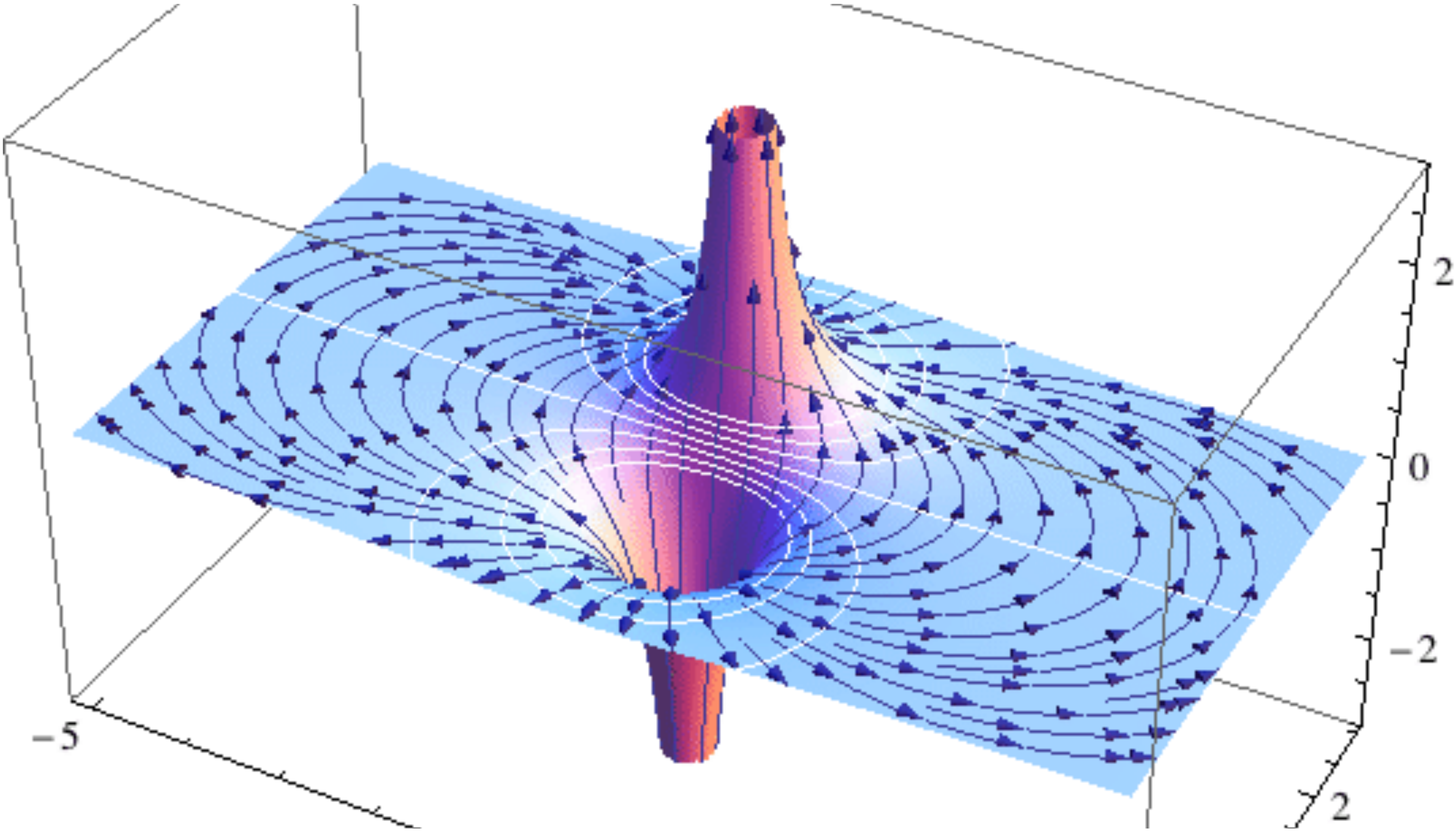
In a system with 2500 ha of intensive agriculture, increasing the current direct payments with 50 % (1.0 = current level) will cause the area of intensive to shrink.



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





2
0
−2
−5
2