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Analysis

Maintaining human wellbeing as socio-environmental systems undergo regime shifts

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ABSTRACT

Global environmental change is pushing many socio-environmental systems towards critical thresholds, where ecological systems' states are on the precipice of tipping points and interventions are needed to navigate or avert impending transitions. Flickering, where a system vacillates between alternative stable states, is an early warning signal of transitions to alternative ecological regimes. However, while flickering may presage an ecological tipping point, these dynamics also pose unique challenges for human adaptation. We link an ecological model that can exhibit flickering to a model of human environmental adaptation to explore the impact of flickering on the utility of adaptive agents. When adaptive capacity is low, flickering causes wellbeing to decline disproportionately. As a result, flickering dynamics move forward the optimal timing of a transformational change that can secure wellbeing despite environmental variability. The implications of flickering on communities faced with desertification, fisheries collapse, and ecosystem change are explored as possible case studies. Flickering, driven in part by climate change and extreme events, may already be impacting communities. Our results suggest that governance interventions investing in adaptive capacity or facilitating transformational change before flickering arises could blunt the negative impact of flickering as socio-environmental systems pass through tipping points.

1. Introduction

Global change impacts, including those resulting from climate change and socioeconomic transitions, are altering the environment and threatening human livelihoods. For example, worsening drought conditions lead to an increased risk of wildfires (McKenzie et al., 2004), and global mean sea-level rise threatens the habitability of low-elevation coastal zones (Vitousek et al., 2017). In ecological systems, these environmental changes are linked to phenomena known as regime shifts, wherein there is a "large persistent change in the structure and function of an ecosystem" (Biggs et al., 2012). Prominent case studies include shifts from productive coral-dominated reefs to degraded macroalgae-dominated systems (Mumby et al., 2007) and shifts from a highly vegetated to a barren state in arid landscapes (Rietkerk et al., 2004). Because these transitions have implications for the ability of humans to thrive in these systems, much attention has been focused on identifying indicators to serve as 'early warning signals' for impending catastrophic changes (Scheffer et al., 2009; Bauch et al., 2016). Whether informed by early warning signals or not, people experiencing ecological regime shifts can attempt to adapt to these changing conditions to maintain their wellbeing. These adaptation measures could include minor changes to practices such as switching target species in fisheries (Katsukawa and Matsuda, 2003), or more major changes such as migration to pursue an alternative livelihood elsewhere (Adamo, 2010).

While identifying and attempting to avoid a transition to an undesirable alternative state remains a challenge, here we focus on how people navigate ecological regime shifts. Adapting to environmental change while maintaining wellbeing poses unique challenges, especially in noisy systems. The global extent of human societies demonstrates the ability of people to adapt to (and prosper under) a broad range of ecological regimes. Other organisms also demonstrate this adaptive capacity in their evolutionary response to environmental change (Carlson et al., 2014). However, in social and environmental systems, stochasticity can result in a phenomenon known as "flickering" when the

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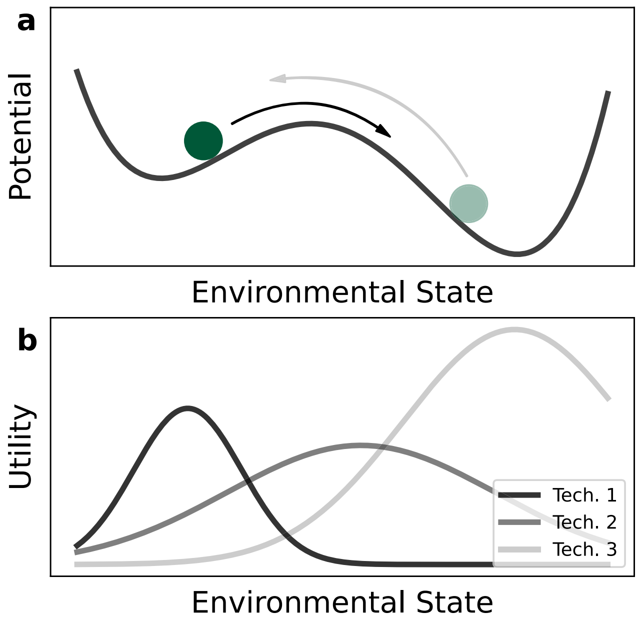

Fig. 1. Panel a illustrates how alternative stable environmental states can be conceptualized as basins where a ball subject to stochastic perturbations (shown by arrows) may settle. Given alternative stable states, noise may cause the environment to tip from a low to a high state or vice versa, a process termed flickering. In agricultural systems, for example, there are often a range of technologies/approaches/strategies that have environmentally dependent utility curves (3 are illustrated in panel b). As environmental states shift, the most favorable strategy changes. While three alternative technologies are illustrated, in principle, a continuum of approaches to adapt to the environment is possible.

system approaches a regime shift (Taylor et al., 1993; Wang et al., 2012; Gatfaoui and De Peretti, 2019). Flickering occurs when a system switches between alternative stable states as a result of stochasticity. In the context of an impending regime shift, flickering leads to time periods that resemble the status quo alternating with time periods defined by a novel socio-environmental state. While stochasticity and environmental variability can impact people's wellbeing, flickering presents a unique challenge for adaptive agents: which regime should one adapt to and when should one shift practices to align with the expected post-regime-shift environment? There may be cases where agents themselves flicker between alternative livelihoods in an attempt to adapt to the intermittent shifts in environmental regimes. Our results suggest that in systems where people have limited adaptive capacity, flickering can yield marked declines in utility.

The importance of adaptation to flickering and nonlinear ecological dynamics can be illustrated through environmentally dependent utility functions. Such utility functions can arise when they depend on environmental production functions. These functions provide a mapping between some measure of the environmental state and production or output. They are typically approximated by hump-shaped functions (Schlenker and Roberts, 2009) (see Fig. 1b). In agriculture, for example, a production function for a particular crop may be dependent on temperature. Multiple functions with peaks that span different ranges of the environmental state (along the x-axis) represent production under different strategies. In this context, climate adaptation can be thought of as people shifting their production strategy, thereby transitioning across the different production functions in order to maintain high levels of output despite environmental change. In agriculture, this could be achieved by choosing different varieties of crops as temperature increases.

However, these production functions do not explicitly account for the non-linear dynamics associated with coupled social-ecological systems. Whereas average temperature in a region may slowly increase in response to climate change and lead to the expectation of a steady advance through a series of production strategies, underlying environmental conditions that shape productivity may exhibit far more complex dynamics in response to gradual global change. To integrate these effects, we consider an environmental model that has the potential for nonlinear dynamics in response to gradual change in an underlying parameter. These nonlinear dynamics associated with changes in the environmental state are often depicted using a well-potential diagram (Fig. 1a). Well-potential diagrams can illustrate how ecosystems (and social-ecological systems) exhibit alternative stable states, and how the resilience of a particular state may be eroded by a relatively slow-changing parameter such as mean temperature. As the resilience of one basin of attraction is diminished and an alternative basin arises, flickering can occur prior to a tipping point being crossed. After the tipping point is crossed, the old basin ceases to exist and the system transitions to the alternative stable state.

In contrast to production functions that are dependent on a gradually changing environmental parameter, the utility functions we model depend on an environment with complex dynamics and can lead to highly stochastic utility as the environment flickers between alternative stable states and as people struggle to adapt to this volatility. Additionally, due to the hump-shaped relationship between the environment and productivity, environmental variability will tend to depress average productivity due to non-linear averaging. By integrating the non-linear dynamics of coupled social-ecological systems – especially the dynamical flickering associated with some regime shifts – with the economic concept of environmentally-dependent production functions, we provide new insight into the potential impacts of regime shifts on human wellbeing. With this framework, we explore the impact of people's adaptive capacity on their ability to track environmental change and maintain their wellbeing. We also examine when transformational change to novel strategies which buffer individuals against environmental change should be adopted given flickering dynamics.

2. Socio-environmental model

We develop a mathematical model to describe the impact of alternative stable states and flickering on the utility of adaptive agents in a coupled socio-environmental system. While relatively simple, this model includes two necessary conditions for flickering, namely the potential for alternative stable states and the presence of stochasticity. We use this model to identify the conditions wherein flickering has the largest negative impact on people's wellbeing and explore how the timing of people's transitions to new strategies should relate to the timing of environmental transitions caused by flickering and tipping points. We discuss three possible case studies that illustrate the potential impacts of these dynamics on communities. We primarily contextualize our model based on the response of Mongolian nomadic pastoralists to rapidly changing environmental conditions. These communities are among the most impacted by the consequences of climate change. In particular, new political regimes have shifted borders, fundamental changes to economic systems have limited the prospects of nomadic ways of life, and extended drought periods have put the health of livestock herds at risk. Using available data from the literature and other publicly available sources, we discuss how global change impacted these communities, with long-term effects that include the migration of people away from their traditional homes. We also discuss how flickering dynamics could have similar consequences for artisanal fishing communities impacted by marine climate shocks and communities impacted by wildfires.

The model has two components: an ecological component where nonlinear dynamics (including flickering) occur, and a social component, where agents adapt their production frontier to align with the environment and maximize their utility.

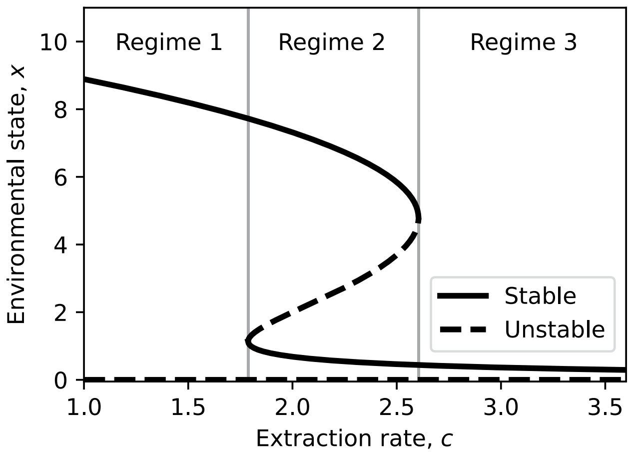

Fig. 2. For low and high extraction rates, the system has only one stable equilibrium. For intermediate extraction rates, bistability occurs and the potential for flickering dynamics arises. We use this distinction to classify our system into three distinct dynamical regimes. In regime 1, only the high environmental state is stable, regime 2 exhibits bistability and potentially flickering dynamics, and only the low environmental state is stable in regime 3. For any extraction rate, actual dynamics of the environment will fluctuate about their equilibria due to stochasticity.

2.1. Ecological dynamics

In our model, we assume that there is an ecological state, x, with dynamics governed by logistic growth and extraction following a type-3 functional response (Holling, 1959). This approach forms the basis for well-studied ecological models that can exhibit alternative stable states and hysteresis (May, 1977; Scheffer, 1989); models of this form have also been used to study flickering dynamics (Dakos et al., 2012). The ecological state, x, could represent the abundance of forage plants in the context of grazing systems, fish biomass in the case of fisheries, or forest biomass in the case of wildfires. The discrete-time stochastic dynamics of x are described by

$$x_{t+1} = rx_t\left(1 - \frac{x_t}{K}\right) - c\frac{x_t^2}{x_t^2 + h^2} + \left(1 + i_t\right)x_t \quad (1)$$

where r is the intrinsic growth rate of x, K is its carrying capacity, c is the extraction rate, h is the half-saturation constant (i.e., the resource level at which half of the maximum extraction rate is reached), and i_t is a noise term that models environmental shocks. Borrowing from the approach of Dakos et al. (2012), we assume that i_t is time-correlated red noise governed by

$$i_t = \left(1 - \frac{1}{T}\right)i_{t-1} + \eta_t, \quad (2)$$

where $i_t x_t$ is the magnitude of the stochastic reduction or increase of the resource at time t, T is the time scale over which noise becomes uncorrelated, and $\eta_t \sim \mathcal{N}(0, \beta^2)$ is an element of a series of independent identically distributed normal error terms. This kind of noise describes situations where random fluctuations in the environment are not independent over time or space, but rather show some pattern of correlation. This form of noise has been widely explored and modeled in ecology, for example in studies of the impact of storms, floods, wildfires and other environmental factors on population dynamics (Lande et al., 2003).

In the absence of noise (i.e., when $\beta = 0$), this system can exhibit a range of dynamics. For large values of r, discrete-time logistic systems such as this can exhibit cyclic or chaotic dynamics (May, 1974). To simplify our analyses, we restrict our attention to those cases where cyclic and chaotic dynamics do not occur in the absence of noise. For harvesting rates c, that are low, the system has a single stable equilibrium corresponding to an environmental state of abundance. For high values of c, the sole stable equilibrium is a depleted environmental state. For intermediate values of c there exists a region with multiple stable equilibria. In this intermediate regime, the inclusion of noise can lead to a flickering dynamic where the system makes irregular jumps from the high to low environmental basins of attraction (Dakos et al., 2012). Fig. 2 shows the stable and unstable equilibrium states across a range of harvesting values, and illustrates that for intermediate extraction rates, the system has two alternative stable states.

2.2. Human adaptation and wellbeing

To model human wellbeing in response to a constantly changing environment, we assume that people can adapt their practices to be in alignment with the environmental state, but that this adaptation process takes time. The rate at which individuals can adapt to a changing environment depends on their adaptive capacity. Here, we conceptualize adaptation as individual or collective actions that allow individuals to be as successful as possible, given the current state of the environment. Adaptation allows individuals to shift the peak of their production function so that it aligns with the current environmental state. Potential avenues for adaptation are myriad and depend on the context of the case study. For pastoralist systems, they include moving to better locations when the local resource level is low, implementing irrigation systems to bolster productivity, and storing feed for cattle (Chen et al., 2015). In agriculture, it could include adjusting the timing of planting and harvesting, and changing (or diversifying) the varieties of crops grown.

We employ a very simple model that captures the notion of adaptive capacity and allows us to explore the consequences of decreased adaptive capacity on people's wellbeing. We let y_t be the environmental state to which individuals are most well adapted. When $y_t = x_t$, agents achieve the highest possible payoff given the current environmental state. The adaptation of individuals to environmental change is constrained by their adaptive capacity, l. When $l = 1$, individuals adapt fully in one time step to the current environmental state. On the other hand, for small l much less than 1, it takes much more time for adaptation to a fixed environmental state to be achieved. We model the dynamics of adaptation as a deterministic discrete-time dynamical system governed by

$$y_{t+1} = l(x_t - y_t) + y_t. \quad (3)$$

We construct a utility function that depends on the best possible payoff, $\pi(x)$, that can be attained given the current environmental state, x, and on the extent to which there is a divergence between the environmental state and the state to which individuals are most well adapted. We assume that the highest achievable payoff given an environmental state x is a linearly increasing function $\pi(x)$, such that the potential for high payoffs improves with the state of the environment (Fig. 3). However, our modeling approach could be applied to more general payoff functions, including those where payoffs depend directly on the extraction rate, c, as can be the case in resource harvesting systems. When there is some degree of divergence between the current environmental state and an individual's adaptation, then utility decreases. We assume that utility can be described as a Gaussian function of environmental adaptation, y, given by

$$U(x, y) = \pi(x)\ \exp\left(\frac{-\ln(2)(x-y)^2}{a^2}\right) \quad (4)$$

where a defines the degree of maladaptation at which utility is cut in half from its peak. This utility function adheres to our assumption that when environmental adaptation, y, is equal to the current environmental state, x, then $U(x, y) = \pi(x)$.

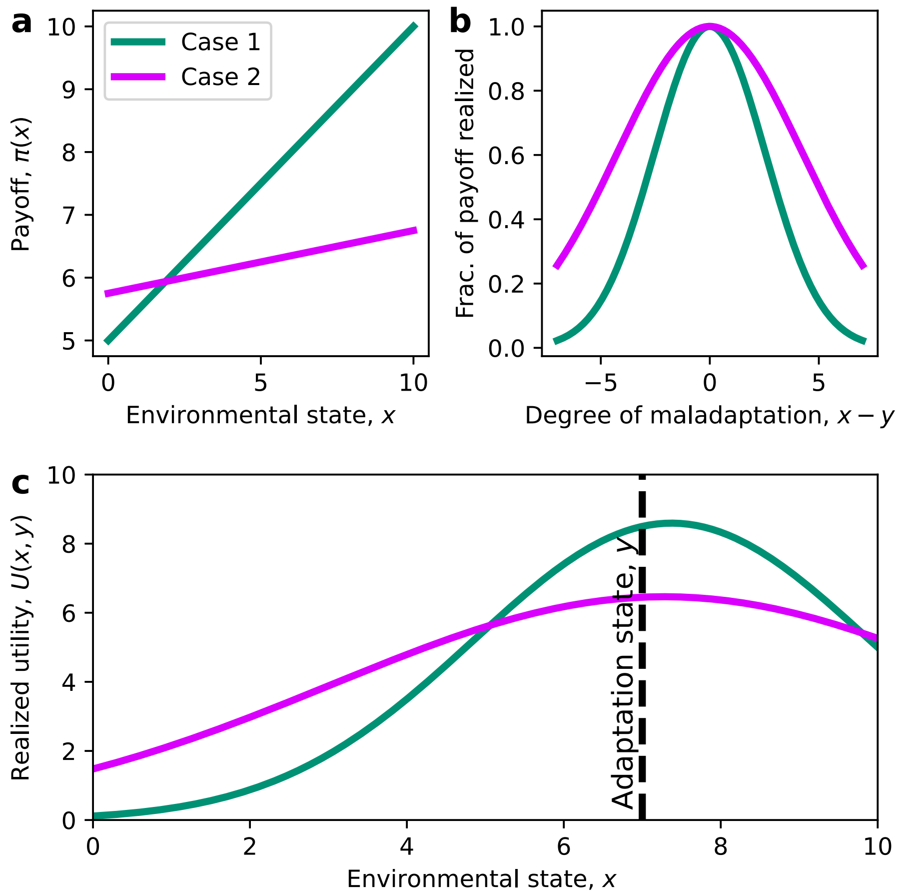

Fig. 3. Illustrations showing two representative cases. Panel a illustrates the relationship between the environmental state and maximum payoff, $\pi(x)$, shown for a case where the payoffs are highly sensitive to the environmental state (Case 1) and where payoffs vary less in response to different environmental states (Case 2). Panel b shows the relationship between the maladaptation to the environment and the fraction of payoffs individuals realize as utility. In Case 1, individuals are more sensitive to maladaptation than Case 2. Finally, in panel c, these impacts are aggregated and utility is shown as a function of the current environmental state (x) given that the environmental state to which individuals are most well adapted is $y = 7$.

2.3. Human-environmental dynamics

The coupled dynamics of the environment and adaptation can be described by the system of difference equations

$$x_{t+1} = rx_t\left(1 - \frac{x_t}{K}\right) - \frac{cx_t^2}{x_t^2 + h^2} + \left(1 + i_t\right)x_t \tag{5}$$

$$i_{t+1} = \left(1 - \frac{1}{T}\right)i_t + \eta_{t+1} \tag{6}$$

$$y_{t+1} = l(x_t - y_t) + y_t, \tag{7}$$

where i is a red noise term, x is the state of the environment, and y is the environment to which individuals are most well adapted. Definitions and ranges of values for the variables and parameters of the model are described in Table 1.

Fig. 2 shows that for low extraction rates, the sole stable equilibrium of the system is a high environmental state, but as extraction increases, a tipping point is crossed and the environmental state collapses. Layered on top of this tipping point is human adaptation, which influences wellbeing. We start by focusing solely on the dynamics of the environment and adaptation. Later we will turn our attention to the implications of these dynamics for wellbeing.

3. Results

3.1. Environmental adaptation in three regimes

Fig. 2 identifies three regimes that exhibit qualitatively distinct environmental dynamics. In regime 1, there is a single stable equilibrium with high resource biomass. In regime 2, there are alternative stable states, one with high biomass and one with a degraded environmental state. Lastly, in regime 3, only the degraded environmental equilibrium remains.

We are motivated by the scenario wherein historical conditions of the system correspond to regime 1. In other words, we start in a scenario where high biomass predominates. Nevertheless, the system is stochastic, and fluctuations about this high-biomass equilibrium can be significant in magnitude. The dynamics of adaptation are governed by the same equation across all three regimes, with agents adjusting their practices towards the current environmental state. Fig. 4a shows that dynamics of the environment in regime 1 exhibit significant variation but that adaptation generally falls within the range of environmental variability.

In response to shifting economic structures and environmental change, we assume that the extraction rate, c, in the system will increase over time and the system will eventually fall within regime 2. Fig. 4b and c with c values corresponding to regime 2 show examples of flickering environmental dynamics. Whereas adaptation largely remains within the range of environmental variability in regime 1, in regime 2 when the system flips from one equilibrium region to the other, there are significant time periods where adaptation is significantly misaligned from the state of the environment. We show that this has important implications for the utility (wellbeing) of agents in regime 2.

Fig. 4d shows a case where the extraction rate is high enough that the system has been pushed beyond a tipping point and is in regime

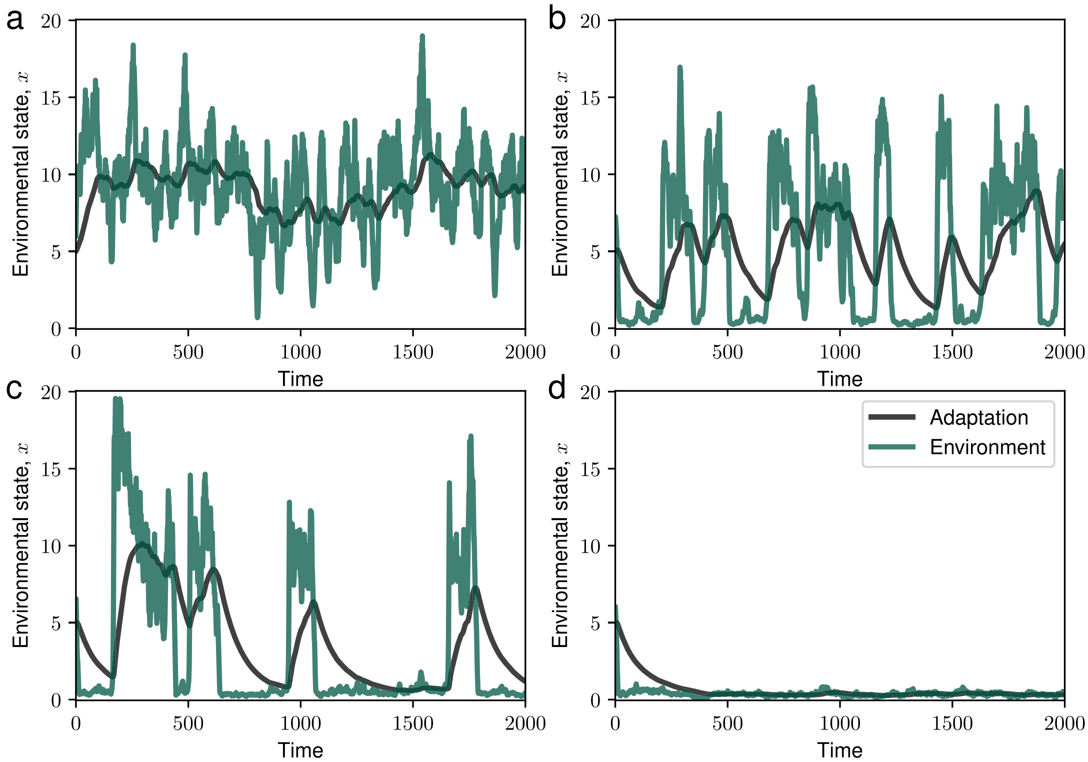

Fig. 4. Temporal dynamics of the environment and adaptation across three regimes. Panel a: Regime 1: $c = 1$ results in a high, but variable environment state. Panel b: Regime 2: $c = 1.95$ shows flickering dynamics with brief periods of collapse. Panel c: Regime 2: $c = 2.45$ results in flickering dynamics with longer periods in a collapsed state. Panel d: Regime 3: $c = 3.1$ yields system collapse, with the possibility of brief periods which resemble recovery. When environmental dynamics fall into regime 1 or 3, individuals adaption generally falls within the range of day-to-day environmental variability. For flickering environmental dynamics as seen in regime 2, when the environment flips from one basin of attraction to another, there are extended periods where individuals are significantly maladapted to the environment. This has important implications for wellbeing.

3. The only stable equilibrium is a collapsed environmental state, but stochastic dynamics may nonetheless lead to ephemeral periods where environmental dynamics resemble historical conditions. In regime 3, agents are more or less able to adapt and maintain relatively close alignment with the environment. Because of this, we expect utility to approach the maximum payoffs that can be attained under perfect adaptation.

3.2. *Wellbeing and environmental regimes*

Wellbeing depends both on the maximum profitability that could be achieved given environmental conditions, as well as the degree to which agents are adapted to the environmental state. In this section, we examine how wellbeing or utility depends on the environmental extraction rate, c.

As discussed, extraction rates structure the system into three qualitatively distinct regimes. Fig. 5 shows how the average payoff, assuming perfect adaptation and average utility, depend on which regime the extraction rate falls within and on the level of adaptive capacity, l. Fig. 5 shows the maximum average payoff,

$$\overline{\pi} = \frac{1}{t_{\max}} \sum_{t=1}^{t_{\max}} \pi\left(x_t\right), \tag{8}$$

that could be achieved through time for different fixed rates, c, of environmental extraction. The figure also represents average utility,

$$\overline{U} = \frac{1}{t_{\max}} \sum_{t=1}^{t_{\max}} U\left(x_t, y_t\right), \tag{9}$$

for several levels of adaptive capacity, l. Unlike $\overline{\pi}$, $\overline{U}$ depends on both the state of the environment, x_t and adaptation, y_t. The simulation results shown in Fig. 3 suggest that decreasing adaptive capacity reduces average utility. This pattern holds across a broad range of adaptive capacity values, as shown in Figure SI 2. However, adaptation ceases when $l = 0$ and $y_t = y_0$ at all time steps. In this case, we show that setting y_0 to an environmental equilibrium can yield higher average utility than environmental adaptation for very small l in some cases (see Figure SI 1).

For higher values of adaptive capacity, l, the qualitative pattern of average utility mirrors that of average payoff. When $l = 0.1$, Both average payoff, $\overline{\pi}$ and average utility, $\overline{U}$ gradually decline as the extraction rate increases through the three regimes. For moderate to low levels of adaptive capacity, (e.g. $l = 0.01$ to $l = 0.001$) the qualitative patterns seen in average payoff, and in average utility under high adaptive capacity no longer hold. In these cases, the flickering dynamics of regime 2 exacts a costly toll on average utility. The repeated switching between high and low environmental states leads to extended periods of maladaptation that diminish average utility and creates a noticeable utility trough in regime 2. In regime 3, the collapsed environment does not vary as widely and even agents with limited adaptive capacity can eventually adapt their behaviors to the permanently degraded environmental state. This leads to an increase in the average utility of agents with low adaptive capacity and a convergence of utilities and payoffs across all scenarios. This result raises important questions about the usefulness of flickering as an early warning signal in socio-environmental systems. Flickering dynamics can depress average wellbeing by creating highly variable environmental conditions with abrupt shifts that require significant time to adapt to, especially for agents with low adaptive capacity. Our simulations suggest that rather than being an early warning signal, in socio-environmental systems, flickering can be a uniquely challenging regime for agents with low adaptive capacity.

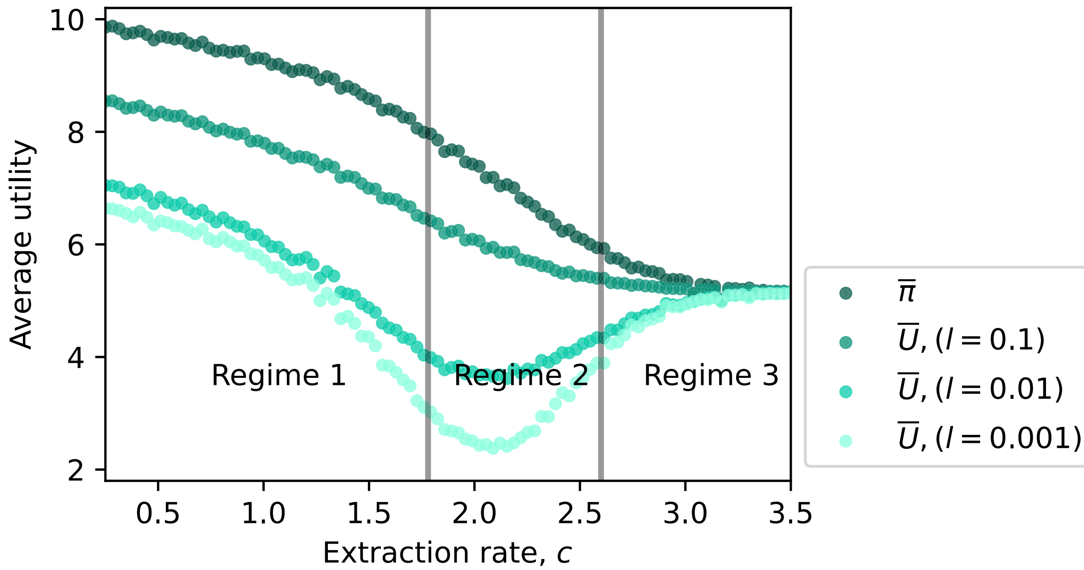

Fig. 5. Average payoff, $\overline{\pi}$, given perfect environmental adaptation and realized average utility, $\overline{U}$, under actual environmental adaptation for a range of extraction rates, c and levels of adaptive capacity, l. Flickering can occur in regime 2 for intermediate extraction rates. Flickering dynamics present unique challenges for adaptive agents, especially those with limited adaptive capacity. When agents have low adaptive capacity, flickering leads to a utility trough that does not occur for agents with high adaptive capacity.

3.3. Transformational change

In this section we consider the option of transformational change, where agents can choose once to dramatically overhaul their practices and adopt a more generalist approach. In Fig. 3 we showed two alternative cases for the structure of the payoff and utility functions. The first case, where payoffs are highly sensitive to the environmental state and utility is sensitive to maladaptation, has been the focus of the preceding simulation results. In essence, we have assumed that individuals attempt to become specialists in their environment. The second case shown in Fig. 3 highlights an alternative possibility, that payoffs are less sensitive to environmental conditions and utility is less sensitive to maladaptation. This corresponds more closely with a generalist strategy, where peak payoffs may never be as high, but adaptation to precise environmental conditions is less important.

Transformation to a generalist approach is an alternative to specialist adaptation to one's environment. Under transformation, agents fundamentally alter their practices in order to switch their payoff and utility functions from those in case 1 to those described by case 2. Fig. 6 shows the maximum average payoff, $\overline{\pi}$, of a specialist approach (case 1, in dark green) and a transformational generalist approach (case 2, in dark purple). In this example, the payoff functions are such that if agents were always perfectly adapted to the environment, they would choose the transformational approach as the system nears regime 3 and the dark purple circles rise above the dark green circles. However, agents will not always be perfectly adapted to the current environment, so their realized average utility will fall below the maximum attainable average payoff. In this case, agents would increase their average utility by adopting the transformational approach (case 2) while the system is still in regime 1. After transformation, the flickering dynamics experienced in regime 2 are far less detrimental to average utility. After crossing into regime 3, the average utility of the transformation approach remains higher than the baseline specialist approach. Other payoff and utility functions can be constructed where the transformational generalist approach is only favored during the flickering regime. In this case, analyzing average payoffs could indicate that transformation is never beneficial, while an analysis focusing on realized average utility could show that transformation can help agents navigate flickering critical transitions without suffering as greatly from the utility trough that might otherwise occur.

Table 1
Variables and parameters in the model, their approximate range of values, and meanings. Exact parameter values used for each figure available in Table SI 1.

Variable	Range of values	Description
x_t	0–20	Current environmental state
y_t	0–20	Current adaptation state
l	.001–1	Adaptive capacity
i_t		Auto-correlated red noise
T	30	Timescale over which noise becomes uncorrelated
η_t	0	i.i.d. normal error term
β	.07	The standard deviation of η's
r	1	Resource growth rate
K	10	Resource carrying capacity
c	0–4	Extraction rate
h	1	Extraction half-saturation constant
$\pi(x)$	5–10	Environmentally dependent payoffs
$U(x, y)$	0–$\pi(x)$	Utility as a function of environmental and adaptation states
a	3–5	Value of $\|x - y\|$ for which $U(x, y) = 1/2\ \pi(x)$

4. Case studies

4.1. Desertification and nomadic pastoral systems in Mongolia

Rising aridity and resulting desertification is expected to increasingly affect drylands around the globe. In combination with socioeconomic changes and increasing land use pressure, desertification could affect up to 2 billion people living in drylands over the coming decades (Berdugo et al., 2020). Here, we investigate these effects on nomadic pastoralists who inhabit the semi-arid areas of Central Asia, the Middle East, North Africa and the Sahel zone, with a particular focus on Mongolia.

Mongolia is the world's most sparsely populated country, has an arid to semi-arid climate with temperatures ranging from −50 °C in winter and +50 °C in summer, few forests, and very limited arable land (Mongolian Statistical Information System, 2021). Nomadic lifestyles are well adapted to these patchy landscapes and highly variable climate conditions (described by environmental state, x, in our model) (Liao et al., 2020). Extreme weather conditions can cause severe winter weather events called Dzud, which can precipitate disasters characterized by extended periods of inaccessible grazing resources (representing

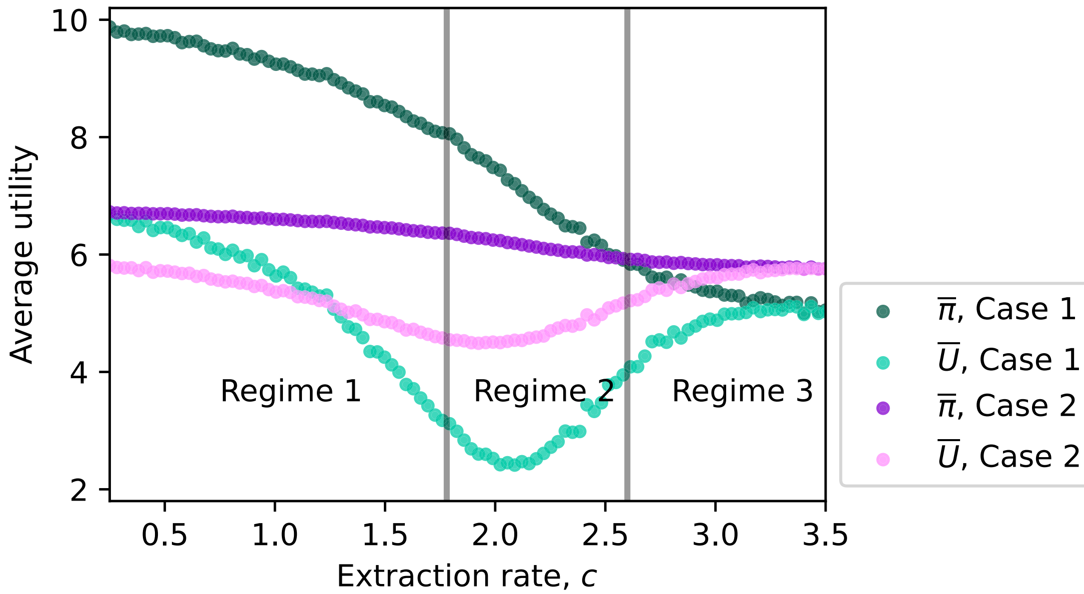

Fig. 6. Average payoff, $\overline{\pi}$, given perfect environmental adaptation and realized average utility, $\overline{U}$, under actual environmental adaptation for a range of extraction rates, c, across two qualitatively distinct cases shown in Fig. 3. Case 1 corresponds to the specialist approach that is examined in Fig. 5, where payoffs are highly dependent on the state of the environment and highly sensitive to maladaptation. Case 2 corresponds to a generalist approach where payoffs are less sensitive to the state of the environment and maladaptation has a smaller impact on realized utility. As c increases, agents are eventually better off adopting a generalist approach. However, the timing of this shift depends on adaptive capacity. Given perfect environmental adaptation, payoffs under case 1 remain higher than those under case 2 until after the system passes its tipping point at the cusp of regimes 2 and 3. On the other hand, when adaptive capacity is limited, optimal transformation timing is earlier, as illustrated by the average utility under case 1 falling below the average utility under case 2 in regime 1. In this case, agents are better off transforming to a generalist approach (case 2) before the system reaches the flickering regime.

noise in our model). In response to the environmental variability, nomadic pastoralists, which represent about one third of the country's population, employ a range of adaptive strategies including storage of fodder for use during poor grazing conditions, mobility between seasons to seek out better rangelands for livestock grazing, water access and shelter from winter storms, and communal pooling of resources and labor, among others (adaptive capacity, l) (Fernández-Giménez et al., 2015; Wang et al., 2013; Sneath, 2003).

In 1990, Mongolia experienced a political transformation during which the centrally controlled socialist regime was abolished and transitioned to a market economy. This brought about changes to public services and institutional structures upon which both settled and nomadic people relied. Prior to 1990, herders were organized into modular collectives of families around community centers known as *'bag'*. These centers provided technical, social, health and veterinary services, as well as emergency stocks of fodder to buffer against Dzud events (Fernández-Giménez et al., 2015). They represented a type of community insurance that allowed families who lost their herd to restock the following year (Fernández-Giménez et al., 2015; Ahearn, 2018), adding to their adaptive capacity and bolstering their resilience even to severe shocks.

As bag centers and their social services all but disappeared (Fernández-Giménez et al., 2015), pastoralist families had to adapt by becoming increasingly self-reliant; they grew their livestock herds to raise income during favorable years and to be able to buffer losses during Dzud years. Prior to 1990, livestock was state-owned and numbers were strictly monitored and capped at 20–25 million. As livestock was privatized and numbers were no longer regulated under the new governance regime, they quickly grew to around 70 million today (Mongolian Statistical Information System, 2021) with grazing pressure (parameter c) growth coinciding with a drop in the density of vegatation (measured by NDVI) (Enebish et al., 2020) (See Supplementary Information, Figure SI 5). Grazing pressure, together with repeated extreme Dzud events have resulted in high levels of livestock mortality, killing 33, 23 and 10 million heads of cattle in 1999, 2003 and 2010, respectively, with devastating effects for nomadic livelihoods (Rao et al., 2015). In response to these losses, external actors, such as the Asian Development Bank, pushed the Mongolian government to privatize land ownership, in order to give exclusive land use rights to individual families and reduce overgrazing (Sneath, 2003). However, land privatization came at the cost of mobility, an essential element of pastoralism adapted to the low average productivity and high spatio-temporal variability of rangelands (Sneath, 2003). This added to the vulnerability of the pastoralist families by further deteriorating local pastures (Fernández-Giménez et al., 2015; Wang et al., 2013). Thus, a number of compounding factors contributed to a decline in adaptive capacity and wellbeing of the pastoralists.

After the devastating Dzud of 2009/10, private insurance models emerged (Ahearn, 2018) and a number of donor-initiated community-based natural resource management organizations were initiated that aimed to establish community-level adaptive capacity and structures resembling those that existed prior to 1990 (Fernández-Giménez et al., 2015). Others responded to the increasing difficulty of maintaining rural lifestyles by migrating to urban centers (akin to a transformational change from case 1 to case 2 in our model), resulting in a doubling of the urban population over the past thirty years (Mongolian Statistical Information System, 2021) (See Supplementary Information, Figure SI 8). For some, moving to an urban setting presented new opportunities for education and employment. For others, the transformation posed insurmountable challenges. Rapid urbanization has overwhelmed urban governance institutions, and the majority of urban migrants in Mongolia have inadequate access to basic services, such as water, sanitation and electricity (Terbish and Rawsthorne, 2016), and are unable to support themselves.

The episodic livestock losses of the past 25 years have co-occurred with a downward trend of summer drought conditions over the past 20 years (Han et al., 2021). Superimposed on these trends has been a long-term significant increase in average annual temperatures of 2.24 °C and a 7 percent decrease in precipitation recorded over the past 75 years (1940–2015) (Han et al., 2021), indicating that Mongolia is undergoing a long-term process of desertification, driven mainly by climate change (Meng et al., 2021; Han et al., 2021). The hotter and drier climate in the region has resulted from a positive feedback loop between soil moisture deficits and surface warming. Increased temperatures and decreased precipitation coupled with land degradation have resulted in more than three-quarters of land in Mongolia being affected by drought and desertification, and over a quarter of lakes greater than 1.0 km^2 dried up in the Mongolian Plateau between 1987 and 2010 (Han et al., 2021). This is confirmed by deep time analyses showing regime shifts over the past 60 million years, which indicate that Mongolia, and Central Asia at large, is at the brink of another such shift, which will lead to a highly reduced vegetation cover, increased precipitation variability, and widespread desertification (Barbolini et al., 2020).

A combination of high mobility and collective social support structures made Mongolia's semi-nomadic society highly adapted to fluctuating weather conditions and productivity of grasslands (Sneath, 2003). However, climate change and the (mal-) adaptive strategies of governance have tested the resilience of these pastoralist communities. While there are strong indications that the region will increasingly desertify, we do not know how long this transition phase may last, which may well be in the order of decades to centuries; a time span which, according to our model, may be increasingly characterized by flickering between the two alternative regimes (vegetated versus desertified). While results for donor-incentivized community-based resource management have been mixed, lessons can be learned from successful cases. Herd size regulations and agreements to share grazing lands among herder families could help sustain the livelihoods of families with smaller herd sizes (Fernández-Giménez et al., 2015). As a growing number of people moves to urban centers, governance mechanisms could be established that facilitate this transformation at an early stage to avoid extended losses in utility (and wealth) resulting from costly adaptation to variable environmental conditions. However, given already insufficient urban infrastructures, sprawling (and under-served) urban settlements and overwhelmed urban management, careful consideration of adequate types of interventions will contribute to greater sustainability of local human-environment systems in the medium- to long-term. Governance interventions could be designed to support both rural and urban livelihoods and to strengthen the adaptive capacity and resilience of social and ecological systems.

4.2. Fisheries collapse

Fisheries support the income and food security of millions of people around the world (McClanahan et al., 2015). In this example, the environmental state x quantifies the abundance of a fishery stock or the condition of the habitat that supports that stock (e.g., the amount of live coral cover on a reef). These states are being severely impacted by climate change; from increases in ocean temperature and acidity that are reducing the structural integrity of coral reefs (Hoegh-Guldberg et al., 2017), to species range shifts that are altering the spatial distribution of fishing effort (Pinsky and Fogarty, 2012), many fisheries systems are changing and represent critical adaptation challenges for coastal communities (Hollowed et al., 2013). These multiple climate stressors combined with the impact of harvest (c in our model) on marine social-ecological systems have, in some cases, led to collapsed fisheries (Lade et al., 2015) that may not recover due to alternative stable states (Gårdmark et al., 2015). In general, evidence of alternative attractors in open ocean systems has been limited due to difficult sampling logistics and the challenges of defining reasonable system boundaries for highly mobile species (Conversi et al., 2015). However, a recent study using global harvesting data identified alternative stable states – stock conservation and stock depletion – in fisheries where maximum stock sizes are relatively low and where cost-benefit ratios are high (Tekwa et al., 2019). Together with the impacts of environmental stochasticity and extreme events, the potential for regime shifts in both coastal and open water marine systems could result in flickering dynamics with similar characteristics to our model.

Fishers have developed several ways of dealing with changes in the environmental state (adaptation rate, l, to environmental state, y). In particular, fishers can track fish stocks as they shift locations with climate change (Selden et al., 2020). Switching fisheries and operating in numerous fisheries over the course of a year is also common. This is one way in which fishers "smooth" their income over the year, but it can be costly in time and money, and sometimes impossible given certain fisheries management institutions (e.g., permits are required to fish, but sometimes not available). Switching between fisheries also requires training, knowledge and different fishing gear. Beyond adapting to the impending low ecological state of regime 3, another potential option involves attempting to shift the system from the flickering regime (regime 2) into the high stock abundance state in regime 1 through policies that impose intense fishing reductions. However, doing so requires that these policies are implemented in time to avoid a shift into regime 3. The relatively slow institutional adaptive responses (relative to ecological responses) that are characteristic of most fisheries (Tekwa et al., 2019), combined with the potential for climate change to accelerate decline through reductions in population growth (Pershing et al., 2015), are likely to make these transitions increasingly difficult. In the Gulf of Maine cod fishery, for example, some scientists suggest that stronger reductions in fishing may have allowed the population to rebuild during cooler years because those conditions are associated with reduced mortality, especially for juvenile fish. However, because management did not account for the effects of warming, the stock continued to decline even under severe fishing restrictions (Pershing et al., 2015).

Exposure to an ecological regime shift can restructure the incentives for what species are targeted. For example, coral reefs around the world are experiencing more frequent and intense marine heatwaves that lead to coral bleaching and mass coral mortality events (Hoegh-Guldberg et al., 2017; Hughes et al., 2018). In addition to impacts on coral cover, bleaching events are altering reef fish assemblages, especially if reefs experience a shift towards an algal-dominated state (Richardson et al., 2018; Robinson et al., 2019). Return times between bleaching events are presently about every six years and because coral requires on the order of 10–15 years for the fastest species to recover (Gilmour et al., 2013), it is possible that reefs today are experiencing flickering between a high- vs. low-coral state or have already transitioned into the latter.

For coral reef fisheries, fishers reduce their sensitivity to climate change, including the impacts of flickering between high- and low-coral cover states, through livelihood diversification (Cinner et al., 2012). For example, in the Caribbean, alternative livelihoods among coastal fishers include agriculture, forestry, aquaculture, construction work, and ecotourism (Karlsson and Mclean, 2020). However, socio-economic barriers including poverty, a minimal social safety net, or a lack of access to capital can limit adaptive capacity and prevent this diversification (Cinner et al., 2012). Governance aimed at dismantling these barriers may also provide second-order benefits by helping to smooth the transition of socio-economic systems though the flickering stages of ecological regime shifts. The main concern suggested by our modeling is that if there is flickering between ecological/fishery states, then fishers might lose income by repeatedly adapting to different states. In addition to the costs associated with gaining the knowledge, the institutional costs such as attaining permits for a new fishery, and the sunk-costs associated with procuring necessary new fishing gear, may force many fishers to take drastic/transformative action, such as leaving fishing altogether. All of these factors indicate that a flickering transition in the underlying ecosystem that a fishery is part of is likely to cause a decline in wellbeing among fishers, potentially reducing the viability of certain fisheries in the future.

4.3. Wildfire risk and ecosystem change

Ecosystem management of forests has been viewed through a socio-environmental systems lens (Kaufmann et al., 1994). The ecological dynamics of forest ecosystems and the stochastic dynamics of wildfire are both coupled with climatic conditions (Millar et al., 2007) and management practices including timber harvesting, fire suppression, and prescribed fire (Luce et al., 2012; Steelman, 2016).

In the forest ecosystems of the western US, climate change has led to increasing frequency and severity of drought, as well as hotter peak summer temperatures (McKenzie et al., 2004). These changes have coincided with a decades-long management emphasis on fire suppression, which has contributed to increased stand density in western forests (Fellows and Goulden, 2008). Furthermore, there has been a dramatic increase in the extent of the wildland-urban interface (Radeloff et al., 2018), which increases the likelihood of ignition events. There has also been growing recognition of the impact of wildfire on air pollution and health outcomes (Burke et al., 2021). Together, these factors elevate the magnitude of damages that could result from a wildfire. These increasing stressors, driven by climate change, management policies and development, have combined to increase wildfire risk (Marlon et al., 2012) and raise the spectre of the collapse of these ecosystems and their transition to alternative states (Adams, 2013). Given the potential for alternative stable ecosystem states and the inherent stochasticity in the ignition and spread of wildfires, forest ecosystems may exhibit flickering dynamics if they undergo a regime shift.

In response to these entangled and increasing risks, the USDA Forest Service has developed a wildfire crisis strategy which emphasizes prescribed fire and mechanical thinning (USDA Forest Service, 2022). Studies have indicated that this approach can lower the health impacts of smoke (Schollaert et al., 2023) while advancing ecological restoration objectives of bringing about more fire resilient ecosystems (Knapp et al., 2017). However, current climatic conditions, high fuel loads, and the vast extent of the wildland-urban interface will make the implementation of prescribed fire and the transition towards a fire-resilient landscape challenging.

In this context, the ecological state, x, from our model would represent a measure of forest ecosystem state where high equilibrium values correspond to historic forest ecosystem conditions and low equilibrium values represent an alternative ecosystem state with different species composition and lower tree abundance. The extraction rate parameter, c, would represent climate stress on the ecosystem and as the magnitude of climate stress increases, the forest ecosystem state may be pushed into a regime with alternative stable states and the potential for flickering, eventually passing a tipping point where collapse into an alternative regime is assured.

Our model suggests that a transition to an alternative ecosystem state that exhibits flickering could strain people's wellbeing, especially when adaptive capacity of management agencies, communities and individuals is low (l in our model). This results from the time it takes for social practices to be reorganized to align with environmental states and result in fire-resilience (y in our model is the environmental state to which individuals are most well adapted). Further, a flickering transition may contain periods of time that resemble the historical ecosystem state, where the pressure to invest in adaptations to increase fire resilience may seem unnecessary or counterproductive. Given flickering, these chapters of unpredictable duration which resemble historical conditions may end with dramatic shifts marked by wildfire. The Forest Service wildfire crisis strategy aims to minimize the risk of these conflagrations by pairing prescribed fire with mechanical fuels treatments so that fire intensity stays low and risks to communities are diminished. This approach may decrease the risk of a flickering transition, but our modeling results suggest that a complementary management focus on increasing people's adaptive capacity may blunt the negative impacts that a flickering transition can cause. For example, investments in programs which provide education about the risks of wildfire smoke (Wen and Burke, 2022; Burke et al., 2022) and resources for improving indoor air quality could help communities mitigate the health impacts of wildfire smoke as they adapt to changing forest conditions.

5. Discussion

Global change is pushing socio-environmental systems towards tipping points where further small changes to underlying conditions could lead to dramatic shifts in system states. Much work has focused on identifying early warning signals of tipping points and governance interventions that can prevent the collapse of the current socio-environmental state. However, as climate change and other anthropogenic impacts continue (e.g., converting Amazonian rainforests for agricultural and cattle use), we may see more social-ecological systems approach and pass through tipping points despite societies' best efforts to avoid them. In this case, in addition to efforts to avert a tipping point, it may be valuable to design governance interventions that minimize the loss of wellbeing that results from passing through a tipping point.

Flickering, where a system switches among alternative stable states as a result of noise, can occur prior to a tipping point and may serve as an early warning indicator (Scheffer et al., 2009). However, there remains debate over the presence and universality of early warning signals in ecological and socio-environmental systems (Hastings and Wysham, 2010; Boettiger and Hastings, 2012; Bauch et al., 2016). Nevertheless, our results suggest that should flickering be present or possible, rather than being a useful early warning signal, flickering may instead be a primary hurdle to successfully navigating a tipping point. This highlights the importance of theoretical methods that help diagnose whether flickering might be a possible dynamic for a given (socio-environmental) system and empirical methods for predicting the presence of tipping points, which has seen recent advances with the use of new machine learning methods and remote sensing (Lenton et al., 2024).

Environmental variability driven by stochasticity and extreme events impacts people's wellbeing even in the absence of flickering, and differentiating between the impacts of environmental variability and flickering can be a challenge. Across the three stability regimes in our simulation experiments, we do not vary the structure of stochasticity. Yet, we see that the largest declines in average wellbeing arise within the regime where flickering dynamics occur. Statistical properties of time series data could be used to empirically assess the presence of flickering dynamics (Wang et al., 2012), but further work is needed to link these with impacts on wellbeing. Our results indicate that adaptation to variable environments can decrease wellbeing and that flickering dynamics exacerbate these impacts.

A concerning possibility is that when people with low adaptive capacity are exposed to environmental flickering, the reduction in their wellbeing might further erode their adaptive capacity, for example by reducing their wealth or health. This could result in a vicious cycle wherein flickering induces a continuous reduction in the set of adaptation options open to people. Such a cycle could induce conditions that force people into adopting outside options, including urban or international migration. Human migration driven by adverse environmental conditions is a well known consequence of climate change (Cattaneo et al., 2020). A term used in the context of sea-level rise to describe the inevitability of community reorganization in the face of environmental change is "managed retreat" (Alexander et al., 2012). The challenge then is to ensure that this retreat is indeed managed in a way that accounts for the unique impacts that flickering could have during a transition through a regime shift. For many people around the world, some form of retreat might be inevitable, either in space (i.e., human migration) or in terms of job sector.

Income diversification is among the primary tools that people use for dealing with environmental risks (Brouwer et al., 2007; Shah et al., 2021). Therefore, flickering could incentivize people to diversify or change the industries that secure their income. This is evident in fisheries, where working in numerous fisheries throughout the year can act as a natural means of buffering the stochasticity associated with harvest (Kasperski and Holland, 2013; Finkbeiner, 2015; Cline et al., 2017). Fishers are also known to work in multiple sectors, including jobs on land within the timber and agricultural sectors (Anderson et al., 2017). Environmental flickering in the oceans could lead to fishers redistributing their efforts over the set of fisheries available to them and other industries that they work in. Analogously to migration, extreme environmental flickering might induce people to permanently leave one industry for another.

Policies that bolster people's adaptive capacity may be vital to ensuring means are available to adapt (and thrive) in coming decades. Tools such as (parametric) insurance (Santos et al., 2021; Watson et al., 2023), climate clubs (Nordhaus, 2021) and risk pools (Watson et al., 2018; Tilman et al., 2018) are examples of mechanisms that could help people maintain adaptive capacity in the face of global change and the impacts of environmental flickering.

While we have studied the impact passing through a single regime shift on people's wellbeing, in reality there may be multiple cascading environmental tipping points (Rocha et al., 2018). In this case of systemic environmental risk, the associated social and environmental flickering could co-occur across various dimensions of a person's income portfolio. This might mean fishers will be unable to adapt by moving sectors, and nomadic herders may no longer find community support structures to help them recover from devastating losses. These impacts could scale-up and result in global systemic risks (Centeno et al., 2015) due to the connected nature of our environment, our socio-technological, and our governance systems. Correlated risks among marine heatwaves at sea, droughts on land and economic volatility could interact to present large-scale challenges for communities.

Early-warning signals of environmental regime shifts may help people manage their adaptation to impending change (Lenton, 2011). However, we find that some early-warning signals of environmental regime shifts describe socio-environmental dynamics that can already have negative impacts on people. In these cases, our results suggest three types of governance interventions may be warranted either individually, or in combination. First, investments in assuring that people have high adaptive capacity can mitigate the impacts of flickering on wellbeing by helping people remain well adapted to the rapidly changing environment. Second, facilitating transformational change, which partially decouples environmental adaptation and wellbeing, can result in greater wellbeing across a broad range of conditions. Lastly, when a wellbeing trough is unavoidable, interventions that facilitate people's transitions to different ways of life or migration to different places may be warranted. Critically, these investments appear to be most beneficial if enacted well before a tipping point is crossed. This suggests that climate adaptation policies may need to be more anticipatory than originally thought.

CRediT authorship contribution statement

Andrew R. Tilman: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Elisabeth H. Krueger:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Lisa C. McManus:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **James R. Watson:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Simulation code is available at https://github.com/atilman/RegimeShift_Wellbeing.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108194.

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