Conceptualising Resilience in a Decision-theoretic Context

Michael Kuhn and Stefan Wrzaczek (IIASA)

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International Institute for Applied Systems Analysis (IIASA)

- Contribute to building sustainable, more resilient and fairer societies/economies
- Lead on applied systems analysis and integrated modelling
- Transform science into policy
- Build capacity to deal with global challenges
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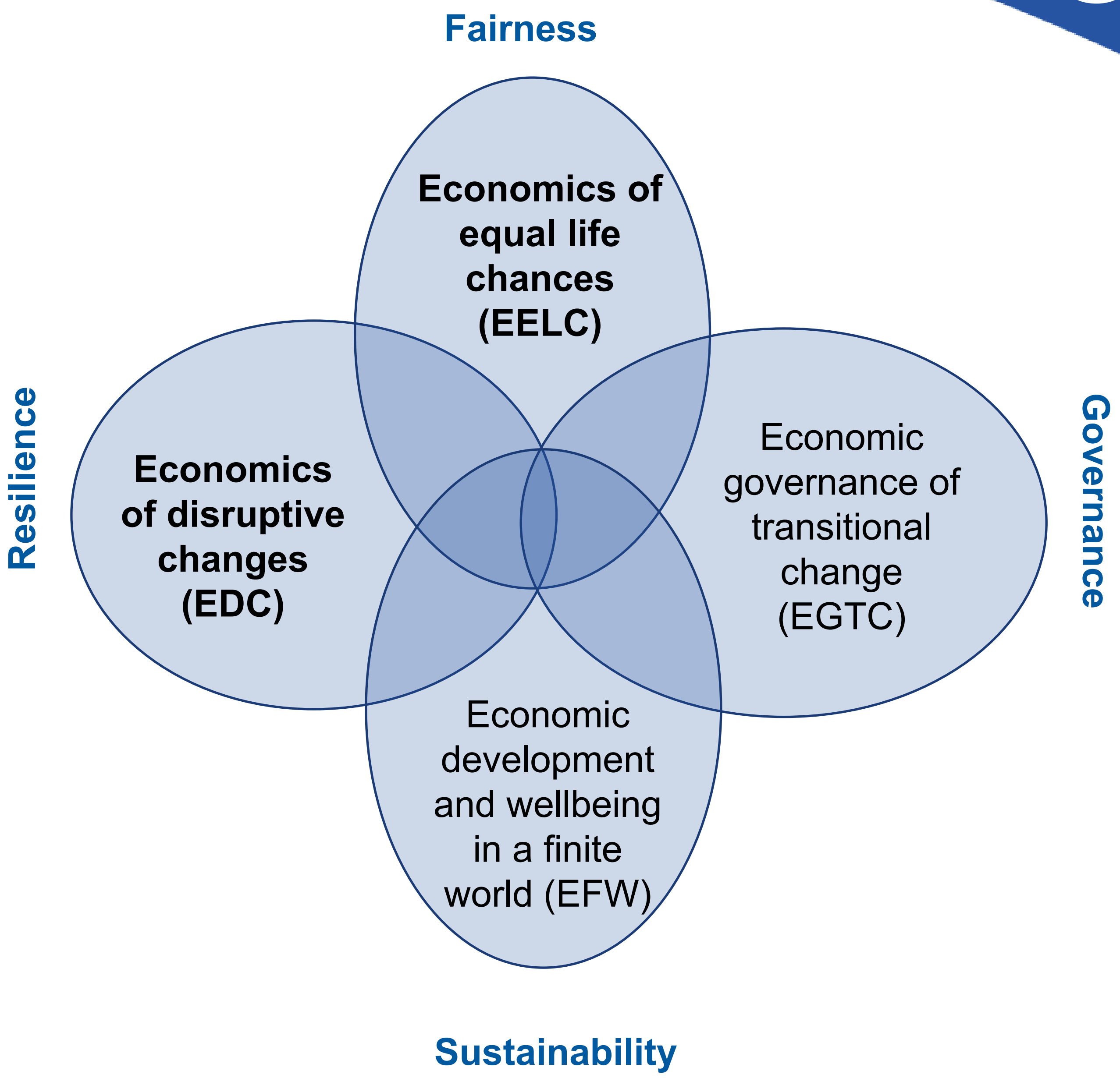
- ~400 staff (300 researchers)
- ~ 22 Mio EUR balance

Six Research Programs

- Advancing Systems Analysis
- Biodiversity and Natural Resources
- Energy, Climate, Environment
- Economic Frontiers
- Population and Just Societies
- Strategic Initiatives

Economic Frontiers

- What **behavioral changes** are required to achieve **social and environmental transformations?**
- What policies and **institutional reforms** are needed to bring about the **required incentives?**
- What **impact on wellbeing** across **social strata, geographical scales** and **time?**



Introduction

Background:

- Well-known measures of resilience based on eco-systems modelling (Holling 1973).
- Some socio-economic conceptualisations (Keating et al. 2014) but **few decision-theoretic formulations** to date (Polasky et al. 2011, Li et al. 2017).

Objectives:

- To set out a (simple) model of renewable resource use and **conceptualise resilience in a rigorous decision-theoretic way**.
- To derive a **model-based measure of resilience** and apply it to assess resilience of resource use.

Introduction

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Model ingredients

- (Optimal) exploitation of a **renewable resource subject to random shocks**
- (Optimal) behaviour leads to **long-term sustenance** of the resource stock **if and only if the level of the stock is above a (Skiba-)threshold**.
- **Random** shock may put resource stock below the threshold.
- Appropriate **actions** (e.g., pre-cautionary extraction) allow the decision-maker **to increase the probability of remaining above the threshold**.

Resource renewal

- Economy in which consumption $C(t)$ is harvested from a renewable resource stock $R(t)$ → **decision**
- Resource dynamics: $\dot{R}(t) = g\big(R(t)\big) - C(t)$ with $g\big(R(t)\big) = \frac{aR^2}{b+R^2}$ as replenishment → **state**
- Shock arrives at exogenous rate η and destroys $D(\tau) = (1-\epsilon)R(\tau)$ of the stock at random time τ.
- Two stages: 1 = before shock; 2 = after shock

Resource renewal

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- Two stages: 1 = b … k; 2 …

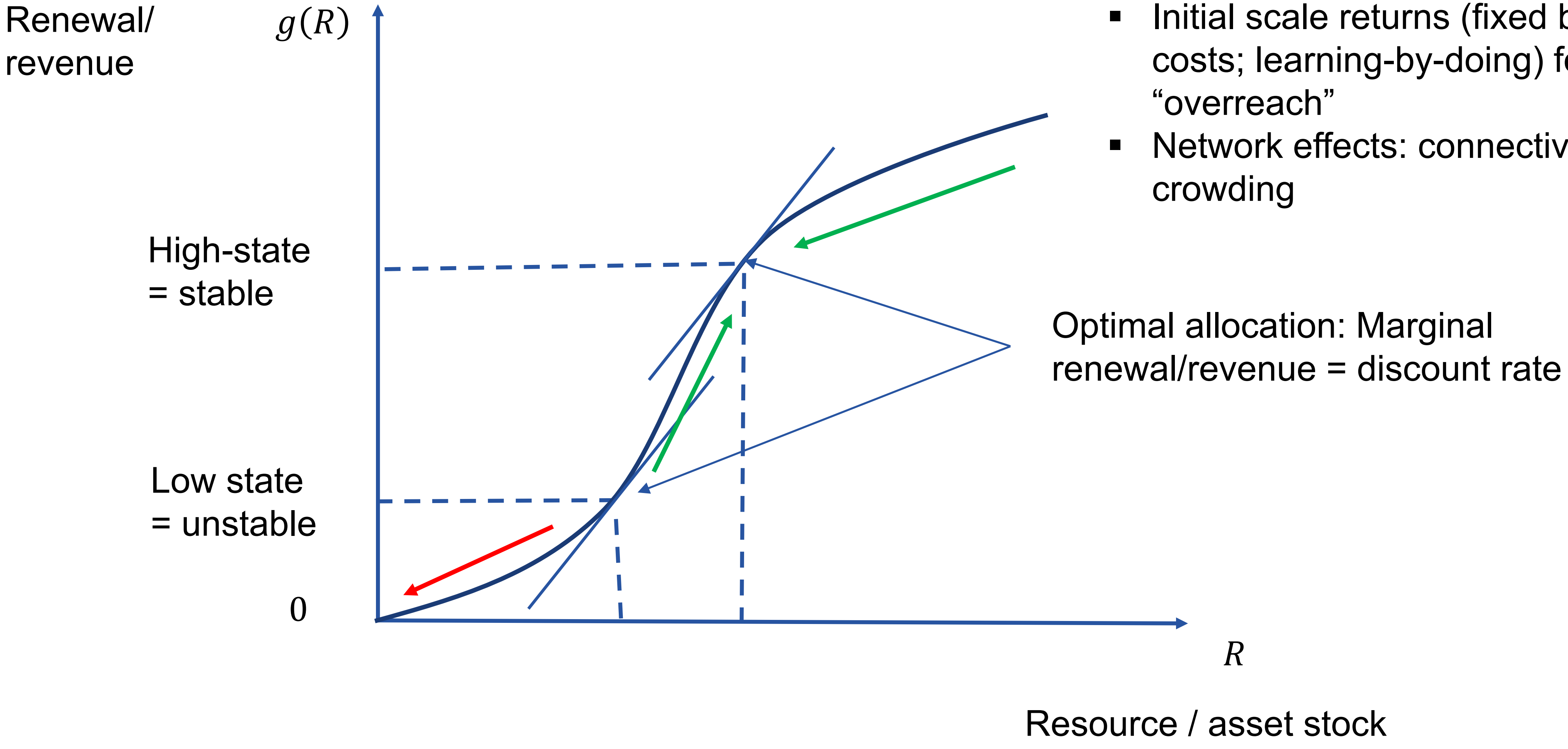
= payouts, dividends in a corporate context

= change in assets

= profit

= devaluation/loss of assets

Convex-concave production



Increasing-then-decreasing returns

- Initial scale returns (fixed baseline costs; learning-by-doing) followed by "overreach"
- Network effects: connectivity vs. crowding

Convex-concave production: marginal returns

Increasing-then-decreasing returns

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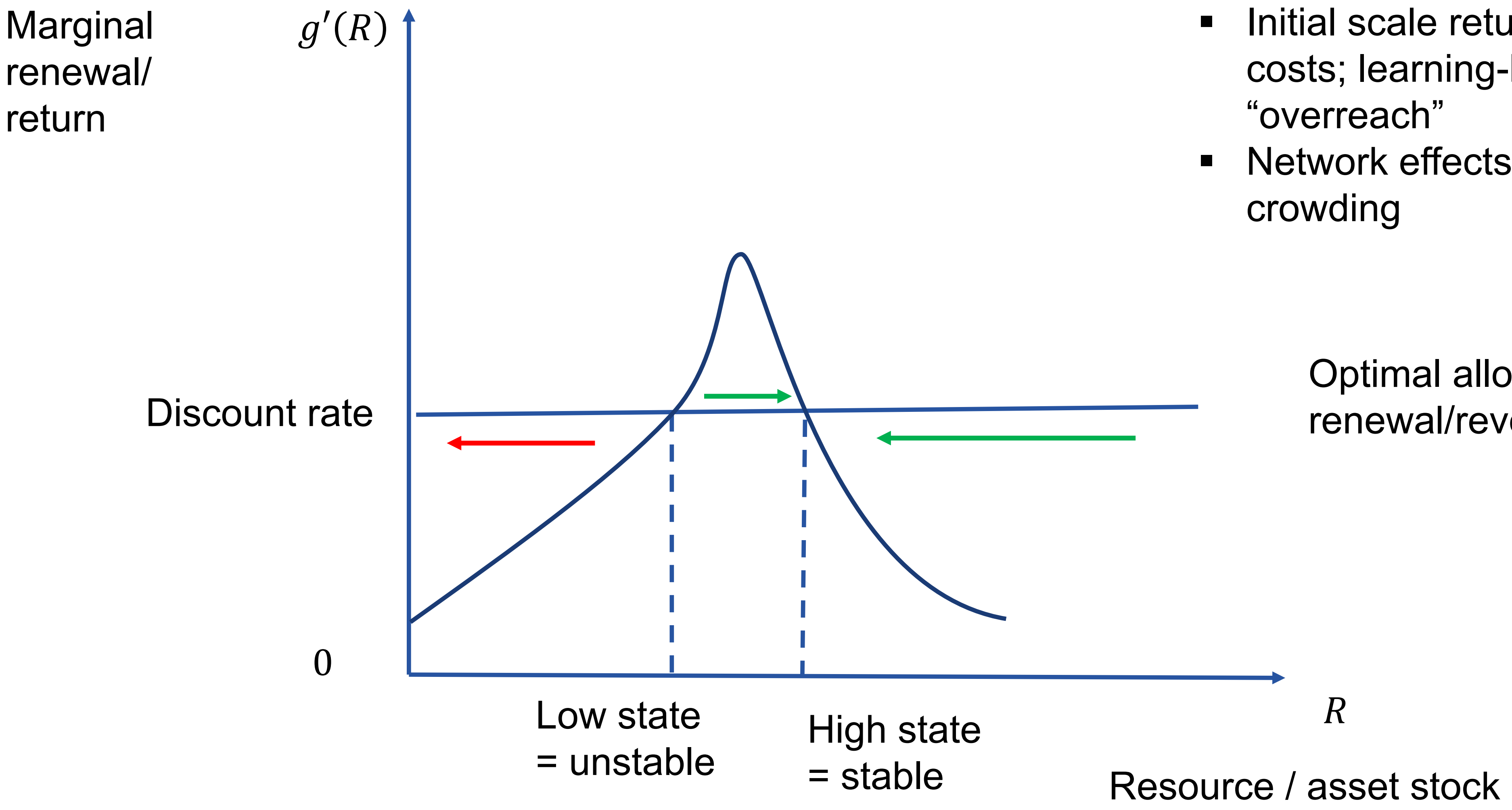
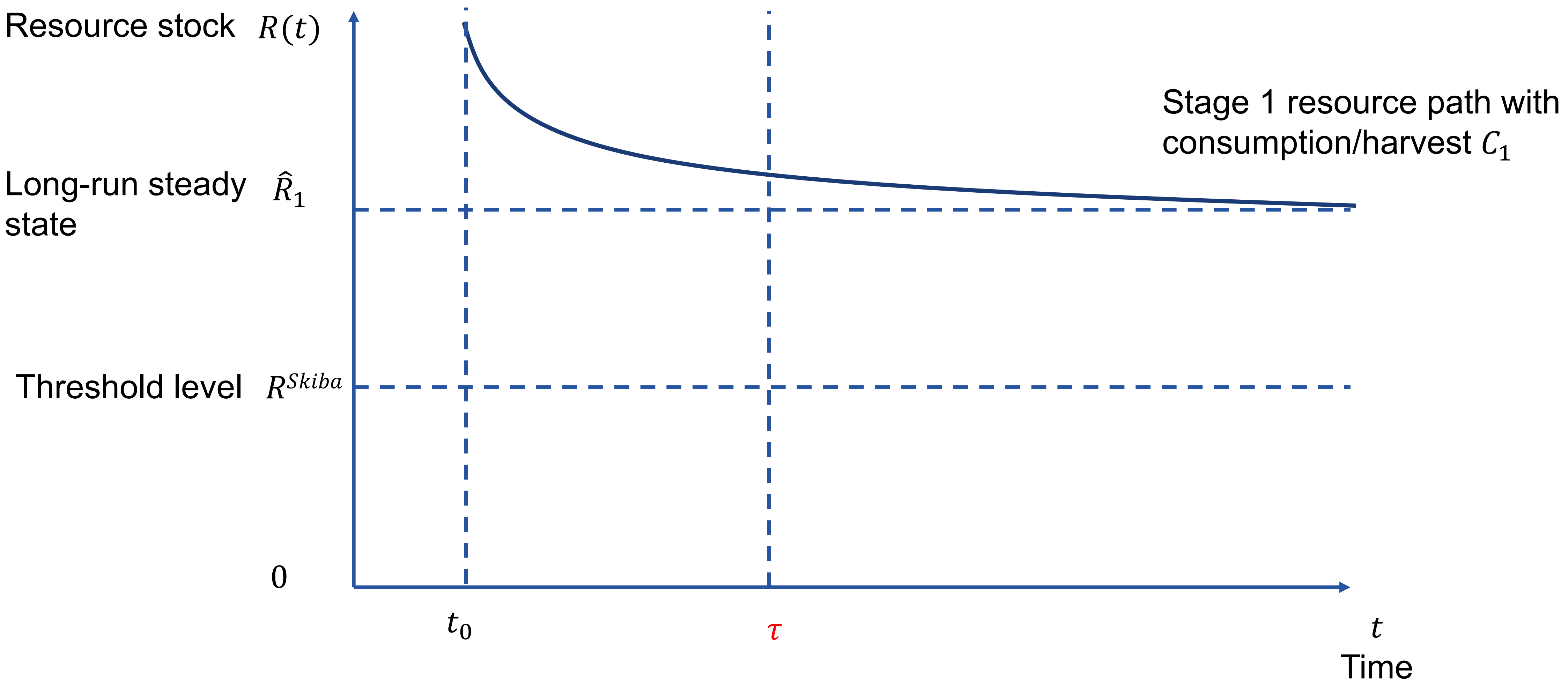
- Network effects: connectivity vs. crowding

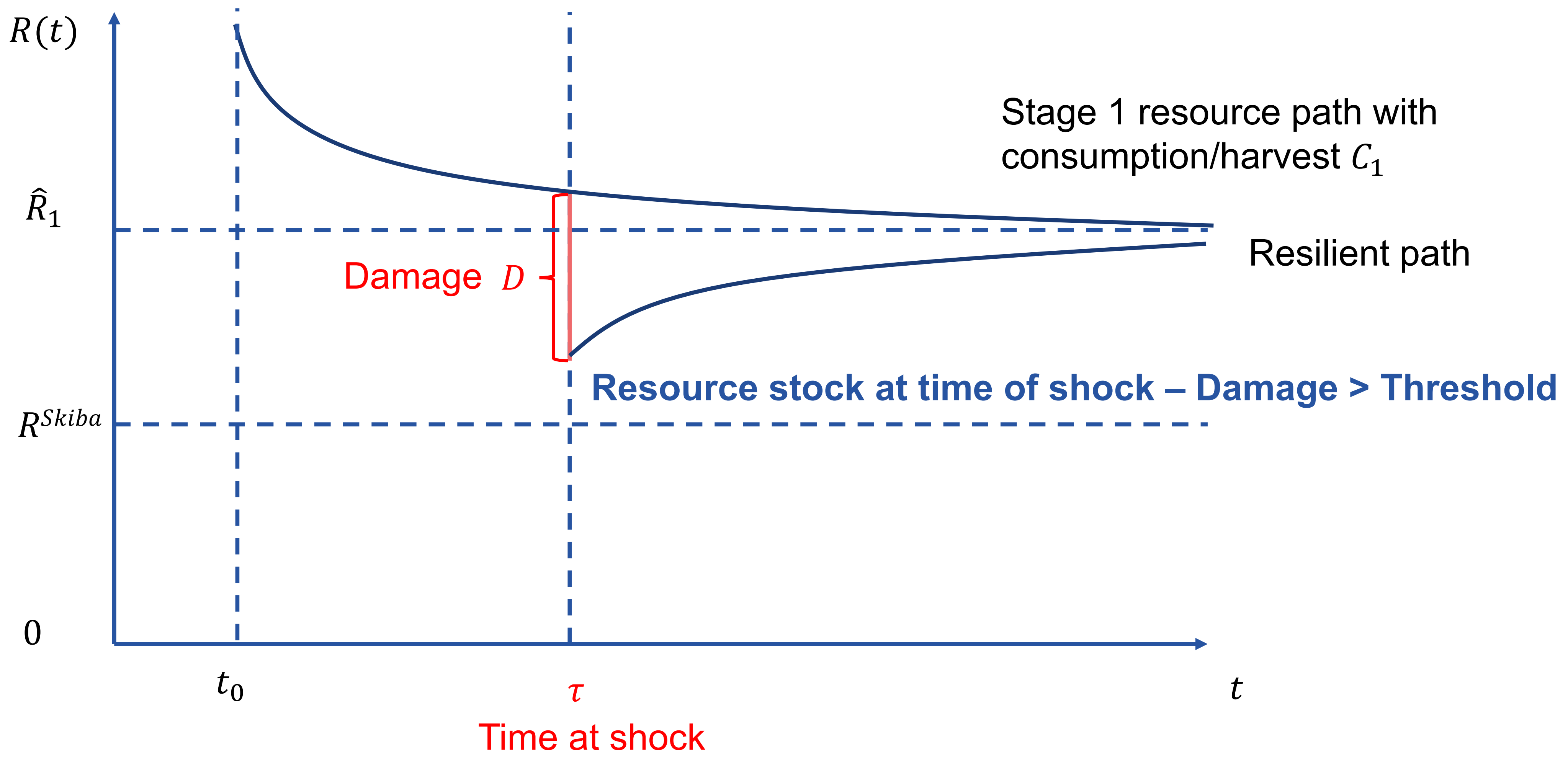


Optimal allocation: Marginal renewal/revenue = discount rate

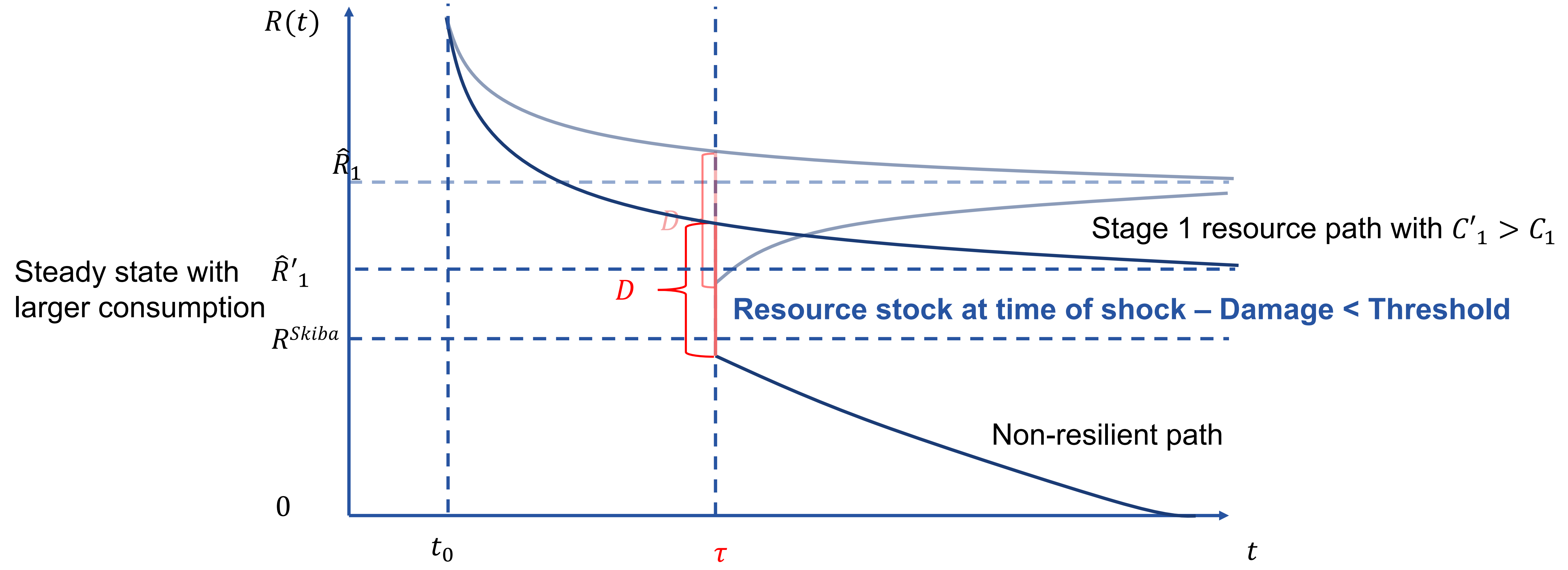
Illustrating resilience



Illustrating resilience

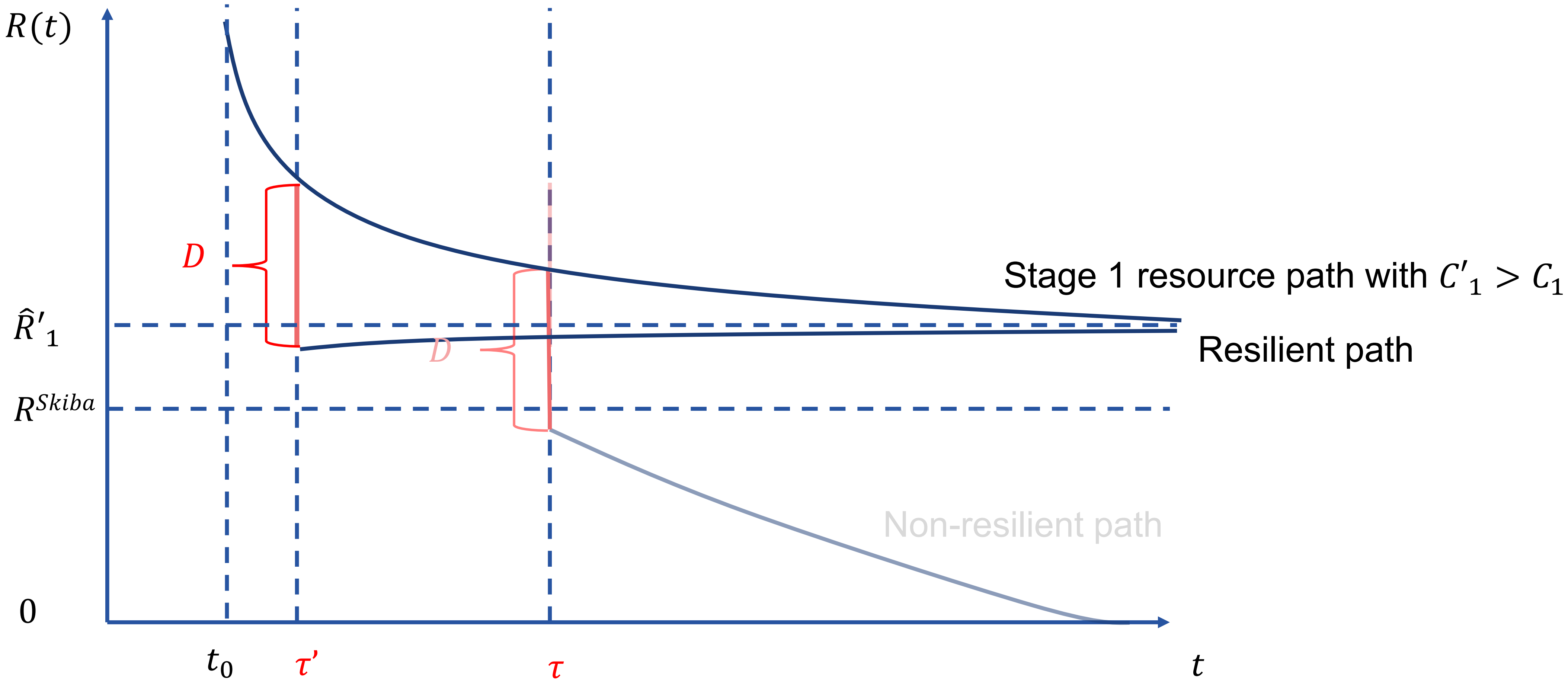


Illustrating resilience: Dependence on ex-ante consumption/extraction policy



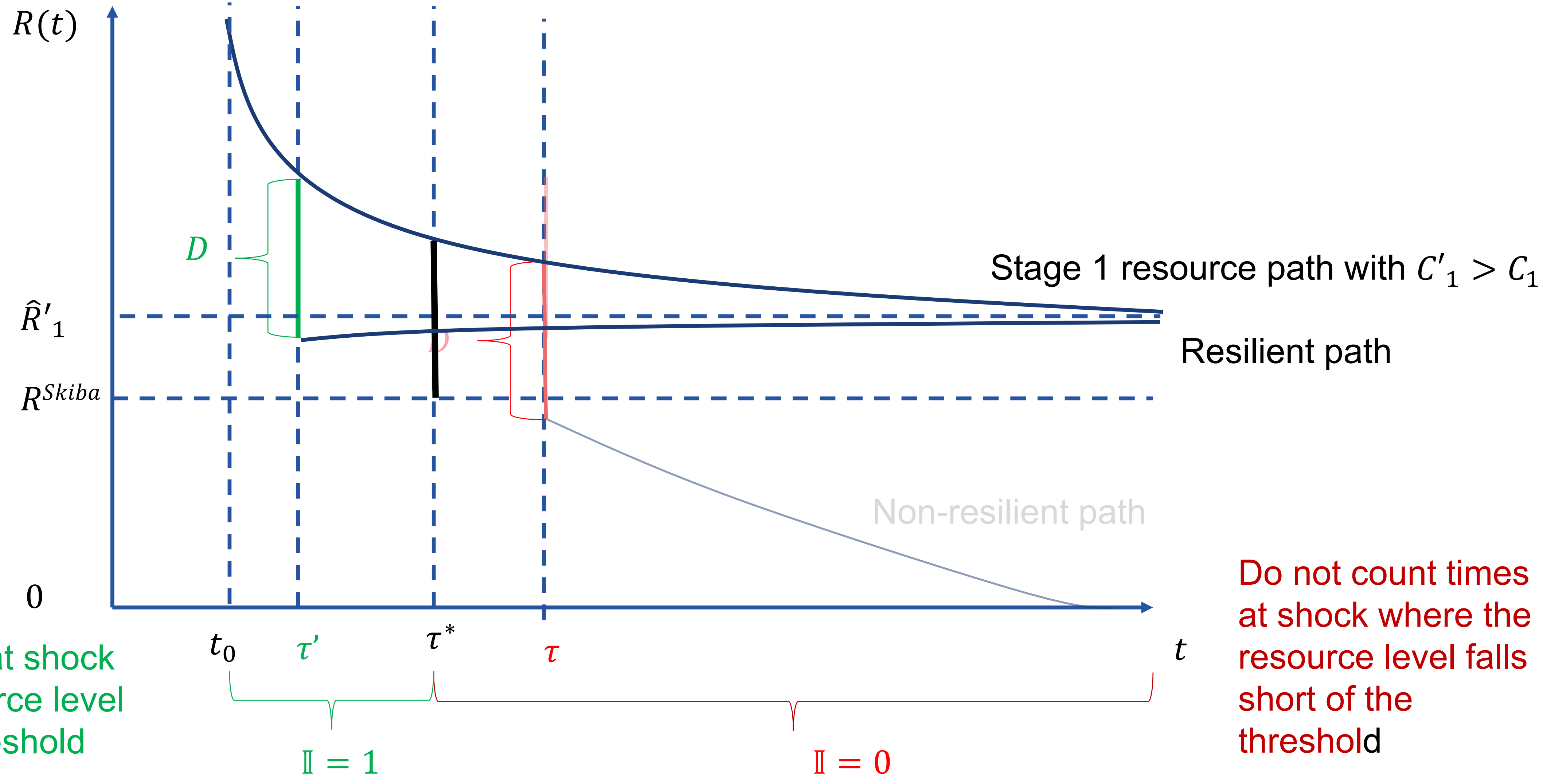
Greater consumption of the resource leads to loss of resilience.

Illustrating resilience: Dependence on timing



(For declining resource levels) a more consumption-oriented policy may be resilient to early-enough shocks. For increasing resource levels the reverse is true: time to build resilience.

Illustrating resilience: Measuring



Count all times at shock where the resource level exceeds the threshold

Do not count times at shock where the resource level falls short of the threshold

Decision problem

Discounted stream of consumption utility up until (random) τ

Discounted continuation value from τ

$$\max_{C(t)} \mathbb{E}_\tau \left[\int_0^\tau e^{-\rho t} C(t)^{0.5} dt + e^{-\rho\tau} V(R(\tau^+), \tau^+) \right]$$

with stage-2 value:

$$V(R(\tau^+), \tau^+) := \max_{C(t)} \int_{\tau^+}^{\infty} e^{-\rho t} C(t)^{0.5} dt$$

Discounted flow of consumption stream post-shock, i.e. from τ onward

Subject to: $\dot{R}(t) = g\big(R(t)\big) - C(t)$, $R(0) = R_0$

$$R(\tau^+) = R(\tau^-) - D(\tau) = \epsilon R(\tau^-)$$

Resource stock following the shock

Solve the model by a method developed in Wrzaczek et al. (2020, JOTA)

Decision problem

Discounted stream of consumption utility up until (random) τ

Discounted continuation value from τ

$$\max_{C(t)} \mathbb{E}_\tau \left[\int_0^\tau e^{-\rho t} C(t)^{0.5} dt + e^{-\rho\tau} V(R(\tau^+), \tau^+) \right]$$

Discounted stream of dividends up until shock

with sta

Discounted flow of consumption stream post-shock, i.e. from τ onward

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Discounted stream of post-shock dividends

Subject to: $\dot{R}(t) = g\big(R(t)\big) - C(t)$, $R(0) = R$

$R(\tau^+) = R(\tau^-) - D(\tau) = \epsilon R($

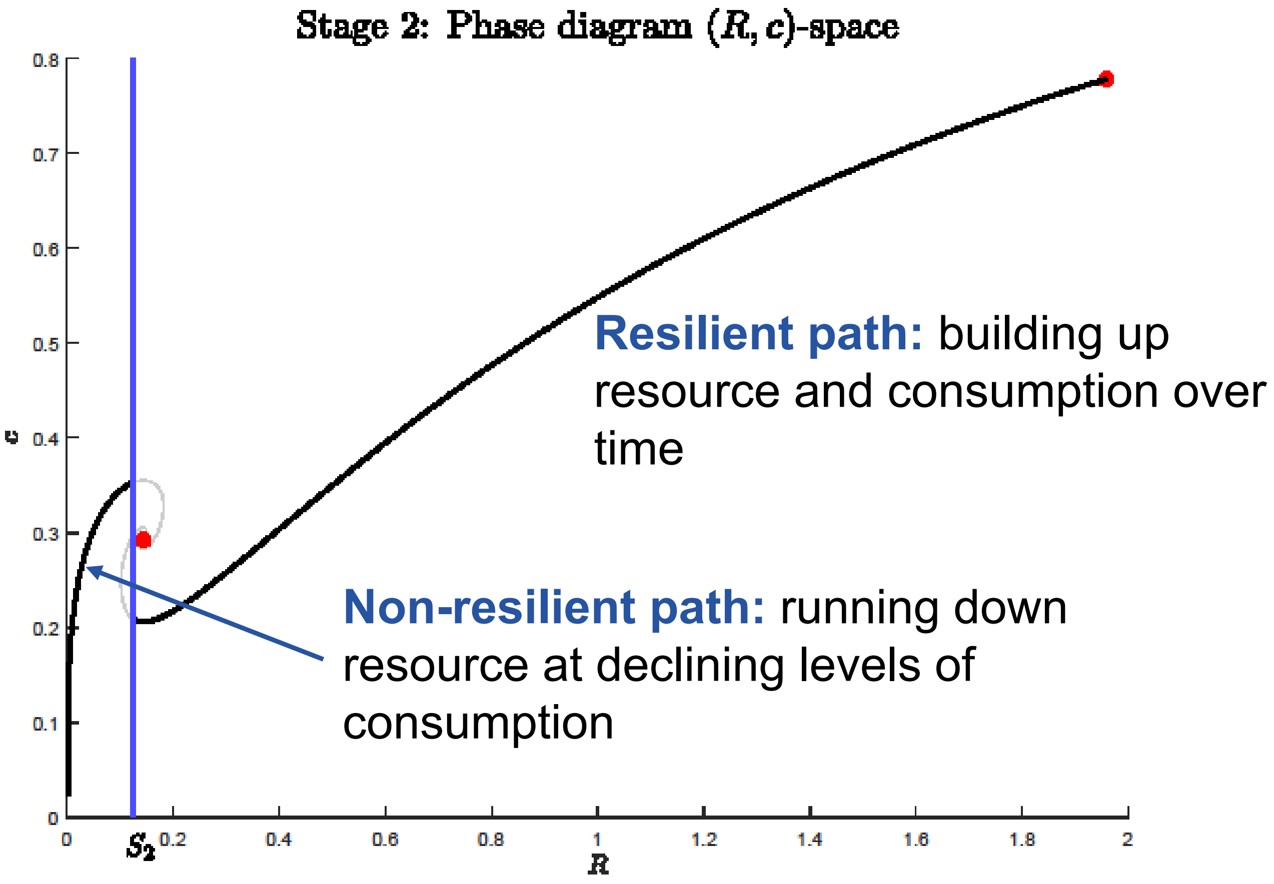
Resource stock following the shock

Solve the model by a method developed in Wrzaczek et al. (2020, JOTA)

Optimal policies in (R, C)-space I

Equilibrium structure:

- stage 2; and stage 1 for $\epsilon = 1$, i.e. **no shock**
- stable/high (resilient) and unstable/low (non-resilient) equilibrium (red dots)
- **Skiba threshold** (blue line): Resource level at which the **decision-maker is indifferent between the high and low equilibrium**

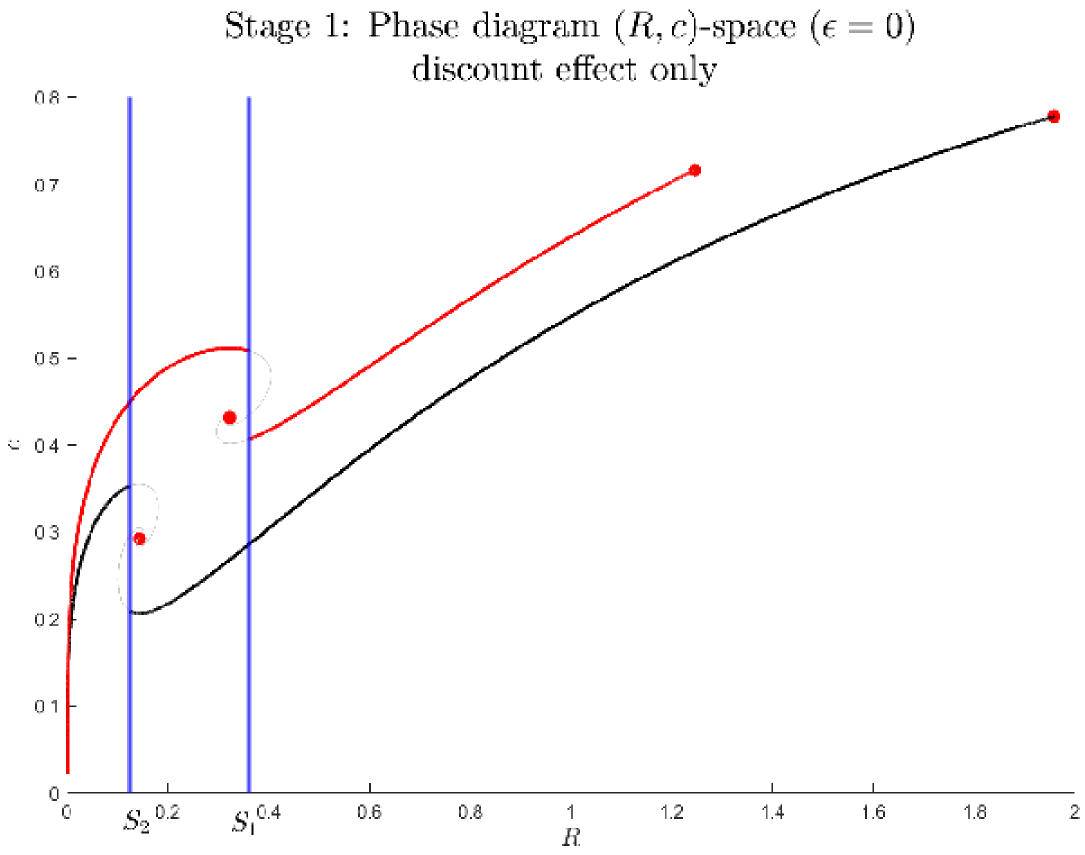


Optimal policies in (R, C)-space II

Stage-1 anticipation of a fully destructive shock ($\epsilon = 0$) :

- shifts high equilibrium downward and low equilibrium and Skiba upward (red curve).

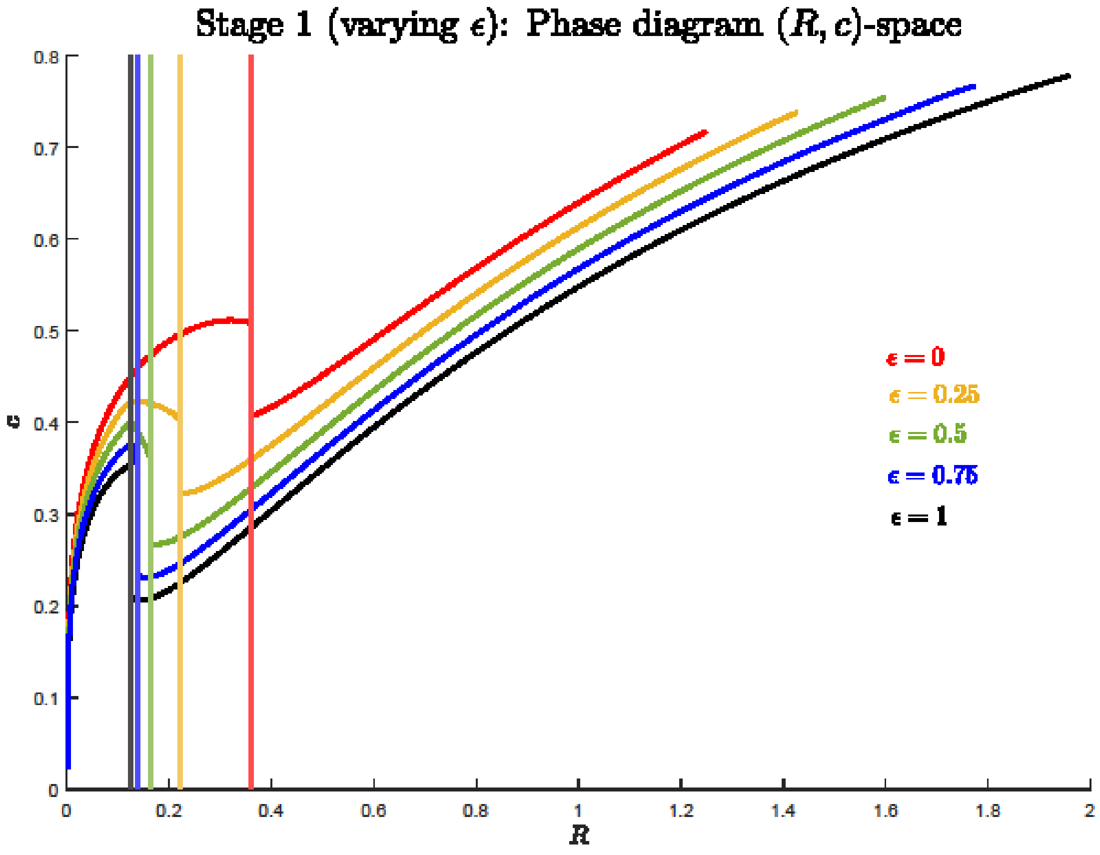
- **Additional discounting compromises resilience**



Optimal policies in (R, C)-space III

For $0 \leq \epsilon \leq 1$…

- …intermediate outcomes with extraction policy…
- **…turning more precautionary with increasing ϵ.**



A measure of resilience I

- **Resilience at time t given resource stock $R(t)$ (adapted to this model)**

$$\mathcal{R}(R(t),t) = \mathcal{R}_1(R(t),t) + \mathcal{R}_2(R(t),t)$$

lies between 0 = no resilience and 1 = full resilience

- **Ex-ante resilience** (averting the shock): $\mathcal{R}_1(R(t),t)$:

(i) is positive only if the decision-maker follows a resilient path in the first place

(ii) increases in the expected duration of the pre-shock stage 1 (declines in the arrival rate of the shock)

- **Ex-post resilience** (dealing with the shock): $\mathcal{R}_2(R(t),t)$:

(i) increases in the arrival rate of the shock

(ii) increases with the total resilience at the time of each possible (future) shock

A measure of resilience II

- **Ex-ante resilience** (averting the shock)

$$\mathcal{R}_1(R(t), t) = \mathbb{I}_{R(t) \geq R_1^S} \frac{\mathcal{L}(t)}{\mathcal{L}(t)+1}$$

- where $\mathbb{I}_{R(t) \geq R_1^S} = 1$ **Resilience** if and only if the resource exceeds the Skiba-threshold R_1^S, and

  $\mathbb{I}_{R(t) < R_1^S} = 0$ **No resilience**.

- and $\mathcal{L}(t) = \eta^{-1}$= life-expectancy in stage 1

A measure of resilience III

- **Ex-post resilience** (adapting to the shock)

$$\mathcal{R}_2(R(t),t) = \frac{1}{\mathcal{L}(t)+1}\int_t^{\infty} e^{-\eta s}\eta\mathcal{R}(s)ds$$

Increases in (i) arrival rate of shock; (ii) and in total resilience at any possible time of shock

measures resilience to future shocks at $s \in [t,\infty[$

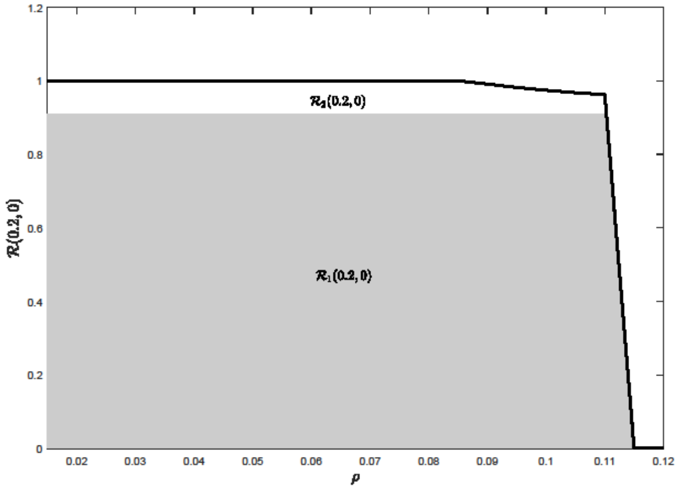
- **Value range:** $\mathcal{R}_i(R(t),t) \in [0,1]$

polar values: $1\ldots$ full resilience $0\ldots$ no resilience

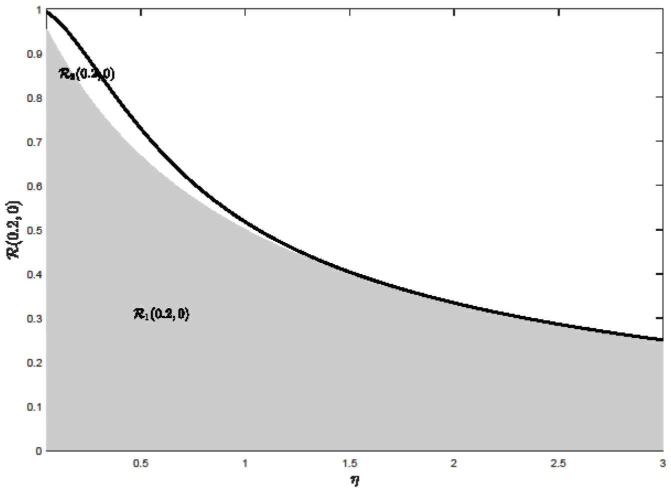
Resilience of optimal policy

- Benchmark scenario: $R_0 = 0.2$; $\rho = 0.1$; $\eta = 0.5$; $\epsilon = 0.5$
- Resilience **diminishes in discount rate ρ and arrival rate** of unavoidable (!) shock η (note that this extends to stage 2 due to reduction in precaution);
- Resilience **increases in initial resource stock** $R(0)$ and **share of surviving resource** stock ϵ

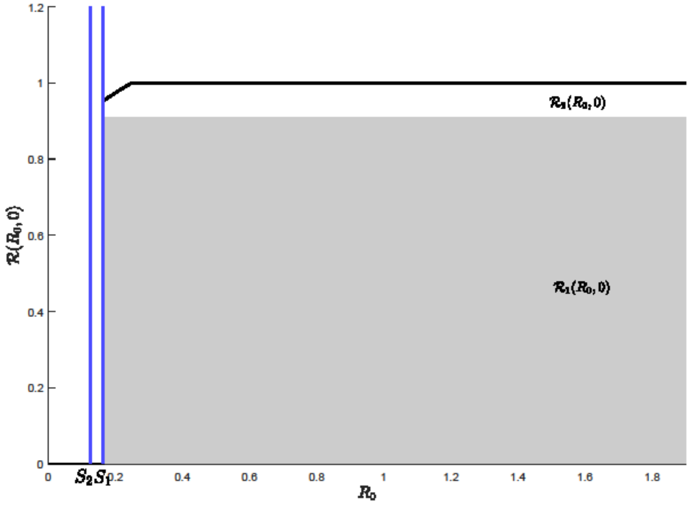
Discount rate ρ



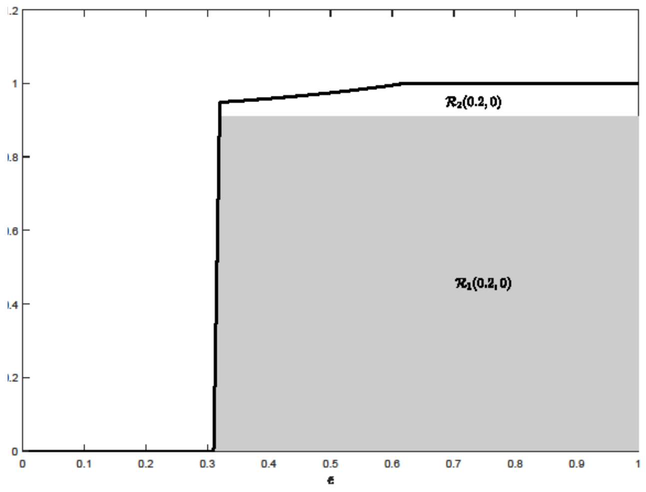
Arrival rate η



Initial resource stock $R(0)$



Share of surviving resource ϵ



What to do with this measure?

Allows to assign a resilience score to…

- **given** sets of **policies** => **assessment tool**.
- **Scenarios of optimal decision-making** => explore e.g.

  (i) role of discount rate
  (ii) measures of risk appetite
  (iii) specific objective function: e.g. corporate vs. welfare oriented policy-maker

- Understand **factors that enhance or hinder resilience** and **incentives** that enhance resilience.

Conclusions

- We **characterise resilience** in a rigorous **decision-theoretic context**

  (i) Elements: Random shocks and possibility of full system collapse

  (ii) There is an element of choice in being resilient and surviving

- We provide a **two-part measure of resilience**

  (i) Resilience and survival in present period (averting shocks)

  (ii) Resilience following regime change (adapting to shocks)

- We provide a **proof of concept** within a simple model of resource extraction

Outlook I

- Incorporation of **additional features** of resilience:

  (i) endogenous hazard and **mitigation**,
  (ii) endogenous damage (**active protection**),
  (iii) **adaptation capital** etc.

- Applications of our framework and measure in richer modelling and/or empirical contexts: **climate mitigation, insurance, political resilience**, etc.

Outlook II

- Consider a setting with **multiple risks** and **multiple assets**
- Allow **variation in impact of each type of shock** depending on the type of asset
- Study **portfolio allocation depending on information** set e.g. about the hazard of each particular shock

Thank you

Questions?

Michael Kuhn
kuhn@iiasa.ac.at