

# Dynamics of resilience–equity interactions in resource-based communities

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Despite the growing focus on understanding how to build resilience, the interaction between resilience and equity, particularly in the context of power asymmetries like those in communities reliant on resource-based industries, or resource-based communities, is not well understood. Here we present a stylized dynamical systems model of asymmetric resource access and control in resource-based communities that links industrial resource degradation, community well-being, and migration in response to economic and resource conditions. The model reveals a mechanism of collapse due to these dynamics in which over-extraction and resource degradation trigger irreversible population decline. Regulating resource extraction can increase resilience (in the sense of persistence) while also shifting the sustainable equilibrium and the implications for equity. Resilience does not guarantee equity at equilibrium, and this misalignment is more pronounced in the transient interactions between short term equity and long term resilience. The misalignment between resilience and equity demonstrates how equity considerations change the policy design process in important ways.

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The scale and intensity of human-induced environmental change exacerbate the need to manage natural resources sustainably and equitably, especially for those most vulnerable to its effects. This is particularly true in rural communities that rely on a single externally controlled industry based on capital-intensive resource extraction or resource-based communities (RBCs)<sup>1,2</sup>. RBCs represent a unique intersection between intense environmental degradation and disparities in resource access and control. The social and economic characteristics of RBCs and their vulnerability to economic and resource shocks have been documented through numerous case studies in forestry, mining, and coastal communities in Canada and the USA<sup>3</sup>. While these communities are diverse, they share characteristics such as high transience, underinvestment in local infrastructure and services, and lack of alternative economic opportunities<sup>3,4</sup>. For example, communities in Appalachia with origins as coal camps struggle with the legacy of headwaters destruction and heavy metals pollution alongside lack of investment in public infrastructure and the development of social capital<sup>5</sup>. California's prolific agricultural industry exists alongside farmworker communities that suffer from poverty, water polluted by fertilizer and pesticides, and dry wells<sup>6,7</sup>.

**RBCs as social–ecological systems (SEs).** RBCs have long been a subject of study in rural sociology, community development, and political economy. These studies have traditionally focused on understanding the trajectory of RBCs, the impacts of the “booms” and “busts” that are common features of these trajectories on community social capital and well-being<sup>8,9</sup>, the persistence of disproportionate rates of poverty, and the land ownership and tenure patterns that tend to correspond to different development trajectories. The literature documents the particular vulnerability of RBCs to economic downturns due to fluctuations in commodity prices and the degradation of the resource base on which extraction relies<sup>10</sup>, exacerbated by the lack of funding for infrastructure, education, and social services caused by tax policies that tend to favor extra-local corporate landowners, causing much of the benefits of production to flow out of the community<sup>5,11</sup>. Studies on the political economy of RBCs have examined the concentration of land and resource rights in the hands of a few, and the tendency for corruption and corporate capture of the state<sup>5,11</sup>.

RBCs lend themselves to being studied from a social–ecological perspective, given the intimate coupling of human well-being and local natural processes and distinct spatial boundaries. Yet, the SEs literature tends to focus on smallholder dominated systems, and on understanding the conditions under which the cooperation and collective action emerges endogenously among relatively homogeneous resource users<sup>12–15</sup>. This approach de-emphasizes intragroup dynamics, conflict, and the equity concerns arising from power imbalances among users<sup>16–18</sup>. However, the SEs literature still provides important insights for understanding social–natural interactions and how they relate to the resilience of communities and the natural resource wealth on which they rely.

Given the distinct challenges RBCs face and their suitability to being studied as SEs, they serve as a natural confluence of two disparate strands of resilience research: community resilience and “ecological” resilience<sup>19</sup>. Community resilience, which is most commonly referred to within the community development and risk and disaster literatures, evolved from the health and developmental psychology tradition<sup>19</sup>. Community resilience conceptualizes resilience as an episodic process of growth and adaptation, rather than as an outcome. Studies have proposed that active local organizations and organizational networks, the presence of community leadership, and strong social safety nets,

among other factors, contribute to the process of building community resilience<sup>20,21</sup>. On the other hand, ecological resilience is based on observations of the dynamics of ecosystems with their uncertainties, abrupt and nonlinear shifts, and multiple stable states, and is defined as the capacity of a system to withstand disturbances while remaining within critical thresholds in which it retains its basic function<sup>22,23</sup>. Ecological resilience is a characteristic of systems rather than of any single component. Unlike with community resilience, ecological resilience does not necessarily imply equity—for example, poverty traps are a state of system functioning that is both resilient and undesirable<sup>23,24</sup>. Emerging concepts of resilience such as social–ecological resilience emphasize the ability of a system to transform and adapt rather than just persist in a potentially undesirable form. However, the concept of persistence as defined by ecological resilience is still a useful and influential one that tends to be mistakenly conflated with the same positive features as community and social–ecological resilience<sup>16,23,25</sup>. Thus, there remains a need to distinguish the equity implications of ecological resilience from the more transformative changes that might be implied by other understandings of resilience<sup>26,27</sup>.

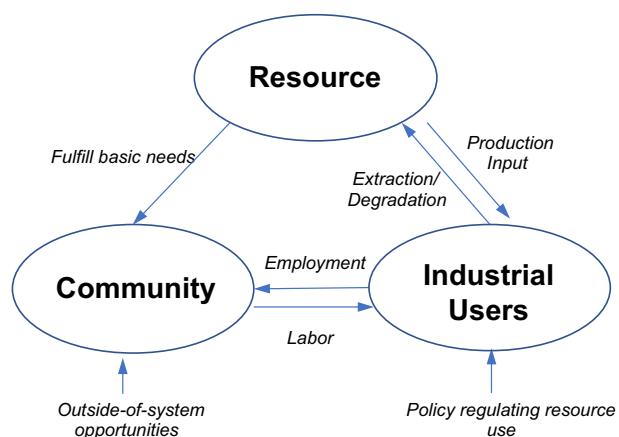
There are many case studies suggesting the potential for tradeoffs between equity and other resource management objectives such as economic return and conservation goals<sup>28,29</sup>. Similarly, studies on the asymmetric commons dilemma suggest tradeoffs between increased system robustness and inequality<sup>13</sup>, and that technology can lead to self-reinforcing inequities<sup>30</sup>. The emerging literature on the social implications of resilience critically analyzes for whom and to what the system is resilient, revealing the differential benefits of resilient systems and their tradeoffs across spatial and temporal scales. For example, a historical case study of the Faroe islands documents how ecological catastrophe was averted at the cost of maintaining and reinforcing exclusionary resource access policies and high levels of social inequality<sup>31</sup>, and a study of the resilience of water management in South Africa over time found tradeoffs between short-term resilience that benefited the powerful and long-term resilience with broader benefits<sup>32</sup>. While there are many individual case studies documenting conflicts between resilience and equity as well as analyses of the shortcomings of the concept of resilience for understanding issues of equity and power<sup>16,26</sup>, there is still much more focus on deriving the principles for building resilience rather than for identifying the circumstances in which it is desirable with regard to equity<sup>23,25</sup>. This study contributes to bridging the gap between individual case studies and a broader theory on resilience–equity interactions by investigating the interaction between ecological resilience and equity in a more general setting while still incorporating potentially important and oft-overlooked factors such as social differences and power asymmetries that are specific to RBCs. Stylized theoretical models have often been used for this purpose, such as in studying when cooperation and self-governance emerges in SEs<sup>12,13,33–35</sup>. Dynamical systems modeling in particular offers an intuitive understanding of ecological resilience<sup>23,36,37</sup>, and the level of disaggregation allows for examining equity within a low-dimensional system.

The study proceeds as follows. First, we introduce the dynamical systems model, which links industrial natural resource consumption and the dynamics of the natural resource system, wages, and migration. The analysis of the model consists of two parts. In “System Dynamics and Equilibria,” we examine the qualitatively different equilibria that result from the model dynamics, and how regulating extraction can intervene in these dynamics. The results reveal how the failure of RBCs to sustain livelihoods depends as much on the social dynamics of migration and how communities experience resource degradation as on the

natural dynamics of resource degradation itself, and how regulating resource extraction can mitigate these effects to increase system resilience. In the second part of the analysis, “Governance Challenges and Tradeoffs,” we consider the interaction between resilience and equity at different timescales. This approach balances conceptual simplicity with the incorporation of sufficient social complexity to explore potential governance challenges that arise in RBCs.

### Model structure

In order to study the fundamental asymmetry at the heart of RBCs, we propose a model that disaggregates resource users into industrial users, who have access to infrastructure and other inputs needed to profit from resource extraction, and domestic users, who do not have the ability to create a livelihood from the resource except through wage labor (Fig. 1). This level of aggregation allows us to focus on inequality between groups with different levels of control and access to the resource, better capturing issues of power than either modeling inequality among individuals or aggregating all resource users. We model the industrial users and domestic users as both relying on a renewable resource system, such as a groundwater aquifer. However, since industries typically have far greater technological and financial capital than domestic resource users, changes in the resource state are modeled as determined entirely by industrial users. The impact of industry on the resource state in the model will be referred to as resource use or extraction, though changes in resource state can represent a reduction in either quantity or quality of the resource. Industrial users aim to maximize profit through their choice of amount of resource and labor usage, constrained by their availability (see “Methods” for the profit function). Their decision determines the depletion or degradation of the resource, which is modeled, for simplicity, with a constant regeneration rate and a maximum capacity at which the resource will stabilize. Marginal extraction costs increase as the resource is depleted or degraded, as is the case, for example, with groundwater extraction as the water table drops and more energy and/or



**Fig. 1 Schematic of the proposed model.** The resource serves as a production input for the industrial users, who profit from extracting the resource, and fulfills the basic needs of the community, who does not extract the resource. The industrial users optimize both the amount they extract and the amount of labor used, which is provided by the community. The amount of labor they use relative to the community population determines how the wages increase or decrease. The community well-being is based on their wages from employment by industrial users and access to the resource to fulfill their needs. Finally, the community migrates in and out of the system based on how this well-being compares to a constant outside-of-system well-being.

deeper wells are required. Labor costs, or wages, increase when there is a shortage of labor, and decrease when there is an excess. Industrial users are modeled as myopic, optimizing only over the short term with no knowledge of resource or labor dynamics, consistent with the behavior of users in general common-pool resource dilemmas<sup>38</sup>.

Changes to the resource state, employment opportunities, and wages in turn affect the community well-being, which depends both on the resource to fulfill basic needs and on employment as a source of income. The effect of the resource state on community resource access is modeled as nonlinear, representing how large shortages and greatly degraded quality have a disproportionately large impact on well-being. In addition, resource access and economic security interact to determine the well-being of communities, for whom these issues tend to be linked (e.g., paying for alternative water sources or high water bills can be a significant economic burden). Community well-being is therefore a product of expected wages and resource access. Individuals then decide whether to migrate out of the system based on their well-being relative to a constant outside-of-system well-being. Changes in population follow replicator dynamics, a model originating in evolutionary game theory that is commonly used to represent how individuals choose between options in a boundedly rational manner, imitating observed strategies that receive higher payoffs<sup>39</sup>. The rate at which individuals switch between strategies—in this case the decision to stay within the system or migrate out—is proportional to the payoff difference between the options. The difference in the way that the migration decision is made compared to the rational (albeit in a myopic) manner in which industrial users make extraction decisions is based on the economic theory that rationality is a social rather than individual construct and that people would be expected to behave rationally in a social context that rewards rational choices and punishes irrational choices, such as a market<sup>40–42</sup>. The industrial users produce for a market, and thus might be expected to make profit-maximizing decisions, while no such context exists for encouraging strictly rational behavior in migration decisions. The results of the migration determine the labor available to industrial users.

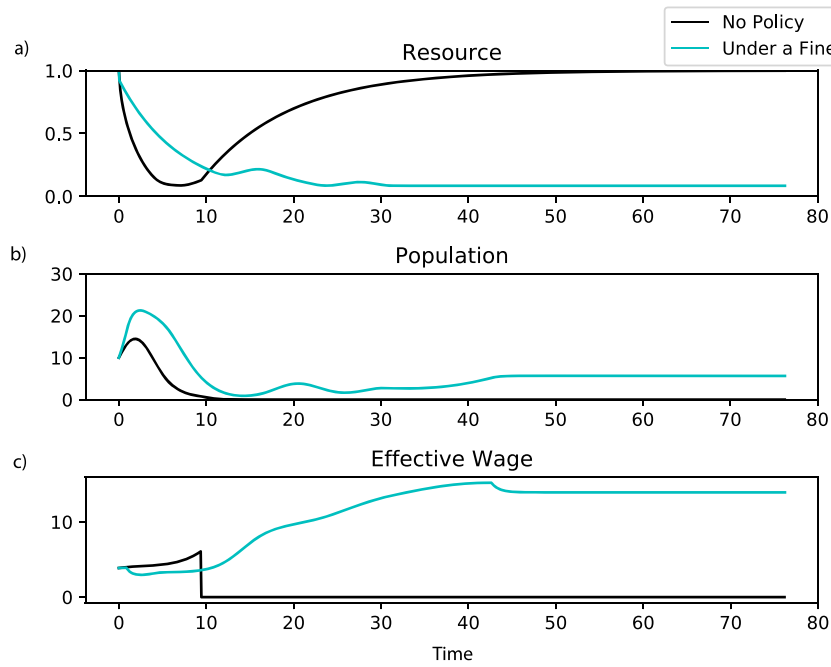
This setup yields a model with three state variables: the resource state, wages, and community population (see “Methods” for a full mathematical definition of the system). The model structure embeds power disparities in two ways: (1) despite relying on the resource to fulfill their basic needs, the community lacks access to the infrastructure and capital needed to impact it to the extent the industrial users do, and (2) the community benefits only through the wages they receive, and do not benefit directly from profits generated by resource extraction despite bearing the cost of resource degradation. These dynamics generate a rich set of feedbacks among industrial users, the community on which they rely for labor, and their shared resource, encapsulating the “self-organized” part of the system.

SEs, however, are part self-organized and part designed<sup>14</sup>. We implement the “designed” component of this system through regulation that aims to mitigate for myopic behavior by regulating industrial users’ resource use. The policies influence industrial users by being incorporated as a cost in their profit function.

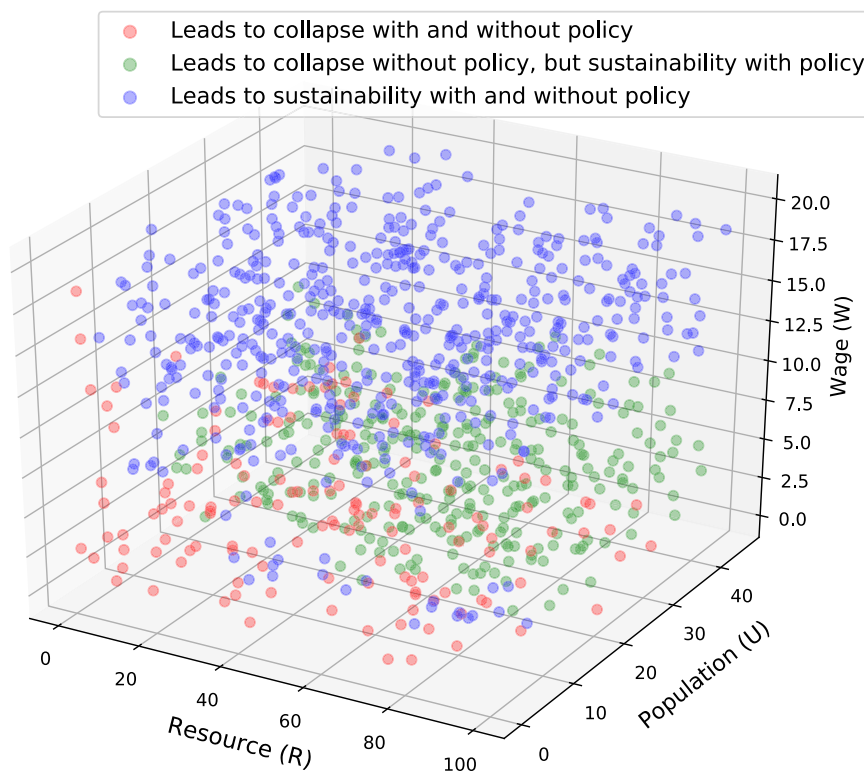
This model formulation now allows us to analyze the mechanism under which the system fails to sustain industrial profitability and community well-being, how regulating extraction can perturb these dynamics, and its implications for resilience and equity.

### Results

**System dynamics and equilibria.** The model dynamics generate two different long-term system outcomes, or equilibria: a



**Fig. 2 Illustrative trajectories with and without regulation.** Time series of **a** resource, **b** population, and **c** effective wage with no policy (black), and with a fine implemented (cyan). Initial conditions are  $R_0 = 1$ ,  $W_0 = 4$ ,  $U_0 = 10$ , and the cap is 0.1 with a fine of 100. The effective wage is the wage scaled by the proportion of available labor that is employed.



**Fig. 3 Increase in resilience under regulation.** Scatterplots of the phase space color coded by their equilibrium condition under no policy and under the optimal fine for increasing resilience (a cap of 0.05 and a fine of 125). A total of 1000 initial conditions are sampled throughout the state space using Latin hypercube sampling (LHS). In this example, the proportion of trajectories that are attracted to the sustainable equilibrium, or the resilience, changes from about 53 to 99% under the policy.

“collapse” outcome involving a failure of the social and economic systems, and a sustainable outcome, in which the system indefinitely supports productivity and community livelihoods (Figs. 2 and 3). The collapse outcome is triggered by industry depleting

the resource to a level where they can no longer profitably extract at the same time that a lack of resource access has caused the population to decline, eventually setting the system on an irreversible course. While the resource recovers when industry is not



productive, the population does not; the lack of productivity leads to a self-reinforcing feedback loop with out-migration, making future productivity impossible as well. This mechanism is similar to the concept of runaway dispersal that has been documented in social species, in which density-dependent copying, as occurs in replicator dynamics, leads to nonlinear and irreversible changes in population<sup>43</sup>. The dynamics of the rapid initial growth followed by collapse is also reminiscent of the “boom-bust” dynamics seen in many case studies of RBCs, particularly throughout Northern Canada, where industry collapse, in part due to overexploitation of the renewable resource base, and out-migration threaten the future of these communities<sup>3,9,44</sup>. The sustainable equilibrium, in contrast, hinges on remaining within the region of the state space in which self-balancing dynamics dominate, particularly in terms of maintaining enough economic opportunity and resource access to support community well-being. Figure 2 shows an example of a model run in which the introduction of a policy to regulate industrial users can intervene in whether a given set of initial conditions leads to collapse by modulating the initial resource decline.

The region of the state space that leads to the sustainable equilibrium (Fig. 3) represents the basin of attraction for the sustainable equilibrium. The (ecological) resilience of the system is the size of the basin of attraction, measured as the proportion of sampled trajectories that lead to the sustainable equilibrium (see “Methods” for more details). Conceptually, this represents the extent to which the system could be perturbed from the trajectories shown, such as by exogenous shocks such as drought, while retaining long-term sustainability. This measure of resilience is not the resilience of the resource, nor any other individual component of the system, and in fact leads to a lower equilibrium resource level than the collapse equilibrium. Rather, it represents the resilience of the system’s functioning as a RBC that sustains an industry and community users. The introduction of a policy expands the basin of attraction (Fig. 3), increasing the ecological resilience of the RBC. The next part of the analysis focuses on understanding the equity implications of the policy within the regime in which the policy can increase resilience (see Supplementary Figs. 6 and 7 and Supplementary Table 2).

**Governance challenges and tradeoffs.** While regulating industrial users promotes the resilience of the system, it also changes the location of the sustainable equilibrium (see Supplementary Fig. 2), which has important implications for equity. The desirability of outcomes for industry and community are represented by their profit and well-being, respectively. The community well-being is measured as the product of the resource access, effective wage, and population. We define equitable policies as those leading to near-optimal well-being for the community, the most vulnerable group in the system. The alignment of equity with resilience in the policy space is calculated as the difference in the proportion of the high resilience region that is equitable and the proportion of the policy space generally that is equitable, or in other words, the gain in the proportion of equitable policies if focusing solely on resilience (see “Methods” for a mathematical definition). This metric is normalized such that it will range from  $-1$  to  $1$ , with  $1$  representing perfect alignment (i.e., the regions of equity and resilience are exactly the same),  $-1$  representing objectives that are completely opposed, and  $0$  representing a lack of correlation, positive or negative, between the two objectives.

The definition of resilience and equity requires that they be at least somewhat aligned at equilibrium, since a high well-being is not possible in a collapse state. However, even at equilibrium, Fig. 4d reveals that resilience, while a necessary condition for equity, does not guarantee it. This difference in the policies that

lead to high resilience and high equity is important if decision-makers are focused only on resilience or have limited knowledge of the system response and therefore cannot accurately determine where the equitable region is.

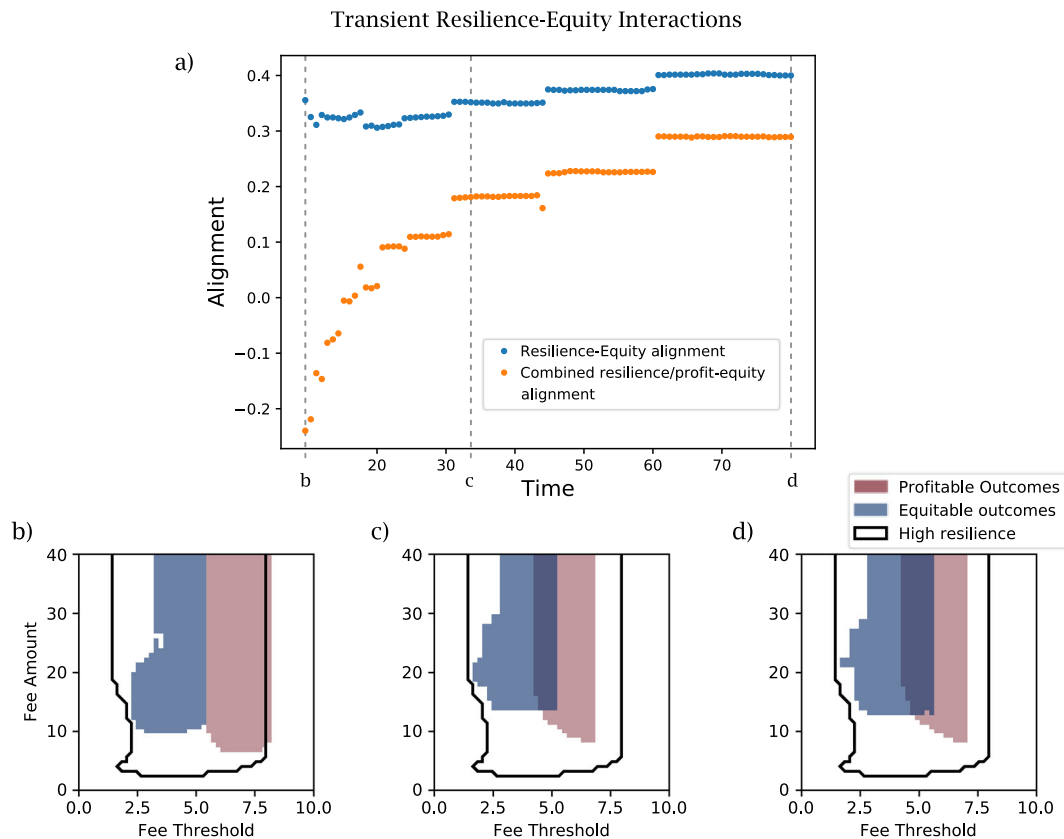
Distinguishing between resilience and equity becomes more important when considering the transient effects of different policies (Fig. 4). While resilience as defined applies only to equilibrium outcomes, the response surface for equity changes over time such that achieving resilience becomes more aligned with equity as the system approaches equilibrium. This dynamic is even more pronounced when considering the common objective of profit in conjunction with high resilience. The combination of resilience and high profit actually conflicts with achieving equity (negative values of alignment) in earlier time periods. Equity therefore warrants standalone analysis, especially when considering transient effects. While the fact that at equilibrium the combination of resilience and high profit does not directly conflict with equity may seem encouraging, even short-term tradeoffs are important to consider in practice, particularly for systems in which variables such as the resource or population are slow drivers. Resilience being insufficient for predicting equity as well as these temporal dynamics hold when considering different thresholds, policy types, and parameters (see Supplementary Figs. 4–8).

The goal of this analysis is not to advocate any particular timescale of analysis or to optimize policy parameters, but to understand how incorporating power disparities in our model formulation and considering equity as an objective complicates the objective of building resilience in ways that are otherwise difficult to anticipate. This analysis allows us to look beyond simple constrained optimization and other standard approaches to understand both the transient and long-term, nontrivial interactions between resilience and equity, which arise from the system-level dynamics of migration, resource extraction, and wage labor, in systems fraught with power asymmetries and uncertainty.

## Discussion

What, then, do these findings mean for broader meanings of resilience in RBCs? As with equity, community resilience may be related to ecological resilience since a stable population can help foster the community cohesiveness and connectivity needed to build community resilience according to the social disruption hypothesis<sup>8,19</sup>. However, since community resilience is process based, transient effects on community well-being and equity are important factors in ultimately determining community resilience. On the flip side, community resilience may be a mitigating factor in the dynamics modeled here, since the model is limited in capturing how communities adapt and evolve to changing resource access conditions rather than having a fixed relationship with a resource. In addition, there are other scales of analysis, temporal and spatial, on which to consider resilience–equity interactions. Increased ecological resilience on the scale of individual communities as studied here, by maintaining an inherently inflexible and inequitable system, may mean reduced social–ecological resilience on a broader scale, as is the case with economies that rely on extractive industries (i.e., the “resource curse”)<sup>10,45</sup>.

Many SESs are characterized by complex social relationships among users, most notably power asymmetries, that have important implications for analyses of the collective action problem. This study focuses on RBCs as a quintessential example of a system with such disparities that exists throughout the world and has been underrepresented in the SES and common-pool resource literature. The results, in addition to revealing a mode of system collapse that is not foreseeable without considering long-term



**Fig. 4 Transient resilience–equity Interactions.** **a** The alignment of equity with resilience (in blue), as well as of equity with a combination of profit and resilience (orange), at different points in time. The alignment is measured as the gain in the proportion of policies with high equity if restricted to the high resilience region compared to the proportion of policies with high equity in the policy space as a whole. **b–d** The regions of the policy parameter space that generate near-optimal (within 5%) industrial profits (in red), community well-being (in blue), and resilience (within the boundary) used in the alignment calculation. See Supplementary Fig. 3 for colormaps of the objectives at equilibrium.

dynamics of migration and extraction, reveal a misalignment between the commonly conflated objectives of resilience and equity. These results hinge on the disparity in the industry and the community’s access to capital and technology for extracting or accessing the resource, and the community receiving limited benefits from extraction. This disparity in who benefits from extraction means that gains in system resilience enabling sustained production are not always aligned with gains in community well-being, as might be the case in the more homogeneous smallholder systems more commonly studied in the common-pool resource literature<sup>15,46</sup>. This study additionally assumes a renewable resource with constant regeneration. However, the fact that a collapse can still occur means this result would hold even if modeling a resource for which a low resource level leads to a low regeneration rate, as is the case with many biological resources. The model also still offers insight for RBCs based on extraction of nonrenewable resources, such as fossil fuels, if considering how communities rely on renewable natural capital, such as water, that also tends to be degraded by extractive industries. Understanding the transient effects on equity also becomes crucial for systems in which collapse is the only possible equilibrium. While the concept of ecological resilience based on multiple equilibria for the resource state would not apply, the transient well-being would be an important driver of community development after the resource collapses. Finally, applying this model for real-world prediction and policy design would require identifying parameter values for a particular case study, which is an area for future work. However, the main contribution of this analysis is disentangling ecological resilience from its normative associations, and

eventually toward developing theory around when building resilience of a particular system is desirable from an equity perspective, as opposed to more transformative changes.

This study represents a first step toward developing models that better capture the social complexity of SESs to understand the processes driving systems to collapse and the tradeoffs inherent in inequitable systems. While this system is characterized by unequal distributions of the resource, capital, and political power, our analysis focuses mainly on how differing control over and access to resources influences social–ecological outcomes. Future work should explore how other manifestations of power asymmetries, such as in access to institutions and political processes, influence social–ecological outcomes, with the recognition that the governance processes represented as exogenous in this model are themselves a commons dilemma<sup>47</sup>. Understanding the dynamics of these systems will only become more important as industrialization and globalization generate greater inequity within resource systems, and along with climate change, leave increasing numbers of rural communities to grapple with the threat of economic decline and environmental degradation<sup>5</sup>.

## Methods

The state variables of the model are the resource state  $R$ , represented as a proportion of the maximum resource capacity, community population  $U$ , and the wage  $W$ . The dynamics of these variables are modeled using the equations presented below.

**Industrial user production function.** Industrial users maximize their profit  $P$  with respect to labor  $L$  and resource extraction  $E$  (Eq. (1)). The first term measures revenue using the general form of a constant elasticity of substitution production

function typically used to represent the relationship between the inputs, typically physical capital and labor, and the amount of output that can be produced by those inputs. In this case, the variable inputs are the resource and labor, and the third input, meant to represent fixed inputs such as land, is held constant. The second term represents the extraction cost, which is proportional to the difference between the resource maximum capacity and the current state of the resource (analogous to the drawdown for an aquifer, for example), and the third term represents the labor cost

$$\max_{E,L} P = a(b_1 E^q + b_2 L^q + 1)^{1/q} - c(1 - R)E - WL - d - T(E) \quad (1)$$

subject to the constraints  $0 \leq E \leq R$  and  $0 \leq L \leq U$ . The parameter  $a$  represents the revenue threshold at which the marginal benefit of resource and labor approaches zero,  $q$  is the substitution parameter,  $b_1$  and  $b_2$  represent the share parameters associated with resource and labor, respectively,  $c$  represents the extraction cost parameter, and  $d$  represents a fixed cost.  $T(E)$  represents the cost imposed by the policy, and is described in greater detail in the Policies section (Eq. (6)).

The optimization is modeled as deterministic, and industrial users have perfect information about the current resource and labor available. The optimization is therefore constrained by the available resource and labor.

**Wage dynamics.** The wage changes were based on the marginal increase in profit of additional labor,  $\frac{\partial P}{\partial L}$ , as shown in Eq. (2). This relationship is meant to represent how wages increase when labor is a constraining factor for production, and decrease when there is excess labor

$$\frac{dW}{dt} = \begin{cases} g \frac{\partial P}{\partial L} & \frac{\partial P}{\partial L} > 0 \\ -h(U - L) & \frac{\partial P}{\partial L} = 0 \end{cases} \quad (2)$$

where  $g$  and  $h$  are parameters modulating the rates at which the wage increases or decreases, respectively.

**Domestic user well-being function and population dynamics.** The domestic users' well-being function is a product of their resource access index,  $S$ , and their effective wage, or expected value wage,  $W \cdot \frac{L}{U}$ . The resource access index is a function of the proportion of the resource state and the maximum resource capacity. The index ranges from 0 to 1, and aims to capture the diminishing marginal benefit of resource once a level of resource sufficient to satisfy basic needs is met

$$S = \frac{1 - e^{-kR}}{1 - e^{-k}} \quad (3)$$

where  $k$  is a parameter for the resource access benefit relative to the proportion of remaining resource.

Domestic users have the choice of working within the system or migrating out of the system based on their well-being. The movement of domestic users in and out of the system is described using replicator dynamics

$$\frac{dU}{dt} = mU \left( SW \cdot \frac{L}{U} - p \right) \quad (4)$$

where  $p$  represents the well-being outside of the system and  $m$  represents the community's responsiveness to differences in well-being inside and outside of the system.

**Resource dynamics.** The dynamics of the resource follows a simple mass balance relationship between a constant natural regeneration,  $r$ , a natural loss rate, and the extraction by the industrial users

$$\frac{dR}{dt} = r(1 - R) - E \quad (5)$$

**Policies.** If implemented, the cost imposed by the policy is included as an additional term in the industrial users' profit function (Eq. (1)).

The fee is calculated as follows:

$$T(E) = \begin{cases} 0 & \text{if } E \leq C \\ f(E - C) & \text{if } E > C, \end{cases} \quad (6)$$

where  $f$  represents the fee amount per unit of extraction above the extraction threshold  $C$ .

**Alignment metric.** The alignment of equity with resilience is calculated as follows:

$$\text{Alignment} = \frac{P(E|R) - P(E)}{1 - P(R)} \quad (7)$$

where  $P(E|R)$  represents the proportion of the resilient region (within 95% of optimal resilience) that is also within 95% of optimal for equity,  $P(E)$  represents the proportion of the whole colormap that is equitable, and  $P(R)$  represents the proportion of the whole colormap that is resilient. Similarly, the alignment between

resilience combined with profit and equity is calculated as follows:

$$\text{Alignment} = \frac{P(E|(R \wedge P)) - P(E)}{1 - P(R \wedge P)} \quad (8)$$

where  $P(E|(R \wedge P))$  represents the proportion of overlapping region between high resilience and high profit that also leads to high equity, and  $P(R \wedge P)$  represents the proportion of the whole colormap that is in the overlap region between resilience and profit. Note that we use probability notation only for conciseness, and not to suggest that these proportions are equivalent to the probabilities of these outcomes.

**Parameter settings.** Parameter values were held constant in all analyses (Supplementary Table 1). A negative substitution parameter in the industrial user production function was chosen to reflect limited substitutability between resource and labor, as is the case in agriculture, for example, Howitt et al.<sup>48</sup>. A constant is included in the revenue term to reflect the limit on nonlabor and nonresource inputs to production (e.g., a maximum area of land available), leading to an asymptotic production function. The remaining parameters are chosen to satisfy the assumption that (1) there are two possible equilibria, and (2) that implementing a policy limiting extraction can increase the resilience (see Supplementary Figures and Tables for how these parameter ranges were determined).

**Policy outcomes.** Overall, 100 initial conditions are sampled throughout the state space using Latin hypercube sampling for each policy or combination of cap and fee amount. The equilibrium industrial profits and well-being, calculated as the product of the individual well-being and population ( $W \times S \times L$ ), are averaged over all of the trajectories. The resilience is calculated as the proportion of the initial conditions leading to the sustainable equilibrium. For the state variables that are not naturally bounded (the wage and population), the sampling bounds on the initial conditions are chosen to encompass both attractors as well as almost the entirety of the trajectories sampled within the bounds (see Supplementary Fig. 1). Thus, the chosen region represents the "realistic" range of states within the system.

The range of policy thresholds was chosen to encompass the full range of thresholds for which the policy has an impact; higher thresholds have exactly the same effect as no policy at all. The range of policy parameters was chosen to incorporate the region for which changing the fee amount changes industrial user behavior. Sufficiently high fees function as a cap, where the extractors never pay the amount, and the system does not respond to further fee increases.

**System solution.** The system is solved numerically with a step size of 0.08. The system is considered to have reached equilibrium when the maximum of the Euclidean distances between the current state of the system and the system state in any of the previous ten steps is less than a tolerance.

### Data availability

No datasets were generated or analysed during this study.

### Code availability

All custom codes used in this study to solve the system and produce all figures are available at <https://github.com/njmolla/SES-equity-resilience>.

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### Author contributions

N.M. and J.H. designed research, N.M. and J.D. performed research, N.M. and J.D. analyzed data, and N.M. wrote the paper.

### Competing interests

The authors declare no competing interests.

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