Ecological Economics 160 (2019) 215–226

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Technology driven inequality leads to poverty and resource depletion

M. Usman Mirza[a,b,*], Andries Richter[b], Egbert H. van Nes[a], Marten Scheffer[a]

[a] Environmental Sciences, Wageningen University, Netherlands
[b] Environmental Economics and Natural Resources Group, Sub-department of Economics, Wageningen University, Netherlands

ARTICLE INFO

Keywords:
Inequality
Technology
Social-ecological systems
Poverty trap
Dynamic systems
Critical transitions

ABSTRACT

The rapid rise in inequality is often seen to go in-hand with resource overuse. Examples include water extraction in Pakistan, land degradation in Bangladesh, forest harvesting in Sub-Saharan Africa and industrial fishing in Lake Victoria. While access to ecosystem services provided by common pool resources mitigates poverty, exclusive access to technology by wealthy individuals may fuel excessive resource extraction and deplete the resource, thus widening the wealth gap. We use a stylised social-ecological model, to illustrate how a positive feedback between wealth and technology may fuel local inequality. The resulting rise in local inequality can lead to resource degradation and critical transitions such as ecological resource collapse and unexpected increase in poverty. Further, we find that societies may evolve towards a stable state of few wealthy and many poor individuals, where the distribution of wealth depends on how access to technology is distributed. Overall, our results illustrate how access to technology may be a mechanism that fuels resource degradation and consequently pushes most vulnerable members of society into a poverty trap.

1. Introduction

In growing societies, long-term poverty can be explained by the concept of a “poverty trap” (Carter and Barrett, 2006). Here, poverty acts as an attractor where individual wealth dynamics can be trapped in poverty's “basin of attraction”. The nature of poverty can be persistent, as individuals trapped in its basin of attraction cannot get out on their own accord (Bowles et al., 2006; Naschold, 2013; Barrett et al., 2006; Dutta and Kumar, 2015; Toth, 2014). At the micro level, poverty can be conceptualized as a self-reinforcing phenomenon limiting the growth of an individual's wealth (Azariadis and Stachurski, 2005; Barrett and Carter, 2013). Self-reinforcing phenomena emerge from a range of wealth-technology positive feedbacks or frictions causing wealth dynamics to be highly non-linear with local thresholds and increasing returns (Ghatak, 2015; Zimmerman and Carter, 2003; Mookherjee and Ray, 2003; Mookherjee and Ray, 2002). These include financial factors such as access to low return assets, the set-up cost of high-tech equipment or political economy aspects such as imperfect markets, credit constraints to better technology adaption, differentiated opportunities (Barrett and Carter, 2013; Barrett et al., 2015; Banerjee and Newman, 1993). The problem with the persistence of poverty is that it is not only devastating for individuals but can also, over time, lead to persistent inequality within an otherwise growing society.

Different theories attempt to explain the long-run behaviour of inequality. Kuznets in 1955 introduced the hypothesis that inequality rises at first and then drops as gains are distributed more evenly in developing economies, giving rise to an inverted U shaped curve (Kuznet, 1955). Recently, Piketty (2014) proposed that in modern capitalistic societies inequality will rise in absence of government interventions or catastrophic events, such as world wars and the great depression. Milanovic (2016) builds upon both Kuznets and Piketty to propose that inequality moves in cycles – the so-called Kuznets waves. Most of existing research on inequality dynamics has focused on macro level analysis, with little or no focus on local level pathways connecting social-ecological interactions to inequality (Hamann et al., 2018). Addressing the need to focus on local level interactions, we develop a stylised dynamic model illustrating how key feedbacks and mechanisms can lead to rising inequality in developing societies relying on an ecological resource for livelihood. In studying this stylized model, our contribution to the literature is twofold. First, we unpack complex inequality dynamics by showing how a simple wealth-technology feedback can explain rising local inequality, and second, what pathways allow rising inequality to trigger poverty and resource degradation, considering dynamic socio-ecological interactions.

Indications of a wealth-technology feedback, as a driver of inequality, can be found in both modern and ancient societies. Kohler et al.'s (2017) reconstruction of wealth inequality dynamics in post-Neolithic societies reveals the marked difference between continents. Wealth disparities long remained limited in North America and Mesoamerica while in Eurasia inequality rose much more. Evidence

* Corresponding author at: Environmental Sciences, Wageningen University, Netherlands.
E-mail address: usman.mirza@wur.nl (M.U. Mirza).

https://doi.org/10.1016/j.ecolecon.2019.02.015
Received 2 May 2018; Received in revised form 6 February 2019; Accepted 18 February 2019
Available online 06 March 2019

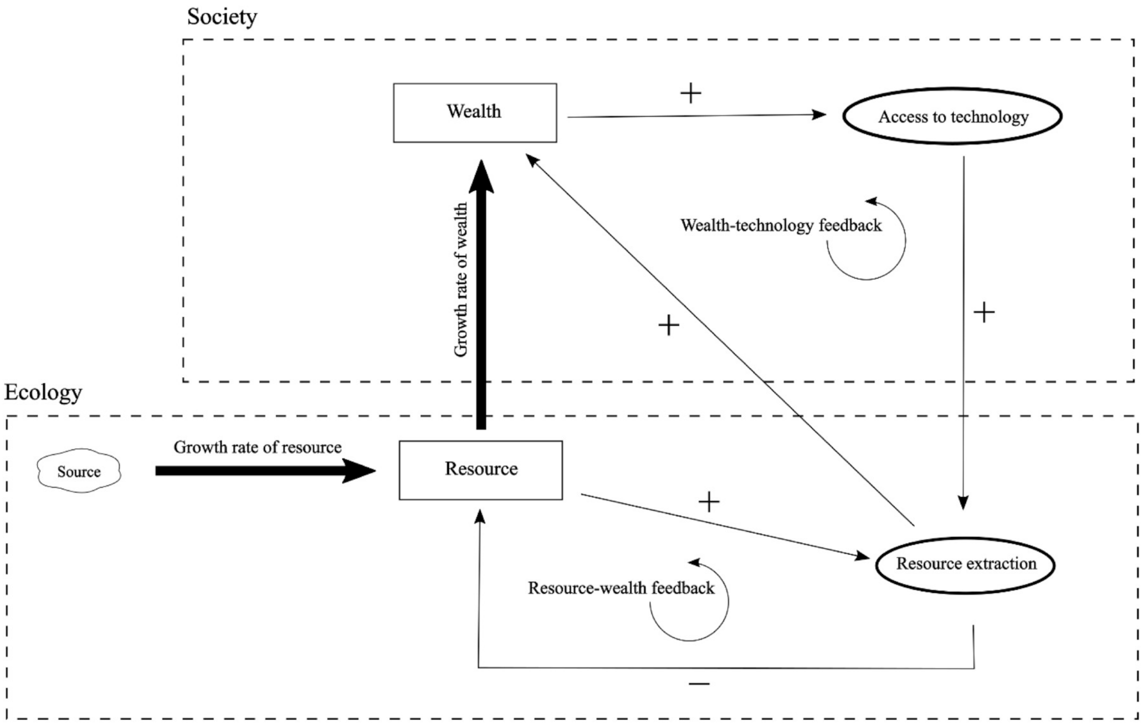

Fig. 1. Conceptual sketch of the model structure and interactions showing two feedbacks – wealth-technology and resource-wealth. Boxes and thick arrows and represent state variables and flows between them. Ovals and thinner arrows represent parameters and processes.

suggests that this contrast is due to the availability of large mammals in Eurasia that were domesticated, which is an ancient equivalent to better technology, allowing agricultural extensification (Kohler et al., 2017). Most likely, only richer households could maintain draft animals allowing them to profit from higher production. Meanwhile in North America and Mesoamerica, such amplification of wealth differences by exclusive access of an elite few to superior productivity was absent.

Similarly, in modern times, numerous case studies illustrate how resource use with technological access to a few can aggravate both inequality and poverty. For example, in Pakistan structural inequality in access to water across regions and between social classes has placed unprecedented stress on water resources (Mustafa et al., 2013; Mustafa, 2007). The roots of inequality can be traced back to colonial times when land rights were based on patronage exclusive for a few chosen groups of elites (Farooqi and Wegerich, 2014; Gilmartin, 1994). Preferential land rights gave birth to big landowners who accumulated wealth and controlled the resource (van Halsema and Vincent, 2006). With modern technology, wealth accumulation took the form of commercial agriculture, where tube wells assisted water overuse (Shah, 2008), and other lucrative but water-intensive production options like textiles, cement, leather, fertilizers and sugarcane. As a result, small and tenant farmers are pushed-off the resource and forced to migrate (Rahman, 2012).

This and other examples from Amazon rainforest (Godoy et al., 2010), Bangladesh (Alam, 2003) and Lake Victoria (Downing et al., 2014), show a recurring pattern of increased resource exploitation that goes hand in hand with growing local inequality. Wealth accumulation by elites is achieved by extracting and controlling natural resources, on which the poor population typically also relies, such as commercial agriculture via groundwater exploitation, overfishing for exports and depletion of forests for timber or alternative land use (Shah, 2008; Godoy et al., 2010; Alam, 2003; Downing et al., 2014; ISSC et al., 2016; Arnold and Townson, 1998). As a result, in unequal societies, fast wealth accumulation by the elites may put excessive pressure on key natural resources thus affecting the dependent poor population. Excessive resource use affects dependent livelihoods (Daily, 1997; Cavendish, 2000; Fisher and Christopher, 2007), especially in developing societies where the poor have a primary dependence on ecological or natural resources (McNally et al., 2011; Coomes et al., 2011; Naughton-Treves et al., 2011; Lybbert et al., 2011). Thus local inequality can be disastrous for social-ecological resilience and social justice, as wealth accumulation of elites may fuel overexploitation, disregarding sustainable resource use limits (Farley and Voinov, 2016) and at the same time disproportionately affecting the poor and most vulnerable members of society.

While equity in distribution is an important aspect of social justice (Sen, 2009), the ability to access resources is also important for the resilience of the poor (Mirza and Mustafa, 2016). If access to capital, technology and resources are restricted to the elites, wealth accumulation and resource extraction for this elite becomes a self-reinforcing phenomenon (Saez and Zucman, 2016; Gabaix et al., 2016; Rosen, 1981). Wealth wields power to extract resources which in turn generates more wealth, thus mounting pressure on the common natural resource. Left unchecked, this pressure can lead to overexploitation causing environmental degradation or even resource collapse, upon passing certain thresholds (Carpenter and Brock, 2008; Scheffer, 2007). Such critical transitions in underlying resources can be sudden, unexpected and in some cases irreversible (Scheffer et al., 2001), with disastrous implications for the dependent population (Lade et al., 2013).

There is a need to understand inherent inequality dynamics to determine whether observed patterns described above can be generalized to a much broader set of conditions. In this paper, based on a simple model of local social-ecological interactions in a developing society setting, we argue that resource extraction with a technological advantage exclusive to a few is an important driver of inequality. In particular, we investigate whether rising local inequality leads to reduced resilience of the interdependent social and ecological systems causing critical transitions such as resource collapse and/or poverty traps.

2. Methods

We develop a simple coupled social-ecological model to analyse and understand the influence of rising local level inequality on poverty and

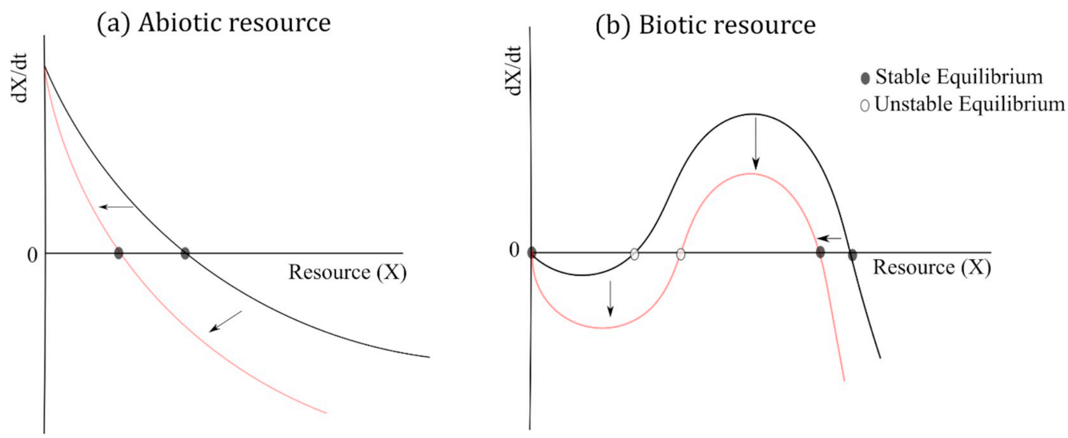

Fig. 2. Two models of resources with a constant harvesting pressure: abiotic (a) and biotic resource (b). A shift from a black to red line represents an increase in losses due to resource extraction or harvesting. Note in (b) the distance between the stable (high resource) and unstable equilibrium decreases indicating loss of resilience of the sustainable equilibrium. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resource use in an unregulated regime. We begin by outlining key model mechanisms through a conceptual diagram (Fig. 1), which is meant to illustrate and aid the actual model description. In the diagram, we see interactions and feedbacks between the social and ecological components of the model through resource extraction and access to technology. Access to technology may give rise to local thresholds (positive wealth-technology feedback) if an increase in the productivity of assets is highly non-linear with respect to increasing assets. For example, a poor farmer may be relatively unproductive because he only owns an ox to plough the fields. A fisherman in a large lake may be limited to smaller radius only due to a small-sized boat. As individuals get richer, they may gain access to technologically better assets with a higher productivity. A farmer investing in a tractor may experience a local increase in total and marginal productivity, and the same may be true for a fisher buying a bigger boat. Technology-driven enhanced resource extraction, while stimulating growth of wealth, also negatively affects the growth of resources, which in turn limits the amount of resource available for future extraction (resource-wealth feedback).

These two feedbacks (wealth-technology and resource-wealth) combined can potentially put exploitative pressure on the resource, which can become depleted or collapse below a certain sustainable threshold.

2.1. Ecological component (resources)

Resource users have access to a common pool resource (X) that provides services used for earning an income. Resource availability is determined by the dynamics of the ecological resource type in question. We use two examples for ecological resources, portraying a simple abiotic resource (e.g. water) and a more complex biotic resource (e.g. a forest or fish population), building upon earlier approaches (Lade et al., 2013; Ibáñez et al., 2004; Tavoni et al., 2012) in specifying the functional form of those resources. These two types of resources are chosen as two examples of qualitatively different resource dynamics. The simple abiotic resource is assumed to increase with a constant rate (for instance due to precipitation) and to lose as a first order process (for instance due to transpiration). This results in growth towards an equilibrium with exponential growth limitation (Richter and Dakos, 2015):

$$\text{Abiotic:} \quad \frac{dX}{dt} = c\left(1 - \frac{X}{X_{max}}\right) - \sum_1^N e_i(\sigma_i, a_i, X) \tag{1}$$

X is the total available resource stock, c is the resource inflow, X_{max} is the maximum resource level, and $\Sigma_1{}^N e_i$ is individual resource extraction summed over all individuals, which in turn is a function of technology σ_i, capital assets a_i and the resource stock itself X. The functional form of e_i is provided later in the section.

The biotic resource is motivated by population dynamics examples where a living resource (e.g. fish population) grows logistically but can also collapse if the population is below a critical size, for instance, due to group behaviour or difficulty in finding partners. This well-studied ecological positive feedback is called the Allee effect (Kuparinen et al., 2014; Allee, 1931; Dennis, 1989), and the following functional form is widely used for a range of biotic population dynamics (Kramer et al., 2009; Berec et al., 2007; Courchamp et al., 1999):

$$\text{Biotic:} \quad \frac{dX}{dt} = \epsilon X\,[X - X_c]\left[1 - \frac{X}{X_{max}}\right] - \sum_1^N e_i(\sigma_i, a_i, X) \tag{2}$$

where ϵ is the maximum growth rate of the resource and X_c is the critical sustainable resource level.

The abiotic resource model has only one stable equilibrium (Fig. 2a), while the biotic resource model can have three equilibria of which two are stable (Fig. 2b). Resources are used as input in a production process through which individuals generate income and accumulate wealth over time.

2.2. Social component (wealth)

In the model, income y_i of individual i is generated using a simplified Cobb–Douglas production function which uses a combination of natural resources and assets [Eq. (3)]. The function has two inputs – capital assets a_i and resource extraction e_i– and is given as:

$$y_i = a_i^{\alpha}\, \sigma_i(a_i)\, e_i(\sigma_i, a_i, X) \tag{3}$$

where $\sigma_i(a_i)$ is the technology function, mapping inputs into output and α is the partial output elasticity of assets. $\alpha < 1$ is assumed for marginally decreasing returns on assets.

2.2.1. Technology

We assume that above a certain level of assets, individuals get access to advanced technology (Fig. 3). In our model, the parameter ρ determines the strength of this non-linear effect. Thus, an individual's asset level may generate non-convexities with locally increasing marginal returns. In the model, non-convexity is introduced through the technology function σ_i as follows:

$$\sigma_i = k_i\left[(1-\rho) + \frac{\rho\, a_i{}^{\lambda}}{a_i{}^{\lambda} + \theta^{\lambda}}\right] \tag{4}$$

σ_i is specified to range from 0 to maximum k, which is a measure of maximum productivity given available access to technology and scaled to 1. λ controls the enhanced wealth generation capacity gained by access to better technology while θ is the asset level where increasing

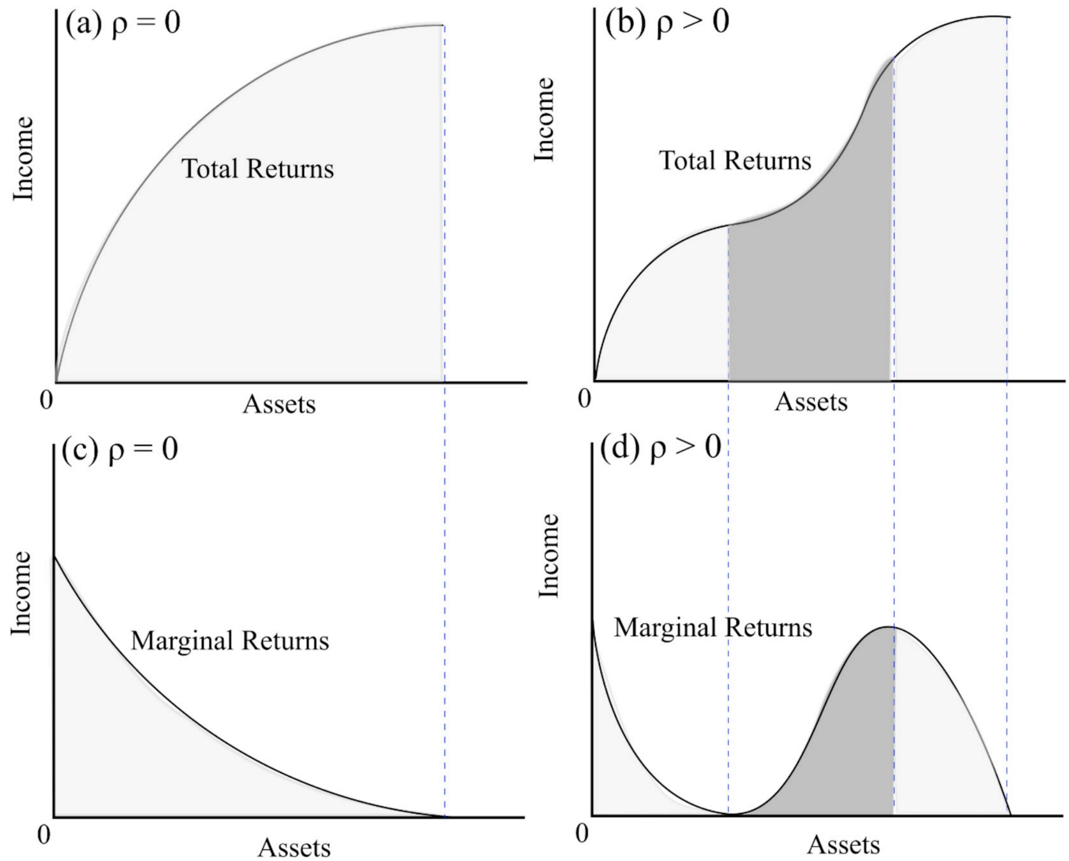

Fig. 3. Effect of technology access (ρ) on total and marginal returns to assets. Dark grey region denotes increasing returns while light grey denotes decreasing returns. (a) & (c) presents the case with uniform access to technology (ρ = 0) where resource productivity diminishes as we deploy more of the same type of assets, while (b) & (d) represent differentiated technology access options (ρ > 0) where resource productivity increases locally when a technological superior asset is deployed. Blue dotted lines delimit areas of decreasing or increasing returns. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

returns start to set in, determining the presence of these locally increasing returns due to investment in better technology for individuals in a continuum between uniform (ρ = 0) to differentiated (ρ > 0) access to technology. When ρ = 0 everyone in the society has access to the same basic technology, giving a standard concave production function with decreasing marginal returns as conventionally assumed in economic models [Fig. 3(a) & (c)]. However, if ρ > 0, the production function will be non-convex and marginal returns of assets may be locally increasing or decreasing, depending on the asset level [Fig. 3(b) & (d)]. Thus in effect, ρ is actually a control parameter allowing us to switch between a basic null model (diminishing returns when ρ = 0) and a model that includes differentiated access to resources (locally increasing returns when ρ > 0).

2.2.2. Resource extraction

Individuals as optimizing agents choose resource extraction to maximize profits. Profits π_i depend on income minus costs of production and are given as:

$$\pi_i = y_i(\sigma_i, a_i, e_i) - C_i(e_i, a_i, X) \tag{5}$$

The cost function depends on the assets owned, amount extracted and resource availability. Marginal costs are assumed to depend positively on the extraction level and negatively on both resource abundance and assets owned. The more one extracts, the higher the costs to extract an additional unit of water. Having better assets and abundant water availability makes it cheaper to extract an additional unit of water. With these properties, the cost function for an individual i is specified as follows:

$$C_i = \frac{e_i(\sigma_i, a_i, X)^2}{2\,X^{\gamma}\,a_i^{\tau}} \tag{6}$$

Parameters γ and τ determine the cost-output elasticity of resource abundance and assets respectively where γ, $\tau < 1$. Substituting income and cost functions gives an expression for the profit function:

$$\pi_i = a_i^{\alpha}\,\sigma_i(\,a_i)e_i - \frac{e_i^2}{2\,X^{\gamma}\,a_i^{\tau}}$$

The institutional regime is described as open access, and therefore discounted long-term profits from the resource cannot be secured. Hence, agents maximize instantaneous profits by setting $\frac{\partial \pi_i}{\partial e} = 0$, provided our cost function is concave $\left(\frac{\partial C_i}{\partial e} > 0, \frac{\partial^2 C_i}{\partial e^2} > 0, \frac{\partial C_i}{\partial X} < 0, \frac{\partial^2 C_i}{\partial X^2} > 0, \frac{\partial C_i}{\partial a} < 0, \frac{\partial^2 C_i}{\partial a^2} > 0\right)$, which gives us the optimal short-term resource use function as follows:

$$e_i = \sigma_i(a_i)\,X^{\gamma}\,a_i^{\beta} \tag{7}$$

where $\beta = \tau + \alpha$. Resource use e_i depends on the amount of resource available X, on an individual's level of assets owned a_i, as well as a technology function σ_i.

Assets generate wealth, thus endowing individual's ability to intensify use of resources. Long-term wealth dynamics for each individual i are given by:

$$\frac{da_i}{dt} = s_i\,y_i(\sigma_i, a_i, e_i, X) - \mu_i\,a_i \tag{8}$$

Here savings rate s_i with income y_i gives assets inflow while a depreciation loss term μ_i gives assets outflow, thus signalling an individual's wealth accumulation or loss respectively in the long run.

From here on, assets and wealth will be used interchangeably based on similarity of usage and broader meaning. Savings rate is assumed to be constant over time for the sake of simplicity. Note that the amount of wealth accumulated depends critically on the individual's savings rate (s), access to technology (ρ) and maximum productivity (k).

This study was conceived as a theoretical exercise and hence chosen parameters are not motivated by any empirical case(s) but selected to show qualitative changes and different stability regimes in the model. Following Ayres, 1988; Juster et al., 2006 and Modigliani, 1986, we focus on technology (ρ), productivity (k) and savings (s) as key parameters in our model, being the most important determinants of wealth creation, analysed systematically to see how the model results change qualitatively. A discussion on other key parameters is provided in the online Appendix.

In our analysis, we begin with simulating social-ecological dynamics in the homogeneous case i.e. parameters are the same across individuals. The state space is explored for stable and unstable equilibrium points. While preserving homogeneity, we also vary key parameters – savings rate (s) and access of technology (ρ) – for all individuals in a bifurcation analysis to study the sensitivity and stability of system's equilibrium states. Bifurcation refers to qualitative changes in a dynamic system's behaviour as we change a control parameter to cross a critical value. The critical value or bifurcation point at which this qualitative change occurs is more popularly known as a tipping point and this behaviour more generally as a critical transition. Later we relax the homogeneity assumption to simulate social-ecological dynamics with heterogeneous individuals. Different technology distributions are investigated to study qualitative changes in inequality dynamics.

3. Results

3.1. Homogenous society case

We begin with simulating a society comprising $n = 100$ homogenous individuals with both resource types – abiotic and biotic. We analyse the role of differentiated access to technology. If individuals have uniform access to technology ($\rho = 0$), there is no opportunity to increase productivity through wealth. This implies that rich and poor individuals would use the same technology, e.g. a hand pump to access water. With differentiated access to technology ($\rho > 0$), individuals enjoy higher productivity as they possess more assets. For example, individuals with low wealth levels can only afford the hand-pump or small boat while those better-off invest in electric pumps and motor boats.

In our analysis, stable states are defined in a dynamic systems context as points where the state variables stabilize or do not change. These can also be interpreted as equilibrium points in the long run. Phase plane analysis shows four qualitatively different scenarios for the system, based on resource type and access to technology [Fig. 4]. For the abiotic resource case with uniform technology access, we get a single stable state (S_W) [Fig. 4(a)]. Since everyone has access to the same technology, all individuals reach the same level of wealth and resource access in the long run. In the case of a biotic resource with uniform technology, we see more complex dynamics [Fig. 4(b)]. The potential for the resource to go extinct results in a folded curve with three internal equilibrium points – two stable (S_C and S_W) and one saddle point (S_T), indicating the threshold between the two stable fixed points. S_W in Fig. 4(b) is the positive wealth and resource access level, which is similar to the Fig. 4(a)'s S_W for the abiotic case. S_C is the new state we see at the origin depicting social-ecological collapse with disappearance of the resource and wealth. Such collapse may be triggered by overexploitation, eroding the foundation of resource viability and corresponding economic activity.

With $\rho > 0$ individual's access to technology is now differentiated depending on wealth levels [Fig. 4(c) & (d)]. For an abiotic resource case, the system now is bi-stable with two stable (S_P and S_W) equilibrium solutions [Fig. 4(c)]. The two stable equilibria correspond to the poor (S_P) and wealthy (S_W) states respectively. The dashed line represents the separatrix, separating the set of individuals whose wealth would evolve to one of the stable equilibria in the long run. Depending on one's wealth level, an individual can either accumulate wealth and grow to S_W or get stuck in poverty at S_P, also termed as a “poverty trap”. Thus both poverty and wealth are stable states, in line with our earlier discussion on poverty traps. For the last scenario of a biotic resource, the system now has three stable points (S_C, S_P and S_W) [Fig. 4(d)]. S_W and S_P depict the rich and poor states respectively as before, while S_C at the origin represents a case of social-ecological collapse with no resource stock and no assets.

3.2. Bifurcation analysis

Savings rates and access to technology are our key control parameters. We argue that both parameters play a key role when societies move through various development phases and are important drivers for both inequality and resource exploitation. We first analyse the role of savings (Fig. 5), where the grey shade signifies region of alternative stable states (bi-stability). Higher savings lead to greater wealth accumulation which in turn allows the individual to invest in enhancing their resource extraction capacity, e.g. using electric pumps. We analyse whether this feedback plays a role in breaking the poverty trap and how this affects the resource at hand.

For the abiotic resource case, we first consider the wealth dynamics [Fig. 5(a)]. With low savings ($s < 0.14$) individuals stay poor (branch P). As savings increase, individuals get richer which allows them to use superior technology and after a certain threshold ($s = 0.3$) they have earned enough to break the poverty trap. At higher savings ($s > 0.3$), individuals stay wealthy (branch W) and wealth keeps rising. For $0.14 < s < 0.3$, the system is bi-stable (grey shaded region), which means that here individuals depending on their initial wealth levels can converge either to the wealthy or the poor state. This is due to the differentiated access to technology which allows higher wealth accumulation to those who are initially wealthy and benefit from access to better technology. For the resource [Fig. 5(b)], similar dynamics are seen but in the reverse direction. As rising savings spur wealth accumulation, the resulting resource use puts increasing stress on resource availability. As a result, resource decreases with increasing s.

For the biotic resource case, starting with the wealth dynamics [Fig. 5(c)], individuals stay in the poverty trap for $s < 0.13$ (branch P), moving on to alternative stable states for $0.13 < s < 0.43$ (grey shaded region) and then finally jumping to the wealthy state at $s = 0.43$ (branch W). However, in contrast to the abiotic case, the wealthy state suddenly becomes unstable again at $s = 0.65$, forming a cliff like figure. With higher savings, as individuals accumulate more wealth and use more resources, the biotic resource collapses below a certain point due to the exploitative pressure. For the resource [Fig. 5(d)], as the pressure builds up with higher savings, it eventually collapses in this rather catastrophic shift, resulting in social-ecological collapse where individuals metaphorically ‘fall off the cliff’ as the resource disappeared which formed the foundation of society's wealth. The two lower bifurcations in Fig. 5(d) are the fold bifurcations of the two saddle nodes with unstable fixed points. They are not important for dynamics past the tipping point as resource collapses after the stable branch W, irrespective of the two lower bifurcations.

We now turn to analysing the role of access to technology (ρ) on wealth and the resource stock (Fig. 6). While savings allow an individual to increase the rate of wealth generation irrespective of the initial endowment, the effects of access to technology (ρ) depend on individual's current wealth level. So in a differentiated technology regime ($\rho > 0$), rich individuals have higher productivity and can increase their wealth accumulation compared to poor individuals.

At low levels of ρ technology is relatively uniform, so initial wealth conditions do not matter, thus there is only one stable state. As we increase technological differentiation, alternative stable states emerge for both $\rho > 0.45$ (abiotic resource) and $\rho > 0.26$ (biotic resource)

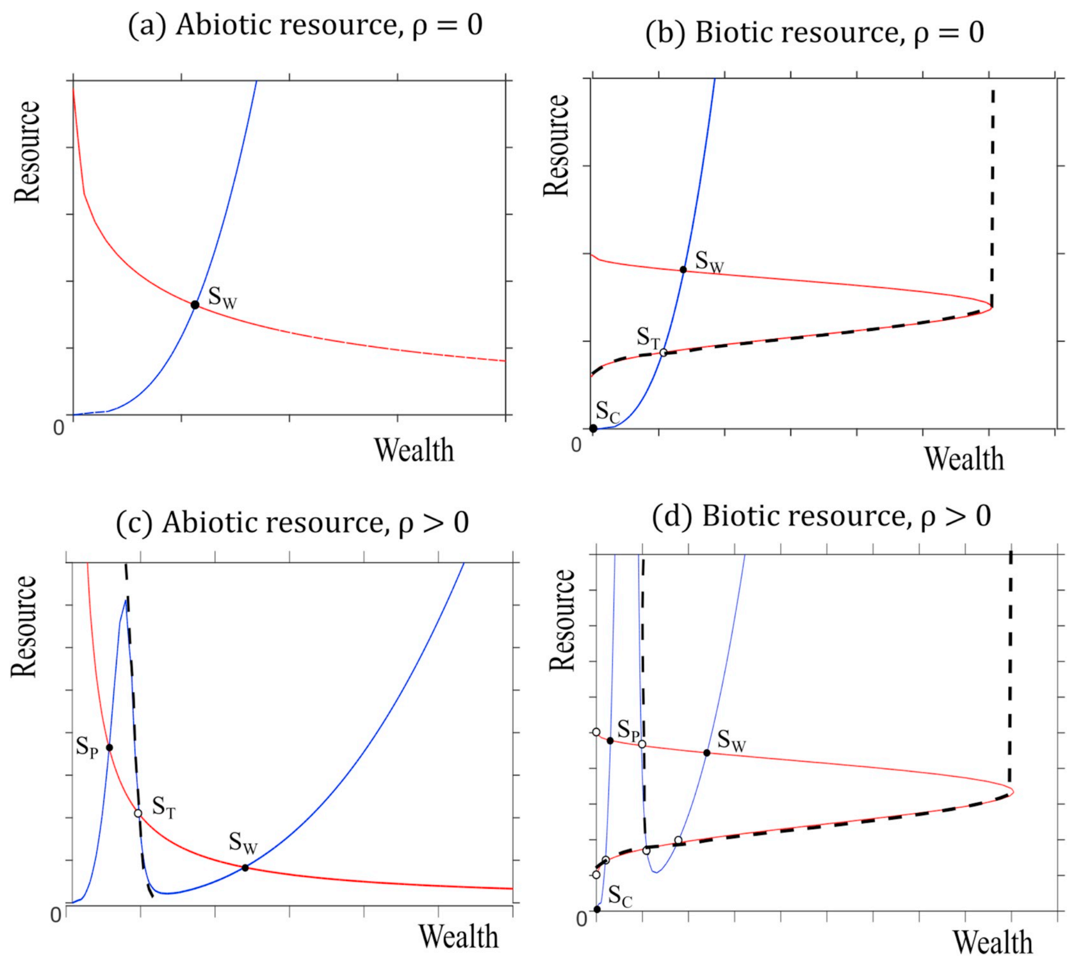

Fig. 4. Phase plane for the coupled system for uniform access to technology (ρ = 0) and differentiated access to technology (ρ > 0) for both biotic and abiotic case. Blue lines indicate wealth nullclines (da/dt = 0) while red lines indicate resource nullclines (dX/dt = 0). Intersection of nullclines give equilibrium points of the system. Solid black points are stable equilibriums while hollow points are unstable equilibriums. Dashed black lines are the separatrix delineating the basin of attraction of stable equilibrium points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively. Beginning from a poor state (branch P) and moving from right to left, as we decrease ρ (i.e. making access to technology more uniform for everyone), a saddle node bifurcation occurs at ρ = 0.45 for the abiotic resource [Fig. 6(a) & (b)] and ρ = 0.26 for the biotic resource [Fig. 6(c) & (d)], where the system jumps to the unique stable equilibrium (branch W where everyone is equally wealthy). As before, the grey shaded area depicts a region of alternative stable states. Interestingly, we find that the more differentiated the technology is (larger ρ), the lower the wealth levels in the poverty state. Intuitively, this happens because with an increasing ρ, productivity of the poor is lower, reinforcing the poor state, and also affecting the absolute poverty level within that state. Consequently, we see that the resource increases as ρ increases in the poor state, simply because of lacking capacity to extract the resource.

To analyse how savings rate and access to technology act in concert, we now project bifurcation results in a two-parameter (s and ρ) space and identify critical transitions [Fig. 7]. For the abiotic resource [Fig. 7(a)], with low savings (s), the system stays in an exclusive poor state, regardless of access to technology. As savings rate increase, the system transitions from an exclusively poor state to either a region with alternative stable states or a region with the exclusively wealthy state, depending on access to technology (ρ). This V–shaped area of alternative stable states, which decreases with increasing savings rate, marks a risky region where the system can potentially flip between poor or wealthy states.

For the biotic resource case [Fig. 7(b)], the situation is similar to the abiotic case, except that the system may undergo another transition into a state of social-ecological collapse. At high savings rates, the excessive pressure erodes the regenerative capacity of the resource and paving the way to resource extinction. The case where the ecological resource collapses is particular to the biotic resource and the key qualitative difference between the two resource dynamics. However, in both cases, access to technology (ρ) regulates this potentially risky region with alternative stable states, such that at high values of ρ, the region expands, while at low values of ρ, it vanishes in what is called a cusp point.

3.3. Heterogeneous society case

We now relax the homogeneity assumption by simulating a society with heterogeneous individuals in a differentiated technology setting i.e. individuals having access to both small and motorized boats with different savings rates and initial wealth endowments. We assume that each individual has an equal chance to receive some initial wealth in some set interval, giving rise to a uniform distribution. Thus, randomly distributed wealth levels drawn from a uniform U(min = 0, max = 100) distribution for $n = 100$ individuals. For simplicity, savings are assumed to be normally distributed with mean 0.2 and standard deviation 0.01. Qualitatively, the model results do not depend on whether we use uniform or normal distributions.

Simulating the system over time we see clusters emerge in the long run as individuals' wealth distributions transform from an initial uniform to a final bi-modal distribution with high and low wealth levels [Fig. 8(a)]. The rich and poor clusters go hand in hand with the

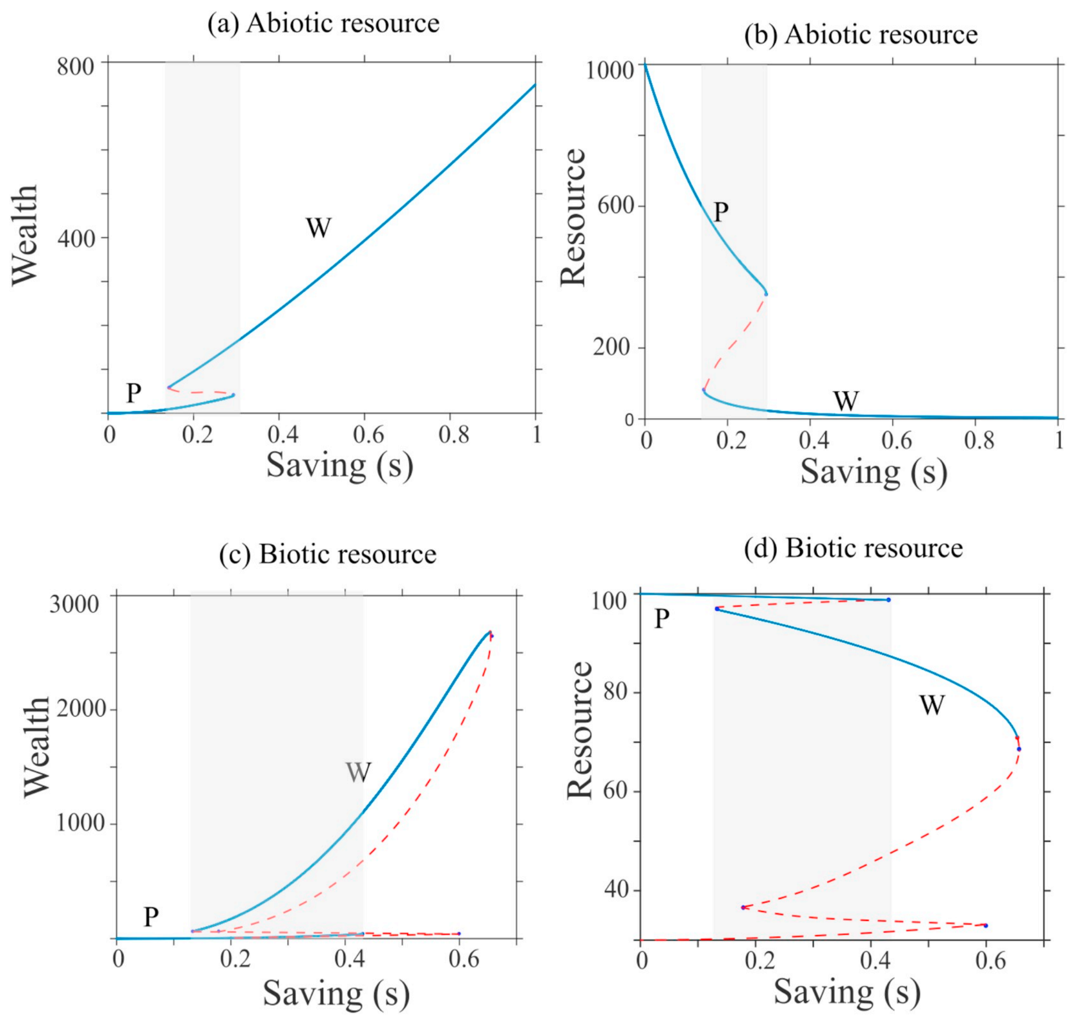

Fig. 5. Bifurcation analysis for wealth and resource dynamics with respect to savings rate, in the abiotic resource and biotic resource case. Solid blue lines represent stable branch of the system while dotted red lines represent the unstable branch. Grey shaded region denotes area of alternative stable states. W and P refer to wealthy and poor stable state respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

evolution of local inequality in our model society. A positive upwards trend is seen between inequality and growth in wealth [Fig. 8(b)], approaching a moderately long-run value of around 0.5 Gini. This positive trend is independent of the type of underlying resource – abiotic or biotic, thus aligning well with our earlier discussion on observed rising inequalities in growing societies.

Having modelled local inequality dynamics with a heterogeneous population we can now use the model to see how in a capitalistic society, rapid technological changes and emergence of highly productive sectors will affect the dynamics of inequality and poverty at the local societal level. By a capitalistic society we mean enhanced overall productivity and technology due to capital growth. In our model, this is captured by the combination of access to advanced technology and overall productivity. To simulate variation in total productive capacity, we have modified the parameter k in the technology function [Eq. (4)], which was so far assumed to be $k = 1$ constant for all individuals. Contrasting with the homogeneous case ($k = 1$), two more realistic but distinct scenarios are constructed where an individual's productivity k is heterogeneous. First, we assume a society of relatively equal opportunities, where everyone has the same probability of benefiting from better technology and k is following a uniform distribution with U ($\min = 0, \max = 2$). Second, we look at the case where a few elite individuals benefit significantly more from the enhanced technology and productivity than the rest of society. Thus, k follows a heavy tail gamma $G(scale = 1, shape = 1)$ distribution. Distribution parameters are chosen to keep average k equal to 1 similar to the fixed k scenario, facilitating comparison.

The evolution of wealth distribution and total resource stock for all scenarios can be seen from the heat maps and resource dynamics plots respectively (Fig. 9). For brevity, we only discuss results for the abiotic resource case. Results for the biotic resource case are provided in the online Appendix. In the uniform scenario, we see that local inequality grows in society and stabilises at a Gini value of around 0.6–0.7 [Fig. 9(c)]. The relationship between inequality and average wealth is similar to that in the fixed k scenario, though in the scenario where k is uniformly distributed, the average wealth is higher. Interestingly, this increase in wealth also leads to a higher final inequality level than what we saw in the homogeneous k scenario (compare Fig. 8(b) with Fig. 9(c)). So we can see that variation in technology may increase wealth in society on average, but this will benefit few individuals, giving rise to inequality.

In a heavy tail scenario, we observe an amplification of the rise of wealth for the elite few. The heavy tail causes local inequality to rise much faster than what we saw with a uniform distribution or homogeneous case, leading to a final long-term inequality value of around 0.8–0.9 Gini [Fig. 9(g)]. Compared to the uniformly distributed technology case, three differences stand out. First, with fast-rising inequality, poverty increases are stronger, as indicated by the expanded blue section of the heat maps [Fig. 9(b & f)]. Second, while average wealth is similar in both cases, we find that inequality is even higher in

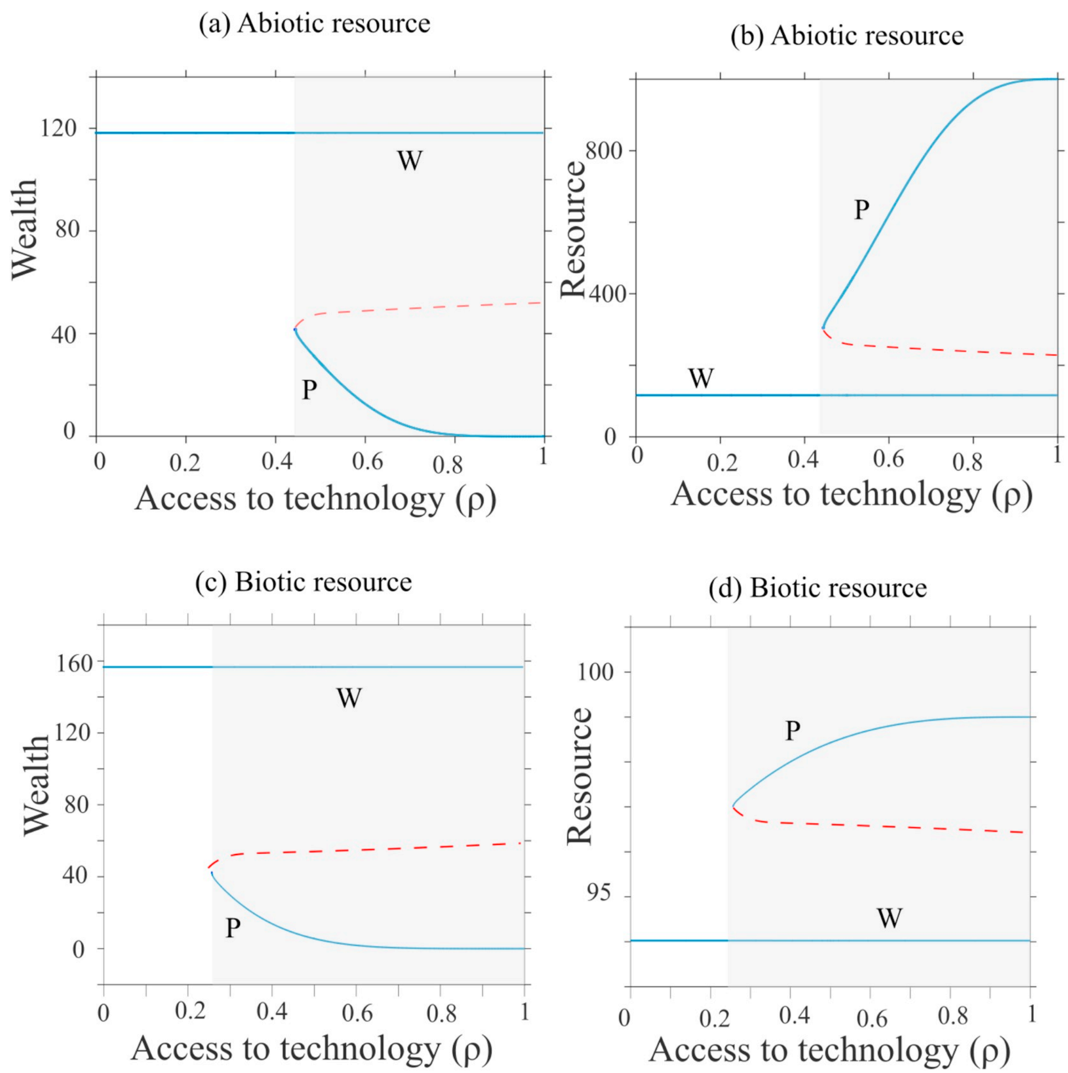

Fig. 6. Bifurcation analysis for wealth and resource dynamics with respect to access to technology in the abiotic resource and biotic resource case. Solid blue lines represent stable branch of the system while dotted red lines represent the unstable branch. Grey shaded region denotes area of alternative stable states. W and P refer to wealthy and poor stable state respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

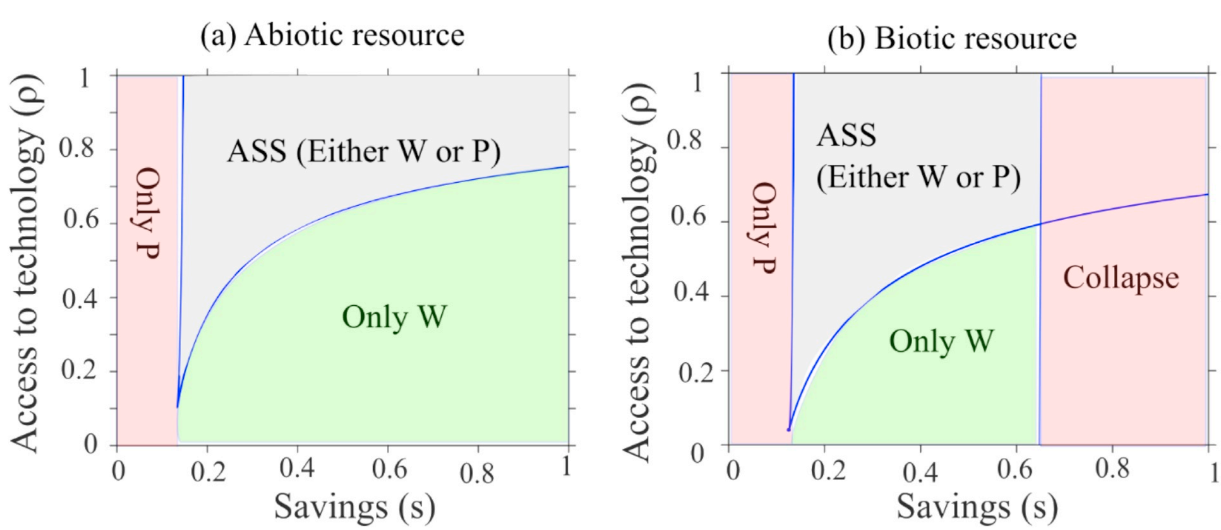

Fig. 7. Two-parameter bifurcation analysis with respect to savings rate and access to technology for the abiotic and biotic resource case. ASS, W and P refers to alternative stable states, wealthy state and poor state respectively.

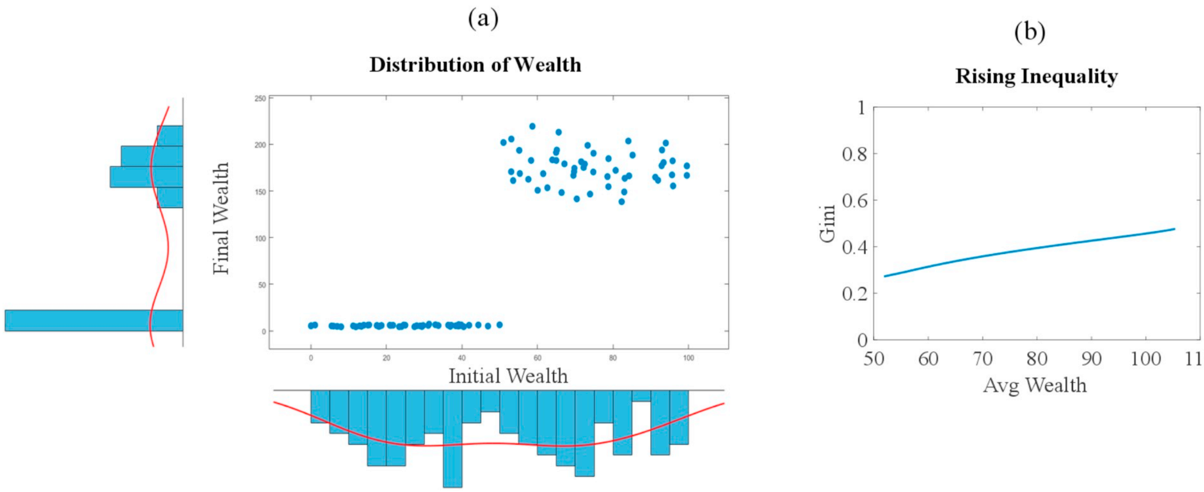

Fig. 8. Individuals with fixed technology, and heterogeneous savings rates and initial wealth levels. (a) Distribution of final (bimodal) wealth by initial (uniform) wealth in society. (b) Rise in inequality with societal growth in average wealth.

the case where technology is beneficial for very few individuals [Fig. 9(c & g)]. Third, in both cases, we see resource depletion, though this effect is much stronger for the heavy-tail case. The poor are particularly disadvantaged by these adverse changes as both poverty increases and resource degrades in the society at the same time.

4. Discussion

Rising inequality, as seen in our model, is consistent with growth in wealth, in line with the positive relationship seen historically (Milanovic et al., 2011). Overall rising average wealth levels do not lift people out of poverty as we see inequality persisting side by side with poverty. This steady persistence of inequality is seen as a standard feature of growing societies (Milanovic, 2016; Ravallion, 2014), where the wealth-technology positive feedback skews growth gains towards the better-off, similar to a preferential attachment process. One example where this patterns can be observed comes from Sub-Saharan Africa where forest products constitute the main source of livelihood for rural households (Mead, 1994; Falconer and Koppell, 1990). While forest income is essential for sustaining livelihoods of the poor, the wealthiest in society are the ones with the ability to harvest at a large scale and are consequently the heaviest users. The wealthy and powerful capture the resource at expense of the poor, due to their better skill set, technology and capital (Arnold and Townson, 1998). As a result, the poor are forced to alter their practices or shift to less productive areas with high failure and closure rates (Arnold et al., 1994; Townson, 1995).

Moreover, from the model results, we see that in the modern capitalized world, access to capital further accelerates these growth gains for a small elite, an observation consistent with literature (Atkinson et al., 2011; Alvaredo et al., 2013; Piketty, 2015). Here inequality rise due to the emergence of new productive sectors and associated increasing returns, as people move from traditional ways of wealth accumulations to more productive capital assets. While, wealth and technology feed on each other, in a positive feedback, to push inequality up, such positive feedbacks may be reinforced by societies having access to highly productive capital intensive pathways to wealth generation, which may create poverty traps and result in rapidly rising inequality in society (Rosen, 1981; Gabaix et al., 2016). However, we show that capital growth may not, in all scenarios, result in a rapid rise in inequality and/or cause sudden changes in social-ecological dynamics. The growth of elites and final distribution in wealth depend largely on how productivity gains are distributed.

In a society with uniformly distributed capital productivity gains, local inequality rises slowly and innocuously while poverty remains at the same level. At the same time, pressure on the resource remains within the sustainable limits, irrespective of the resource type. However, if the same productivity improvement is achieved via a heavy-tailed distribution, the type of resource becomes important and inequality rises much faster. With few elites harbouring most of the productivity gains, the rapid rise in local inequality is seen to correlate with significant changes in wealth and resource dynamics. Wealth levels rise fast for the highly productive elites as they intensify extraction pressure due to their particularly high productivity. Pressure on the resource directly affects income for the poor who do not have the assets allowing for high productivity, while facing a depleted resource. Poverty levels and resource pressure both rise, where the impact is more severe for the biotic resource. This is due to the nature of biotic resources which are prone to collapse below a critical threshold abundance level. Nonetheless in both cases, the poor are pushed off the resource and into poverty. This is consistent with what is seen in intricately connected social-ecological systems, where catastrophic changes such as a rapid rise in persistent poverty and resource degradation can coincide dynamically in time, forming a tipping point (Barrett et al., 2011; Scheidel, 2013).

Current model simulations and results need to be interpreted with caution as this was conceived as a theoretical exercise. While our work is theoretical in nature, an obvious next step is to test the theoretical predictions with empirical cases and data. Furthermore, our model attempts to capture key mechanisms needed to analyse inequality dynamics within social-ecological interactions. In this ambition, we make a series of simplifying assumptions that make the model tractable and analysable while retaining key features. Below we discuss some of our key assumptions and give cautionary notes where necessary.

Wealth in the model is accumulated via income-generating activities, using a harvested resource as input. Since we have a single common pool resource, it is assumed that all parties whether rich or poor compete in generating income from the same source. We realize that in the real world multiple resources exist that may interact in ecologically and socially complex ways (Barrett, 2008). For instance, rich and poor people may not necessarily compete for the same resource, as evidenced in Lake Victoria, where poor people harvest a smaller species (*dagaa*) than big companies (*Nile perch*) (Downing et al., 2014). A natural extension of our model would be to include n resource types (where n is small), thus investigating the effects of different ecological interactions between the resources and the effects of a secondary resource on society. Although the outcome of these complex interactions is hard to predict, we expect that it is still likely that the wealthy have an advantage in both the capacity to harvest and also access to a greater number of resources than available to the poor. It would be exciting to compare the relative importance of ecological

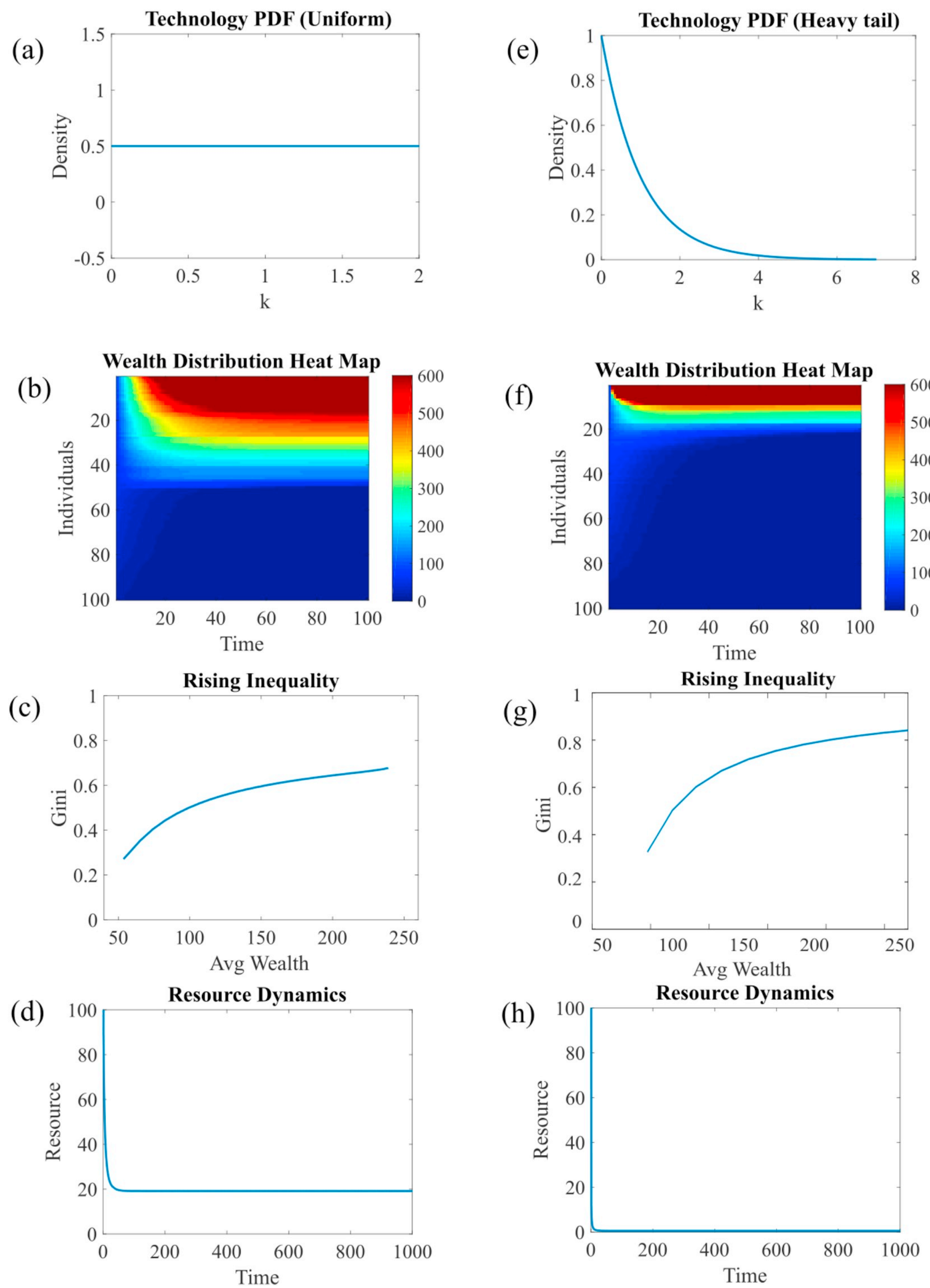

Fig. 9. Effect of heterogeneous productivity via uniform (a–d) and heavy tail (e–h) distributions. For both cases, we see the effect on the evolution of wealth, inequality, and resource stock.

interactions (e.g. predator-prey relationships) and economic interactions (e.g. wage or price effects) that could potentially magnify or reduce inequality.

In our social-ecological model, there is no response from policy or resource users as the resource is depleted based on the assumption of open access. A worthwhile extension to the model would be to analyse the policy response and effectiveness close to the tipping point, in an explicitly dynamic setting. An effective response would require decision makers to anticipate a potential resource collapse, potentially in the form of early-warning signals and coordinate on an effective policy response. It remains doubtful whether both conditions will be met given that the time window to prevent a collapse is limited (Richter and Dakos, 2015; Biggs et al., 2009).

Our paper paints a rather bleak picture of a developing society based on the assumptions that the system is capitalistic (Piketty and Zucman, 2014) and there are no real effective redistribution mechanisms (Besley and Persson, 2014). Without a government implementing tax mechanisms or social safety nets for the poor, we see the stabilization of poverty levels in the long run. One could hypothesize that with rising inequality societal mechanisms will unfold that will allow for a further redistribution of income. In such cases, we would expect cyclic behaviour in poverty levels depending on the resource pressure and the effectiveness of government interventions. Such an analysis is no doubt a worthwhile exercise and a project in itself. We will leave this as a topic for future research. In a similar vein, countries that initially leave their resources to open access may start implementing private or common property right regimes upon technological improvements, potentially safeguarding the sustainability of such resources (Copeland and Taylor, 2009). At the micro level, users may start making cooperative agreements or craft rules to move towards a regime of sustainability (Richter et al., 2013). It is an entirely open question whether evolving institutions would benefit the whole society or would be favouring the ruling elite.

5. Conclusion

Our results present key mechanisms which may explain the emergence of local inequality in a society. A positive feedback between wealth and technology will allow moderate levels of inequality to emerge in a growing society. Furthermore, if the initial distribution of technology and productivity are heterogeneous, as in a capitalistic society, this can potentially lead to a rapid rise in inequality. With a heavy-tailed distribution of improved technology in society, fast rise in inequality is observed where a small elite group achieves accelerated wealth accumulation due to the convolution of better technology, capital income and resource control. Left unabated, this fast rise in inequality will have catastrophic effects such as overharvesting of resources and throwing those dependent on the resource off the resource and into poverty.

Main results from the paper can be summarized as follows: First, in growing societies, inequality rises in our model society due to an inherent positive wealth-technology feedback. Second, capitalistic development may result in a much faster rise in inequality and poverty depending on the distribution of productivity gains in society. Third, for uniformly distributed capital productivity gains, results show a slow innocuous rise in inequality. Pressure on resource use goes up, but stays within sustainable levels. Fourth, for heavy-tailed distributed capital productivity gains, results show (i) rapid rise in inequality triggering a collapse in wealth and resource dynamics at the societal level, and (ii) sharp rise in poverty while resource stocks fall below sustainable levels. Finally, if the ecological system is prone to collapse, we see that the positive feedback between wealth accumulation and resource extraction results in social-ecological collapse with resource extinction.

From a policy perceptive, the key message here is that a growth based agenda may not only fuel inequality, but also resource depletion. While it is a public policy choice, how to rank objectives in importance, our results are a cautionary note on an agenda that is purely driven by economic growth, i.e. wealth accumulation, without any consideration for equity. We show that ensuring equality in access to key resources is not only essential for social justice, but also for improving ecological resilience and reduction in poverty. We also show that there is not necessarily a trade-off between inequality and total welfare, as inequality may fuel overexploitation which erodes the foundation of society's wealth, making everyone worse off in case of a collapse.

Authors' contribution

MUM, AR, EN, and MS designed the research. MUM developed the model and carried out the analysis. All authors contributed to writing the final manuscript.

Code availability

The model was implemented and simulated using modelling platform GRIND version 2.0 for MATLAB version R2016b (available online at http://www.sparcs-center.org/grind). Code to run simulations is available upon request from the corresponding author.

Data availability

Raw data were generated using the dynamic model presented in the paper. Model parameters used in the study to generate this data are available in the online Appendix.

Acknowledgement

This project received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 643073.

Appendix A. Supplementary information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2019.02.015.

References

Alam, S., 2003. Environmentally induced migration from Bangladesh to India. Strateg. Anal. 27, 422–438.
Allee, W.C., 1931. Animal aggregations: a study in general sociology. University of Chicago Press, Chicago. https://doi.org/10.5962/bhl.title.7313.
Alvaredo, F., Atkinson, A.B., Piketty, T., Saez, E., 2013. The top 1 percent in international and historical perspective. J. Econ. Perspect. https://doi.org/10.1257/jep.27.3.3.
Arnold, M., Townson, I., 1998. Assessing the potential of forest product activities to contribute to rural incomes in Africa. Nat. Resour. Perspect. 37.
Arnold, J., Liedholm, C. & Mead, D. Structure and growth of small enterprises in the forest sector in southern and eastern Africa. OFI Occas. Pap. (1994).
Atkinson, A.B., Piketty, T., Saez, E., 2011. Top incomes in the long run of history. J. Econ. Lit. https://doi.org/10.1257/jel.49.1.3.
Ayres, R.U., 1988. Technology: the wealth of nations. Technol. Forecast. Soc. Chang. 33, 189–201.
Azariadis, C. & Stachurski, J. in Handbook of Economic Growth Volume 1, Part A 1, Part A, 295–384 (2005).
Banerjee, A.V., Newman, A., 1993. Occupational choice and the process of development. J. Polit. Econ. 101, 274–298.
Barrett, C. B. in Economics of poverty, environment and natural-resource use 31, 17–40 (Springer, 2008).
Barrett, C.B., Carter, M.R., 2013. The economics of poverty traps and persistent poverty: empirical and policy implications. J. Dev. Stud. 49, 976–990.
Barrett, C.B., et al., 2006. Welfare dynamics in rural Kenya and Madagascar. J. Dev. Stud. 42, 248–277.
Barrett, C.B., et al., 2011. On biodiversity conservation and poverty traps. In: Proceedings of the National Academy of Sciences. 108. pp. 13907–13912.
Barrett, C.B., et al., 2015. Well-being dynamics and poverty traps. Ann. Rev. Resour. Econ. 8.
Berec, L., Angulo, E., Courchamp, F., 2007. Multiple Allee effects and population management. Trends Ecol. Evol. 22, 185–191.
Besley, T., Persson, T., 2014. Why do developing countries tax so little? J. Econ. Perspect. 28, 99–120.
Biggs, R., Carpenter, S.R., Brock, W.A., 2009. Turning back from the brink: detecting an impending regime shift in time to avert it. Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas.0811729106.
Bowles, S., Durlauf, S. N. & Hoff, K. [Ed]. Poverty traps. Poverty traps. (2006).
Carpenter, S.R., Brock, W.A., 2008. Adaptive capacity and traps. Ecol. Soc. 13.
Carter, M.R., Barrett, C.B., 2006. The economics of poverty traps and persistent poverty: an asset-based approach. J. Dev. Stud. 42, 178–199.
Cavendish, W., 2000. Empirical regularities in the poverty-environment relationship of rural households: evidence from Zimbabwe. World Dev. 28, 1979–2003.
Coomes, O.T., Takasaki, Y., Rhemtulla, J.M., 2011. Land-use poverty traps identified in shifting cultivation systems shape long-term tropical forest cover. Proc. Natl. Acad. Sci. U. S. A. 108, 13925–13930.
Copeland, B.R., Taylor, M.S., 2009. Trade, tragedy, and the commons. Am. Econ. Rev. 99, 725–749.
Courchamp, F., Clutton-Brock, T., Grenfell, B., 1999. Inverse density dependence and the Allee effect. Trends Ecol. Evol. 14, 405–410.
Daily, G. C. Nature's Services: Societal dependence on naturla ecosystems. Nature's services: societal dependence on natural ecosystems 412 (1997). doi:https://doi.org/10.1017/S1367943098221123.
Dennis, B., 1989. Allee effects: population growth, critical density, and the chance of extinction. Nat. Resour. Model. 3, 481–538.
Downing, A.S., et al., 2014. Coupled Human and Natural System Dynamics as Key to the Sustainability of Lake Victoria's ecosystem Services.
Dutta, S., Kumar, L., 2015. Is poverty stochastic or structural in nature? Evidence from rural India. Soc. Indic. Res. https://doi.org/10.1007/s11205-015-1064-9.
Falconer, J. & Koppell, C. R. S. The Major Significance of 'Minor' Forest Products: The local use and value of forests in the West African humid forest zone. Community Forestry Note 6, UN FAO, Rome (1990).
Farley, J. & Voinov, A. Economics, socio-ecological resilience and ecosystem services. J.

Environ. Manag. 183, 389–398 (2016).
Farooqi, H., Wegerich, K., 2014. Institutionalizing inequities in land ownership and water allocations during colonial times in Punjab, Pakistan. Water Hist. 7, 131–146.
Fisher, B., Christopher, T., 2007. Poverty and biodiversity: measuring the overlap of human poverty and the biodiversity hotspots. Ecol. Econ. 62, 93–101.
Gabaix, X., Lasry, J.-M., Lions, P.-L., Moll, B., 2016. The Dynamics of Inequality. Econometrica 84, 2071–2111.
Ghatak, M., 2015. Theories of poverty traps and anti-poverty policies. World Bank Econ. Rev. 29, S77–S105.
Gilmartin, D., 1994. Scientific empire and Imperial science: colonialism and irrigation technology in the Indus Basin. J. Asian Stud. 53, 1127.
Godoy, R., et al., 2010. The effect of wealth and real income on wildlife consumption among native Amazonians in Bolivia: estimates of annual trends with longitudinal household data (2002–2006). Anim. Conserv. 13, 265–274.
Hamann, M., et al., 2018. Inequality and the biosphere. Annu. Rev. Environ. Resour. 43, 61–83.
Ibáñez, J., Martínez, S. & Martínez, J. Competitive and optimal control strategies for groundwater pumping by agricultural production units. Water Resour. Res. 40, n/a-n/a (2004).
ISSC, IDS & UNESCO. World Social Science Report 2016, Challenging Inequalities: Pathways to a Just World, (UNESCO Publishing, 2016).
Juster, F.T., Lupton, J.P., Smith, J.P., Stafford, F., 2006. The decline in household saving and the wealth effect. Rev. Econ. Stat. 88, 20–27.
Kohler, T. A. et al. Greater post-Neolithic wealth disparities in Eurasia than in North America and Mesoamerica. Nature nature24646 (2017). doi:https://doi.org/10.1038/nature24646.
Kramer, A.M., Dennis, B., Liebhold, A.M., Drake, J.M., 2009. The evidence for Allee effects. Popul. Ecol. 51, 341–354.
Kuparinen, A., Keith, D.M., Hutchings, J.A., 2014. Allee effect and the uncertainty of population recovery. Conserv. Biol. 28, 790–798.
Kuznet, S., 1955. Economic growth and income inequality. Am. Econ. Rev. 45, 1–28.
Lade, S.J., Tavoni, A., Levin, S.A., Schlüter, M., 2013. Regime shifts in a social-ecological system. Theor. Ecol. 6, 359–372.
Lybbert, T.J., Aboudrare, A., Chaloud, D., Magnan, N., Nash, M., 2011. Booming markets for Moroccan argan oil appear to benefit some rural households while threatening the endemic argan forest. Proc. Natl. Acad. Sci. U. S. A. 108, 13963–13968.
McNally, C.G., Uchida, E., Gold, A.J., 2011. The effect of a protected area on the tradeoffs between short-run and long-run benefits from mangrove ecosystems. Proc. Natl. Acad. Sci. U. S. A. 108, 13945–13950.
Mead, D.C., 1994. The contribution of small enterprises to employment growth in southern and eastern Africa. World Dev. 22, 1881–1894.
Milanovic, B., 2016. Global Inequality: A New Approach for the Age of Globalization.
Milanovic, B., Lindert, P.H., Williamson, J.G., 2011. Pre-Industrial Inequality. Econ. J. 121, 255–272.
Mirza, M.U., Mustafa, D., 2016. Sustainable Development and Disaster Risk Reduction: Methods, Approaches and Practices. pp. 143–159. https://doi.org/10.1007/978-4-431-55078-5_9.
Modigliani, F. Life cycle, individual thrift, and the wealth of nations. Science (80-.). 234, 704–712 (1986).
Mookherjee, D., Ray, D., 2002. Contractual structure and wealth accumulation. Am. Econ. Rev. 92, 818–849.
Mookherjee, D., Ray, D., 2003. Persistent inequality. Rev. Econ. Stud. 70, 369–393.
Mustafa, D., 2007. Social construction of hydropolitics: the geographical scales of water and security in the Indus Basin*. Geogr. Rev. 97, 484–501.
Mustafa, D., Akhter, M., Nasrallah, N., 2013. Understanding Pakistan's Water-Security Nexus.
Naschold, F., 2013. Welfare dynamics in Pakistan and Ethiopia – does the estimation method matter? J. Dev. Stud. 49, 936–954.
Naughton-Treves, L., Alix-Garcia, J. & Chapman, C. a. Lessons about parks and poverty from a decade of forest loss and economic growth around Kibale National Park, Uganda. Proc. Natl. Acad. Sci. U. S. A. 108, 13919–13924 (2011).
Piketty, T. Capital in the 21st Century. Cambridge Harvard Uni 696 (2014). doi:9780674430006.
Piketty, T., 2015. About capital in the twenty-first century. Am. Econ. Rev. 105, 48–53.
Piketty, T., Zucman, G., 2014. Capital is back: wealth-income rations in rich countries 1700–2010. Q. J. Econ. 129, 1255–1310.
Rahman, T. The class structure of Pakistan. (Oxford University Press, 2012).
Ravallion, M. Income inequality in the developing world. Science (80-.). 344, 851–855 (2014).
Richter, A., Dakos, V., 2015. Profit fluctuations signal eroding resilience of natural resources. Ecol. Econ. 117, 12–21.
Richter, A., van Soest, D., Grasman, J., 2013. Contagious cooperation, temptation, and ecosystem collapse. J. Environ. Econ. Manag. 66, 141–158.
Rosen, S., 1981. The economics of superstars. Am. Econ. Rev. 71, 845–858.
Saez, E., Zucman, G., 2016. Wealth inequality in the United States since 1913: Evidence From Capitalized Income Tax Data. Q. J. Econ. 131, 519–578.
Scheffer, M., 2007. The evolutionary basis of rigidity: locks in cells, minds, and Society. Ecol. Soc. 12.
Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413, 591–596.
Scheidel, A., 2013. Flows, funds and the complexity of deprivation: using concepts from ecological economics for the study of poverty. Ecol. Econ. 86, 28–36.
Sen, A. The idea of justice. (Belknap Press of Harvard University Press, 2009).
Shah, T. Taming the Anarchy: Groundwater Governance in South Asia. Taming the Anarchy: Groundwater Governance in South Asia 1–310 (2008). doi:https://doi.org/10.4324/9781936331598.
Tavoni, A., Schlüter, M., Levin, S., 2012. The survival of the conformist: social pressure and renewable resource management. J. Theor. Biol. 299, 152–161.
Toth, R. Traps and Thresholds in Pastoralist Mobility. Am. J. Agric. Econ. 97, aau064–332 (2014).
Townson, I.M., 1995. Patterns of Non-timber Forest Products Enterprise Activity in the Forest Zone of Southern Ghana. Draft Rep. to ODA For. Res, Program.
Halsema, G. E. van & Vincent, L. F. in A history of water. (eds. Tvedt, T., Jakobsson, E., Coopey, R. (Richard) & Oestigaard, T.) 55–91 (I.B. Tauris, 2006).
Zimmerman, F.J., Carter, M.R., 2003. Asset smoothing, consumption smoothing and the reproduction of inequality under risk and subsistence constraints. J. Dev. Econ. 71, 233–260.