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Endogenous technological and population change under increasing water scarcity

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Abstract

The ancient civilization in the Indus Valley civilization dispersed under extreme dry conditions; there are indications that the same holds for many other ancient societies. Even contemporary societies, such as the one in Murrumbidgee river basin in Australia, have started to witness a decline in overall population under increasing water scarcity. Hydroclimatic change may not be the sole predictor of the fate of contemporary societies in water scarce regions and many critics of such (perceived) hydroclimatic determinism have suggested that technological change may ameliorate the effects of increasing water scarcity and as such counter the effects of hydroclimatic changes. To study the role of technological change on the dynamics of coupled human-water systems, we develop a simple *overlapping-generations model* of endogenous technological and demographic change. We model technological change as an endogenous process that depends on factors such as the investments that are (endogenously) made in a society, the (endogenous) diversification of a society into skilled and unskilled workers, a society's patience in terms of its present consumption vs. future consumption, production technology and the (endogenous) interaction of all of these factors. In the model the population growth rate is programmed to decline once consumption per capita crosses a "survival" threshold. This means we do not treat technology as an exogenous random sequence of events, but instead assume that it results (endogenously) from societal actions.

The model demonstrates that technological change may indeed ameliorate the effects of increasing water scarcity but typically it does so only to a certain extent. It is possible that technological change may allow a society to escape the effect of increasing water scarcity, leading to a (super)-exponential rise in technology and population. However, such cases require the rate of success of investment in technological advancement to be high. In other more realistic cases of technological success, we find that endogenous technology change only helps to delay the peak of population size before it inevitably starts to decline. While the model is a rather simple model of societal development, it is shown to be capable of replicating patterns of technological and population changes. It is capable of replicating the pattern of declining consumption per capita in presence of growth in aggregate production. It is also capable of replicating an exponential population rise, even under increasing water scarcity. The results of the model suggest that societies that declined or are declining in the face of extreme water scarcity may have done so due to slower rate of success of investment in technological advancement. The model suggests that the population decline occurs after a prolonged decline in consumption per capita, which in turn is due to the joint effect of initially increasing population and increasing water scarcity. This is despite technological advancement and increase in aggregate production. We suggest that declining consumption per capita despite technological advancement and increase in aggregate production may serve as a useful predictor of upcoming decline in contemporary societies in water scarce basins.

1 Introduction

Recently Pande and Ertsen (2013) proposed a theory of endogenous change in the context of water management under water scarce conditions at basin scale. The authors suggested that an exogenous (external to the system) change in hydro-climatology can lead to endogenous changes in cooperative structures such as socio-political organization and trade (see also Pande and McKee, 2007). They also showed that this may bring about other endogenous changes such as in demography, thus may lead to a (virtuous or vicious) cycle of future changes in cooperative structures and demography.

Van der Zaag (2013), in a commentary on Pande and Ertsen (2013), criticized the proposed theory by suggesting that it ignored the role of technological change in shaping human societies. Van der Zaag (2013), in our interpretation, stressed that without any consideration for technological change, the theory proposed an outcome that is hydro-climatologically deterministic and that technology may play a key role in the

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departure of a society's evolution from one predicted by hydro-climatic determinism. The historical development of water resources within the Murrumbidgee basin in Australia over the past century is a case in point (Kandasamy et al., 2013).

If we broadly interpret technology as any innovation that scales up production, then increases in storage capacity and drip irrigation that ameliorates fluctuations in water supply and technologies to reduce soil salinity that enhance productive use of water, as happened in the Murrumbidgee, may indeed be categorized as technologies. The basin witnessed a rapid rise in population amid increasing concerns of salinity and declining ecosystem services. It was able to sustain the growth in population and agricultural production by first increasing reservoir capacities and then through investments in infrastructures and technologies to control soil salinity and algal blooms, such as efficient irrigation systems, barrages and upgrade of sewage treatment plants. Yet it was unable to curb the eventual decline in population and domestic production that began around 1990.

The sustained decline in water available for the environment and hence its ultimate degradation led to the rise of the notion of the environmental consumer in the basin by 2007 (Kandasamy et al., 2013). This implied a change in preferences of the population within the basin and society at large towards the environment. The system reached the stage whereby inhabitants of the Murrumbidgee basin were no longer solely driven by consumption from the income that agriculture generates at the cost of environmental degradation. They reached the point where they were willing to give up consumption for improved environment quality and higher environmental flows. Such a change in the values and norms of individuals within the basin resulted in a different dynamics between agricultural production and environment quality (Chen and Li, 2011). The changing values and norms, via changes in the dynamics of human consumption and environment quality, fed back to changes in the delivery of ecosystem services. This nonetheless led to the continued decline in population and rice production within the basin. Overall, the rise and the fall of population and crop production led to the spatio-temporal pendulum swing in the area under irrigation within the basin. What is observed in the Murrumbidgee river basin is an intrinsic part of the natural dynamics of coupled human-water systems, as per the conceptual socio-hydrologic framework proposed by Sivapalan et al. (2013).

Of course, technological change may buffer the response of a system to change. Technological innovation or adoption can compensate for the effect of increasing population and reducing water resource availability on individual wellbeing that an economy can ensure (Aghion and Howitt, 1997). Technological innovation is almost a necessity if “timeless” growth is desired, which is when a society is sustained forever (Sachs and McArthur, 2002). However, it can still be debated whether technological change should be treated as an exogenous (a historical treatment, see for e.g. Burlingame, 1961; Wright, 1997) or as an endogenous process (Jaffe et al., 2003; Eicher, 1996; Romer, 1990). In context of coupled human water systems, the latter is when technological change emerges from the intrinsic dynamics of the human and the water system.

Both human agency and societal structures are needed to understand technological development in context of water. It is conditioned by factors such as earlier innovations, human resource development, market demand and the structure of a water economy (Van de Poel, 2003, 1998; Ertsen, 2010). We conceptualize technological development with Sewell’s and Giddens’ concept of societal structure in mind (Sewell, 2005; Giddens 1979, 1984). Here societal structure is understood as rules and resources (not to be confused with natural resources but human related resources such as technology), that emerges from the evolutionary dynamics of a social system (Latour, 2005).

One may then suggest that humans construct technologies in social interaction in a similar manner as they construct society since technology partly defines a social structure. In context of a human dominated water system (or a coupled human water system) this would mean that technology emerges from the intrinsic dynamics of the system. That is, humans reproduce existing, historically grown sets of water related technologies by applying and changing them. This path-dependency in its evolution is a symptom of an endogenous process of technological change (Lyon and Pande, 2005; Pande and McKee, 2007). Such continuity necessarily excludes the case that technology develops like some external force, with a will of its own, without any possibility for humans to influence its course. We however acknowledge that fierce debates may still take place on the nature of technological change (see Bijker, 1995 for examples).

In the context of water scarce societies, with water being a limited resource, one would indeed expect such fierce debates. Irrespective of these debates, no technological innovation can surmount this physical limit of water resource availability (Smart, 2005), except under a special condition which we term “singularity”. Thus a suggestion that technological change “necessarily” empowers a society to be “on top” of nature in terms of its limited water resources may not be realistic. We argue in this paper that technological change many times may delay a society’s response to change, which may give an impression that it is on top of change. It may lead to a feeling of timeless superiority of humans over nature in certain other “singular” cases.

In order to demonstrate and defend this claim, we propose a simple model of endogenous technological change, along the lines of Romer (1990) and Eicher (1996), in the context of water and change. It determines the evolution of a society under increasing water scarcity by endogenous feedbacks between population growth and technological change. The nature of feedbacks (whether they are positive or negative) are not exogenously (externally) imposed by a modeler but are endogenously determined. Thus our model, though simple, is general enough to emulate a variety of feedbacks between population growth and technological change, depending on how a society is conceptualized (parameterized) in the model. All the cases that are considered assume that the water resources available at any time are entirely consumed by the production activity that the society engages in. The change in water resources is assumed to be exogenous to mimic hydro-climatic change.

2 The model

2.1 Endogenous technological change model

We consider an *overlapping-generation* model with 2 generations. This is a simple conceptualization of a society that is assumed to be composed of 2 generations that overlap with each other as they evolve in time. Each generation lives for only 2 time periods (when young and when old), thus young individuals of one generation always overlap with old individuals of the other generation. Each generation grows at a certain rate (based on a population growth model to be described in Sect. 2.2), with a rate of growth that depends on consumption per capita. The individuals in a society produce one composite good (that conceptualizes the entire spectrum of goods and services that a population lives on) that is water intensive and requires unskilled labor and skilled labor as the other two inputs. The technology scales this production linearly (Romer, 1990; Eicher, 1996). The technology is such that 1 unit of additional skilled labor produces more composite good than 1 unit of unskilled labor (hence skilled labor is more valuable to society than unskilled labor), which in turn produces more per unit than per unit of additional water.

Within each generation the newborns at any time are born without any endowment, i.e. they are born penniless and have to work to earn a living. They have to choose between either becoming a researcher who invests her time in innovation to advance current technology or becoming an unskilled worker and start to earn a living already. The unskilled uses her living to consume and save. The unskilled is assumed to retire in the next time period and live on the savings (that may endogenously appreciate or depreciate in value) that she made in the previous time step. The researcher becomes a skilled worker in the next time period, earning a higher wage than an unskilled worker in that time period. Since the researcher does not yet make a living, she has to live on a loan against her future earning that she would make as a skilled worker. The loan is provided by the savings of unskilled workers in that time period. It is assumed that only the unskilled workers reproduce. Both the skilled and unskilled workers die penniless. See for e.g. Eicher (1996) for a similar model conceptualization of a society.

2.1.1 Production of composite good and technological change

We assume a Cobb–Douglas production function that produces y_t amount of the good for a given amount of available water X_t, unskilled workers U_t, and skilled workers E_t.

$$y_t = f\left(X_t, U_t, E_t; \mathrm{v_t}\right) = \mathrm{v_t} X_t^{\alpha} U_t^{\beta} E_t^{1-\alpha-\beta}.$$

Here, $\mathrm{v_t}$ represents the current technology that scales up the amount of production linearly (see for eg. Romer, 1990; Eicher, 1996), $0 < \alpha < 1$ and $0 < \beta < 1$ are the parameters such that $\alpha < \beta < 1 - \alpha - \beta$. We here emphasize that water availability here holistically represents the productive supply of water. It encompasses the effects of both water quality and quantity. The supply of water may effectively be reduced due to lower water quality, for example salinity that may lower plant water uptake thereby affecting crop production.

Technological change, in a particular time period, is brought about by researchers, S_t, but depends also on the current state of technology. If each researcher consumes c_t^{S}, the technological innovation is thought of as a random process that is proportional to the total consumption of the researchers $c_t^{\mathrm{S}} S_t$ thereby measuring total energy available for innovation. The change in technology per unit current technology, $\frac{\mathrm{v_{t+1}} - \mathrm{v_t}}{\mathrm{v_t}}$, is then given by,

$$\frac{\mathrm{v_{t+1}} - \mathrm{v_t}}{\mathrm{v_t}} = \gamma c_t^{\mathrm{S}} S_t.$$

Here, $0 \leq \gamma \leq 1$ represents the success rate with which a unit of energy available for innovation results in technological advancement. It therefore represents how efficiently available energy gets converted into technological advancement. It further bounds a change in technology in a particular time period.

2.1.2 Livelihood (utility) maximization

We assume all the individuals in a society have identical preference structures between the present and future consumption of the composite commodity. The choices of an individual born at time t, are driven by her tendency to maximize her livelihood (utility) function of consumptions at time t and $t+1$. However, she is limited by the income that she generates through her participation in the production activity of the society.

For a researcher, who consumes c_t^{S} at time t, becomes a skilled worker at time $t+1$ and consumes $c_{\mathrm{t+1}}^{\mathrm{E}}$, choice of $\left\{c_t^{\mathrm{S}}, c_{\mathrm{t+1}}^{\mathrm{E}}\right\}$ is determined by the following maximization problem

$$W^{\mathrm{S}} = \max_{\left\{c_t^{\mathrm{S}}, c_{\mathrm{t+1}}^{\mathrm{E}}, b_t\right\}} \ln c_t^{\mathrm{S}} + \beta_0 \ln c_{\mathrm{t+1}}^{\mathrm{E}},$$

such that,

$$\begin{aligned} c_t^{\mathrm{S}} &= b_t \\ c_{\mathrm{t+1}}^{\mathrm{E}} &= w_{\mathrm{t+1}}^{\mathrm{E}} - b_t(1+r_t). \end{aligned}$$

Here, b_t is the amount that the researcher at time t plans to borrow to support herself only to return it once she participates as a skilled worker in the production activity in the next time period and earns an income of $w_{\mathrm{t+1}}^{\mathrm{E}}$ as a result. The amount that she has to return, i.e. $b_t(1+r_t)$, may be larger or smaller than the amount that she borrowed (determined by the rate of return r_t) and depends on the availability of the funds and propensity of agents to save. The parameter $\beta_0 > 0$ represents how she weighs her future consumption to present. This parameter is equal to $\frac{\theta}{1-\theta}$ where $0 \leq \theta \leq 1$ is an individual's propensity to save. Thus larger the β_0, larger is the propensity to save.

The researcher, for given skilled labor income in the next time period ($w_{\mathrm{t+1}}^{\mathrm{E}}$) and the current rate of return r_t plans her consumption over her lifetime such that her livelihood function is maximized.

Similarly, for an unskilled worker, who consumes c_t^{U} and saves m_t at time t but does not work at time $t+1$ when she consumes c_{t+1}^{U} from what she saved at time t, choice of $\left\{c_t^{\mathrm{U}}, c_{t+1}^{\mathrm{U}}\right\}$ is determined by the following maximization problem

$$W^{\mathrm{U}} = \max_{\left\{c_t^{\mathrm{U}}, c_{t+1}^{\mathrm{U}}, m_t\right\}} \ln c_t^{\mathrm{U}} + \beta_0 \ln c_{t+1}^{\mathrm{U}},$$

such that,

$$\begin{aligned} c_t^{\mathrm{U}} &= w_t^{\mathrm{U}} - m_t \\ c_{t+1}^{\mathrm{U}} &= m_t(1+r_t). \end{aligned}$$

Here, w_t^{U} is the income that the unskilled worker earns at time t. At $t+1$, she reproduces to provide offsprings for time $t+2$.

2.1.3 Population dynamics

The population of a generation at time t, Ω_t, grows at a rate of r_t^{Ω}. The unskilled worker at time t has the role of reproducing at time $t+1$ when she does not work and lives off her savings made at time t. Thus, it is assumed that the rate of population growth may reduce or even become negative if consumption per capita of unskilled worker reduces. This is to reflect the tendency of population to outmigrate or to decline when livelihood of individuals deteriorates. We model the rate of population growth to become negative once unskilled worker's consumption, c_t^{U}, falls below a certain threshold, $\underline{c}^{\mathrm{U}}$.

$$\Omega_{t+1} = \Omega_t \left(1 + r_t^{\Omega}\right),$$

where,

$$r_t^{\Omega} = \begin{cases} \bar{r}^{\Omega} > 0 & \text{if } c_t^{\mathrm{U}} > \underline{c}^{\mathrm{U}} \\ \underline{r}^{\Omega} < 0 & \text{if } c_t^{\mathrm{U}} \leq \underline{c}^{\mathrm{U}} \end{cases}.$$

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This conceptualization is the similar to the dominant mode analysis of Cuypers and Rademaker (1974) of the World2 model of Forrester (1971). Cuypers and Rademaker (1974) found that the complex set of coupled equations of the World2 model can be simplified to a hierarchical system where the population dynamics is driven by natural resource availability and capital investment. The consumption per capita represents the joint effect of water resource availability and food production on population growth rate.

2.1.4 Equilibrium conditions

The partitioning of total population at any time t, $\Omega_t = \mathrm{S}_t + \mathrm{U}_t$, into S_t and U_t is determined by assuming that an individual at time t is indifferent to choosing to contribute to production activity as an unskilled worker or investing herself in advancing current production technology. It is therefore assumed that the utility maximized by being a researcher is the same as the utility maximized by being an unskilled worker over her lifetime, i.e.

$$W^{\mathrm{S}} = W^{\mathrm{U}}.$$

The rate of return on savings m_t or the cost of borrowing b_t is r_t and it is determined by the balance between total demand for borrowing $S_t b_t$ and the total supply of funds that is the sum of total amount of savings, $U_t m_t$ and surplus Q_t generated by the production activity. The surplus Q_t that is generated by the production activity is the produce left after paying for the labor of unskilled workers, w_t^{U}, and skilled workers, w_t^{E}. By pooling the surplus into the total supply of funds, we assume that gains from production activity and gains in efficiency by advancing technology feedback to advance technology in the future. Higher surpluses lower the cost of borrowing, hence it encourages higher participation of researchers in technological advancement. The balance of funds for borrowing and savings by surplus is given by,

$$S_t b_t - U_t m_t = Q_t.$$

Here $Q_t = y_t - w_t^{\mathrm{U}} U_t - w_t^{\mathrm{E}} E_t$.

The wages that workers are paid are at their marginal productivity. Thus,

$$w_t^{\mathrm{U}} = \frac{\partial f\left(X_t, U_t, E_t; v_{\mathrm{t}}\right)}{\partial U_t}$$

and

$$w_t^{\mathrm{E}} = \frac{\partial f\left(X_t, U_t, E_t; v_{\mathrm{t}}\right)}{\partial E_t}.$$

We here note that since workers earn a living at the rate of their marginal productivity, $w_t^{\mathrm{U}} U_t = \beta y_t$ and $w_t^{\mathrm{E}} E_t = (1 - \alpha - \beta) y_t$. The surplus generated is the implicit value of water or the contribution of water in total production, i.e. $Q_t = w_t^X X_t = \alpha y_t$. Here w_t^X represents the marginal productivity of water. This has an interesting bearing on the discourse of scale of cooperation and technological change that Pande and Ertsen (2013) proposed. Larger surpluses per unit additional water are generated when water is relatively scarcer. Thus an extension of the scale of cooperation under water scarce conditions, which results in an increase in total availability of water, generates more surplus per unit additional water than when conditions are not as scarce. This may inturn reduce the cost of borrowing and hence spark innovation per unit additional water more in the case when water is scarcer. We may thus find positive correlation between technological innovation and rise to maturity of a society under water scarce conditions.

Finally, a researcher at time t becomes a skilled worker at time $t + 1$, i.e. $\mathrm{S}_t = E_{\mathrm{t+1}}$.

2.1.5 Model equations

A set of model equations for labor diversification, wages, rate of return, production and surplus generated, technological change and consumption per capita are obtained based on the livelihood maximization, technological advancement, production activity and the above equilibrium conditions.

The diversification of labor, i.e. the ratio of individuals who choose to be unskilled workers and those who choose to be researchers in order to become skilled workers in the next time step, is a constant. The diversification depends on how critical water is to the production activity and individuals propensity to save.

$$\frac{U_t}{S_t} = \delta = \frac{1}{\beta_0\left(1+\frac{\alpha}{\theta\beta}\right)}.$$

Since the sum of the unskilled workers and researchers define the population of the generation starting at time t, i.e. $\mathrm{S}_t + \mathrm{U}_t = \Omega_t$, the number of unskilled workers and researchers at any time t can be obtained as,

$$S_t = \frac{\Omega_t}{1+\delta},$$

$$U_t = \delta\frac{\Omega_t}{1+\delta}.$$

Since the income earned by individuals is at their marginal productivities, the wage rates for unskilled and skilled workers is given by,

$$w_t^{\mathrm{U}} = \beta v_t X_t^{\alpha} U_t^{\beta-1} E_t^{1-\alpha-\beta},$$

$$w_t^{\mathrm{E}} = (1-\alpha-\beta)\mathrm{v_t} X_t^{\alpha} U_t^{\beta} E_t^{-\alpha-\beta}.$$

The surplus Q_t that is generated at time t is given by,

$$Q_t = \alpha f\left(X_t, U_t, E_t; \mathrm{v_t}\right).$$

The savings made by the unskilled workers, m_t, and the borrowing of the researchers, b_t, is given by,

$$m_t = \theta w_t^{\mathrm{U}},$$

$$b_t = \theta\frac{w_{\mathrm{t+1}}^{\mathrm{E}}}{\beta_0\left(1+r_t\right)},$$

where the rate of return on savings, r_t, is given by,

$$\frac{1}{(1+\beta_0)}\frac{w^{\mathrm{E}}_{\mathrm{t+1}}}{\left(\theta\delta w^{\mathrm{U}}_t + Q_t/S_t\right)} - 1.$$

The consumption per capita of unskilled and skilled workers can now be given as,

$$c^{\mathrm{U}}_t = w^{\mathrm{U}}_t - \theta w^{\mathrm{U}}_t,$$

$$c^{\mathrm{S}}_t = \theta\frac{w^{\mathrm{E}}_{\mathrm{t+1}}}{\beta_0\left(1+r_t\right)}.$$

Meanwhile the consumption of the same individuals at time $t+1$ is given by,

$$c^{\mathrm{U}}_{\mathrm{t+1}} = m_t(1+r_t),$$

$$c^{\mathrm{E}}_{\mathrm{t+1}} = w^{\mathrm{E}}_{\mathrm{t+1}} - b_t(1+r_t).$$

Finally the endogenous technology change equation is given by:

$$v_{\mathrm{t+1}} = v_{\mathrm{t}}\left[1+\gamma S_t\left(\theta\delta w^{\mathrm{U}}_t + Q_t/S_t\right)\right].$$

Note that the rate of technological change is never negative, i.e. technology never deteriorates and builds upon previously generated technology, in addition to other factors. The rate of change is endogenous because it depends on factors that are endogenously determined in the evolution of a society. It is proportional to a random variable γ that determines the rate of success of (implicit) investment in technological advancement. The investment is the sum of the wage of an unskilled worker forgone by a researcher (since she decides to work on advancing the technology, she lives on a debt and forgoes the income that she could have earned had she rather worked as an unskilled worker) and the surplus generated by the production activity.

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3 Results

For our simulations we assume that (renewable) water resource availability X_t declines exponentially over time at the rate of 1 % ($k = -0.01$), i.e. $X_{t+1} = (1+k)X_t = 0.99X_t$. We consider that a system reaches a physical limit once X_t falls below 1 % of $X_{t=0}$ and the evolution of the society abruptly stops. We also assume that γ is a gamma distribution, with a mean of $\overline{\gamma} > 0$, to represent sparks of innovation. Thus, we assume that a positive surplus is not sufficient to spark an innovation, there by certain additional other factors exogenous to the system that determine the rate of success.

We assume $\alpha = 0.3 < \beta = 0.35$. The coefficient β_0 that measures the patience of an individual in terms of her present to future consumption is assumed to be 0.99. We therefore model a society with individuals who prefer, though marginally, to consume a unit at present rather than relegating it to the future. We assume the positive and negative population growth rates, $\overline{r}^{\Omega}$ and $\underline{r}^{\Omega}$ are 0.01 and −0.02, which suggests that population increases at a rate of 1 % and once the consumption per capita of an unskilled worker crosses a certain threshold, $\underline{c}^{U}$, it falls to −2 % representing decline due to outmigration or higher death rate than birth rate. We assume that is this critical threshold is $0 < \eta < 1$ fraction of the consumption per capita that unskilled workers witnessed under water abundance, i.e. $\underline{c}^{U} = \eta c^{U}_{t=0}$. Thus varying sensitivity (resilience) of populations to the critical threshold is modeled. We consider $\eta = 0.1$, unless otherwise stated. Finally, we initialize the model with an initial technological level, $v_{t=0} = 0.02$, initial population level $\Omega_{t=0} = 1$ and initial water resource $X_{t=0} = 1$. The model can be scaled up by appropriately setting $X_{t=0}, \Omega_{t=0}, v_{t=0}$ and k.

3.1 Population decline under technological advancement

Consider the case of a resilient society in the sense that its population growth rate is only affected once its consumption per capita fall below 10 % of the initial level (at $t = 0$), i.e. $\eta = 0.10$. Let the long run rate of success in technological innovation be $\bar{\gamma} = 0.10$. We assume that the randomness in the rate of technological success (i.e. ramdomness

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in γ) is represented by a gamma distribution with a mean $\bar{\gamma}$ and a standard deviation of $100\bar{\gamma}^2$.

The technology of the society advances throughout the period until the society reaches its physical limit around 350 time units (Fig. 1a). Even though technology advances throughout, it does not allow the individuals in a society to escape the physical limit. The technological advancement is also not sufficient to support an ever increasing population (Fig. 1b). The population initially increases under technological advancement that leads to an initial increase in production even under increasing water scarcity (Fig. 1c). However, the increase in production, both due to technological advancement and increasing population that contributes skilled and unskilled workers, is not sufficient to support consumption per capita of an increasing population (Fig. 1d). Note that the consumption per capita of a researcher and an unskilled worker is the same for all t. This leads to an persistent decrease in consumption per capita over time.

The ever decreasing consumption per capita and not too high rate of success in technological advancement finally catches up with an increasing population growth. Since technological advancement not just depends on its rate of success but also “endogenously” on consumption per capita, persistently decreasing consumption per capita feedbacks into the human capacity (or capital) to innovate and reduces the rate of technological change. While the technology still advances, it advances at a slowing rate over time.

Once the population peaks and starts to decline, lower availability of workers reinforces the feedbacks of increasing scarcity and decreasing per capita consumption (equivalent to attrition of human capital) on the rate of technological advancement and aggregate production. The reduction in the rate of technological advancement is now sharper, and technological advancement can no longer stop the decline in aggregate production. While declining population negatively feedbacks to reduce the rate of decline in per capita consumption, the society soon reaches its physical limit of water availability.

The decline of the society is triggered long before it reaches its physical limit. While reducing water resources availability has a role, population decline is not determined by it. The rate of technological innovation (as represented by $\bar{\gamma}$) is not sufficiently high. The individuals in a society cannot escape the decline since they cannot innovate sufficiently fast, which inturn affects their future capacity to innovate (measured in terms of consumption per capita). The society witnesses a persistent decline in consumption per capita inspite of technological advancement and increasing production (till around 270 time units). This prolonged reduction in human capacity to innovate finally triggers a decline around 270 time units.

This suggests that a society need not immediately decline once water scarcity starts to increase. A certain population level may contribute to technological advancement and an initial increase in production through individual contribution to innovation and production. This inturn may initially support an increasing population even under increasing scarcity condition.

Consider Fig. 2 that displays the time series of reservoir storage capacity, population and rice production for Murrumbidgee basin (Kandasamy et al., 2013) and a proxy for consumption per capita for New South Wales state in Australia (see Appendix for an explanation). The basin witnessed population decline in 1990 amid ecological and salinity concerns since early 1960 (Kandasamy et al., 2013). Thus the basin witnessed declining water availability, under our definition, for nearly 4 decades. If the reservoir storage capacity (Fig. 2a) that scales up production by smoothing the intra-annual supply of water can be considered a proxy for technology, the similarity of its pattern with Fig. 1a is clear. The patterns of population and production are also similar (comparison between Figs. 1b, c and 2b, c). The census derived consumption per capita (Fig. 2d) show a declining trend the decade before the eventual decline of population in the Murrumbidgee basin in early 1990. It therefore appears that declining consumption per capita under declining water resource availability, even in presence of technological change, may be a credible predictor of upcoming population decline. Surely Murrumbidgee basin has ample opportunity to access and adopt smart water saving and purification technologies. Yet, it has been unable to stem the eventual population decline. This example therefore serves as a counterfactual to the suggestion that technological advancement is sufficient for societies to be on top of physical limits imposed by nature.

Whether consumption per capita is a credible predictor of eventual decline is further supported by the outputs of Limits to Growth World3 model (Hayes, 2012). The model is a complex collection of coupled differential equations of major societal variables such as population, natural resources, pollution, capital investment and food per capita. Figure 3a demonstrates the major variables for a comparison with related variables of the model presented here (Fig. 3b). The declining natural resource availability and increasing pollution output represents declining water resource availability in the context of this paper. The outputs suggest that population and production (industry) initially increase inspite of declining resource availability and increasing pollution. However, the eventual decline is preceded by a persistent decline in consumption per capita (food per capita) for over 50 yr. Similar patterns are replicated by the model of endogenous technological change in Fig. 3b. Note here that a S-shaped function is used to represent declining water resource availability (unlike the exponential decline that has been used elsewhere in the paper) in order to reproduce a similar shaped decline in natural resource availability produced by the World3 model (in Fig. 3a). However, the model currently is unable to replicate the bell shaped patterns of consumption per capita that appear both in Figs. 2d and 3a, possibly due to its parsimonious nature.

3.2 Role of the rate of success in innovation on the nature of population change

The point in time of decline in population depends on the resilience of population growth to consumption per capita. Figure 4b shows that the decline begins earlier when it is assumed that population growth becomes negative when consumption per capita falls below 25 % of initial consumption per capita, i.e. $\eta = 0.25$ than when $\eta = 0.10$ is assumed. For the remainder of the paper, we let $\gamma = \bar{\gamma}$, i.e. we do not allow any randomness in the rate of success in technological innovation (γ) for a given long run mean ($\bar{\gamma}$), and investigate the effect of the rate of technological innovation on the timing of societal decline. All initial conditions are assumed to be the same as in Sect. 3.1.

Figure 4a demonstrates the evolution of endogenous technological change for 3 rates of success: modest ($\gamma = 0.10$), low ($\gamma = 0.01$) and zero ($\gamma = 0.00$). The last case represents the case of no technological change. Figure 4 demonstrates that an increase in the rate of success delays the peak of population growth. Nonetheless, population eventually declines for the cases considered here. The evolution of population also closely follows a gradual increase and then fall in production (even under no technological change) in Fig. 4c. The consumption per capita appear not to be too different across the 3 cases.

Figure 4 illustrates that societies may decline when the rate of success of technological innovation is not sufficiently high. In these case, technological change may at best delay the advent of decline but may not allow individuals in a society to escape from it.

However, it appears that individuals in society may escape an eventual decline if the rate of success in technological innovation is sufficiently high. Note that technological change is a function of human capital (represented in terms of total consumption of the researchers) and the rate of success. Furthermore, production is function of technological level, water resource availability and availability of skilled and unskilled workers. While increasing population and water scarcity put downside pressure on aggregate production, increasing population and technological levels attempt to pull up aggregate production. Thus sufficiently fast increments in technological levels may overcome the downside pressure on production to the extent that consumption per capita ultimately begins to rise, positively reinforcing technological advancement. A virtuous cycle ensues, allowing individuals in a society to “escape” water scarcity.

This is illustrated by Fig. 5, which demonstrate the effect of the rate of technological success on population growth. For $\gamma = 0.5$ and $\gamma = 1.0$, the technological level explodes (a “technological singularity” is reached) before the society reaches the physical limit. The level of technology at this singularity is infinite, implying that the society can sustain infinite population irrespective of water resource availability. Figure 5b shows that for $\gamma = 0.5$ the population explodes to infinity around the time when physical limit in water resource availability is reached, while for $\gamma = 1.0$ it explodes to infinity around 190 time units. In both the cases, the consumption per capita initially declines slightly but recovers at later time steps. The consumption per capita recovers before the society reaches its singularity and this rise (super-exponential growth) in consumption per capita accelerates its approach to singularity.

The implausibility of the notions of singularity and escape from the ultimate resource may suggest the implausibility of rates of success such as 0.5 and 1.0. Nonetheless, the model of endogenous technological and population change allows for it.

Unlike the cases when the rates of success (γ) are high, population and technology are not always positively correlated even under technological advancement (Fig. 6a and b). The population first rises and then falls with increasing technological level. The maximum population that is achieved increases with increasing γ. However, the rise to a maximum and fall thereafter with increasing technology are steeper for lower values of γ. Even for a given rate of success, γ, the fall in population with increasing technology is steeper than the rise. These observations illustrate the complex feedbacks between population growth and technological change that this model implements. These complex feedbacks are communicated through variables such as aggregate production and consumption. Figure 6c and d demonstrate that consumption per capita is first negatively correlated with production followed by a positive correlation once population reached its maximum. After a mild rise to a maximum, aggregate production sharply drops per unit reduction in consumption once the population peaks for each of the 3 rates of success. These results demonstrate that the model is capable of endogenously imputing a relationship between variables of interest that may change over time.

Figure 6a suggests that the population peak occurs before the technological change asymptotes. However both the peak population and "mature" (asymptotic) technological level, v^*, increase with increasing γ. Figure 7a shows that the change in v^* with γ is itself super-exponential. A technological singularity is achieved for a critical rate of success γ_c around 0.49, suggesting that unlimited population growth is possible for $\gamma \geq \gamma_c$. Thus societies may escape from the physical limit posed by water scarcity at high rates of technological success.

Figure 7b shows that technology continues to advance, though at slow rates, for low to medium rate of success ($\gamma < \gamma_c$) till the time when the physical limit of water availability is reached. The population peaks before the time of hitting the physical limit. Thus societies decline before its individuals witness the physical limit of water resource availability. However, for $\gamma \geq \gamma_c$, societies witness technological singularity. The populations explode to infinity before the time of the physical limit and at the same time when its individuals witness technological singularity. The time to singularity decreases with increasing rate of success, γ, when $\gamma \geq \gamma_c$. Hence the time to population peak coincidentally decreases with increasing rate of success, γ, when $\gamma \geq \gamma_c$.

4 Discussion and conclusions

The paper presented an *overlapping-generations* model of endogenous technological change and population growth under decreasing water availability. The overlapping generation model parsimoniously represented an economy where only one good is produced and consumed by 4 different types of agents: young researcher, young unskilled worker, retired (unskilled) worker and a skilled worker. Balances of the good produced and the payments were maintained.

The technological change was either induced or adopted based on the total consumption of young researchers who subsisted on loans provided by unskilled workers and the surplus maintained by the society. However, the model assumed that the total consumption is not sufficient for technological advancement. It assumed that realization of technological innovation, conditional on a given amount of total consumption of young researchers, is random. This meant that not all investments in technological advancement by the same amount lead to the same level of technological attainment.

Multiple feedbacks between population, production, consumption and innovation were modeled. The strengths of these feedbacks were endogenously determined; hence they may vary over time. Population growth was determined by consumption per capita realized by the various agents. Population, depending on how it endogenously splits into 4 different types of agents, contributed to production activities and implicitly determined consumption per capita. Consumption per capita depended on how much income an agent made, which in turn endogenously depended on the production technology, the labor participation and the level of specialization. Production depended on available technology, available resources and the specialization of the labor force (between skilled and unskilled workers).

In order to sustain a growing population, the technological advancement led production must surpass the consumptive demands of a growing population. It must counter the downward pull of decreasing water resource availability (though population growth also increases production at a constant level of other inputs). Unfortunately water availability decreases over time. The only way to avoid this physical limit is a state of singularity wherein technology is so infinitely superior that the physical limit no longer applies. In more realistic, non-singular, cases technological advancement can at best delay the effect of declining water availability on consumption per capita and hence on eventual population decline. In all these realistic cases, it therefore appears that persistent decline in consumption per capita, in spite of increasing production and technological change, is a credible predictor of eventual population decline. Needless to say, technological advancement may not be sufficient to allow societies to be limitlessly on top of nature.

This was hypothesized to be the case for the ancient Indus valley civilization by Pande and Ertsen (2013) and for the contemporary case of the Murrumbidgee basin by Kandasamy et al. (2013). The Indus valley civilization rose to maturity in spite of decreasing water resource availability and advances in technology such as sophisticated water management systems. Yet it eventually declined. The Murrumbidgee basin also witnessed a rise in population and agricultural production amid increasing concerns of water quality. The population also eventually declined in the 1990s and continued its decline in spite of heavy investments in improving water management and changes in values and norms of individuals with respect to their use of water.

Both the cases and the results from model analysis suggest that technological innovation might have at best delayed the eventual decline. This pattern that the model faithfully replicates across the two basins is possibly due to the endogenous nature of technological growth. We do not consider technological change as a process external to the evolution of a society but that it is engendered by antecedent technologies, investments and human resource development. We therefore emphasize that models that consider changes in technology, population and their relationship with the water system in an endogenous way are needed to credibly anticipate long run dynamics of coupled human water systems.

The model developed in this paper is one of the first models that simulate endogenous growth with technological and population changes. The conceptualization is parsimonious. Only one type of technological change is considered that scales up production level (Jaffe et al., 2003). Other types of inputs such as land or other resources have not been considered. Stratification in the society is simplistic and only one type of good is considered. Net population growth rate depends only on consumption per capita. Important aspects such as environmental quality and taxation to support technological innovation have been ignored (Chen and Li, 2011). Whether the conclusions drawn in this paper would change with such additional complexity remains to be explored. We hope to pursue this in our future work.

Appendix

The census data for years 1976, 1981 and 1986 for New South Wales, Australia were downloaded from the Australian Bureau of Statistics website (http://www.abs.gov.au/AUSSTATS/abs@.nsf/ViewContent?readform&view=ProductsbyCatalogue&Action=Expand&Num=2.2.). The tables on Income by

Occupation statistics were accessed and income levels for agricultural managers and laborers were obtained. Weighted (weighed by number of persons employed by the agricultural sector in a particular income bracket divided by total persons employed by the agricultural sector) sum of agricultural income was thus calculated in Australian dollars per unit agricultural labor for each of the 3 census years.

In order to convert income per unit labor into rice produced per unit labor, the income per unit labor is multiplied by its US dollar value in the December of that year and dividing it by the real price of Thai 5 % Rice in (2005 US dollar mton^{-1}) for that year. The historical data for US dollar value of AUS dollar was obtained from Reserve Bank of Australia historical monthly exchange rate data set (http://www.rba.gov.au/statistics/hist-exchange-rates/index.html?accessed=2013-09-17-14-08-00) and the price for Thai rice was obtained from the World Bank collection of commodity prices from 1960 to present (http://data.worldbank.org/data-catalog/commodity-price-data).

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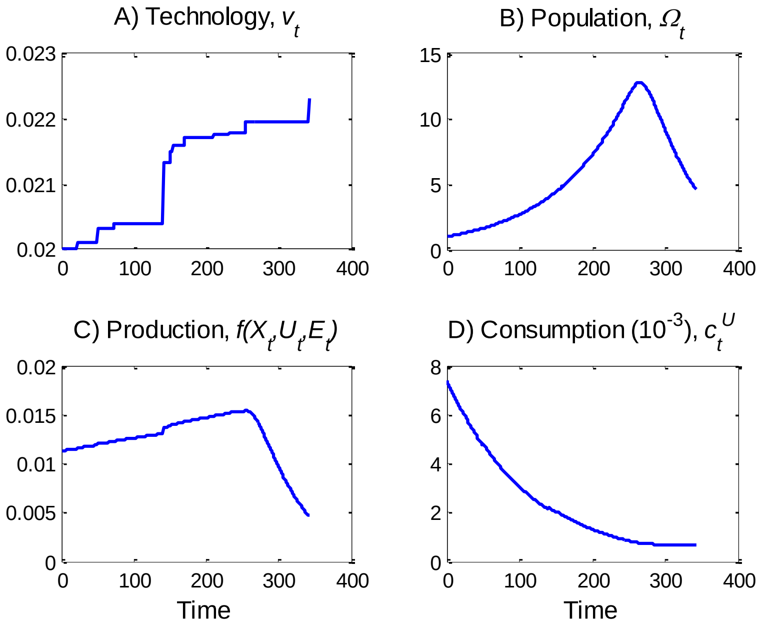

Fig. 1. The co-evolution of technology, population, production and consumption per capita under modest rate of success ($\bar{\gamma} = 0.10$). The population growth rate threshold $\eta = 0.10$. Randomness in technological rate of success is assumed to be gamma distributed with mean $\overline{\gamma}$ and variance $100\bar{\gamma}^2$.

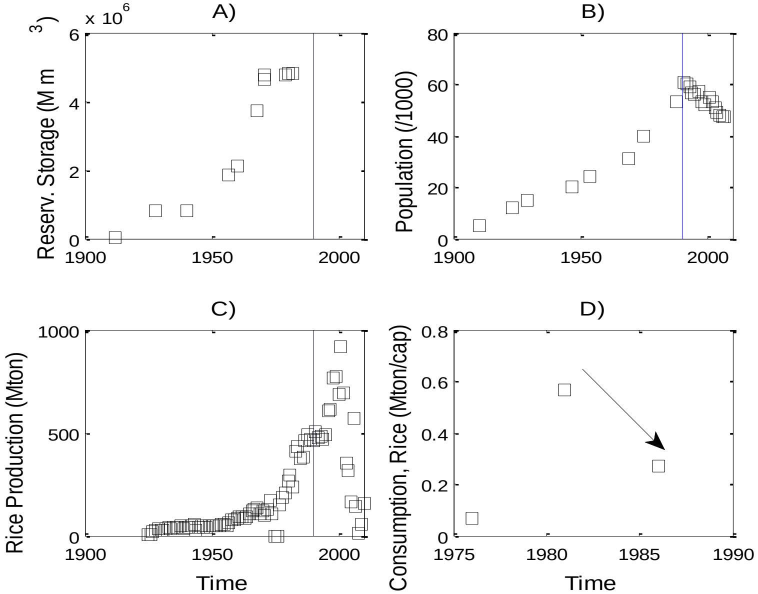

Fig. 2. (A)–(C) Historic reservoir capacity, population and rice production in Murrumbidgee river basin, Australia (Kandasamy et al., 2013). The vertical lines indicate the year 1990. **(D)** Imputed Agricultural Income per unit labor, in units of mton capita^{-1}. Based on New South Wales censuses 1976, 1981, 1986. See appendix on how the values are imputed and converted into rice amounts. A decline in consumption per capita for a decade before 1990 (the year of eventual decline in Murrumbidgee population) is evident.

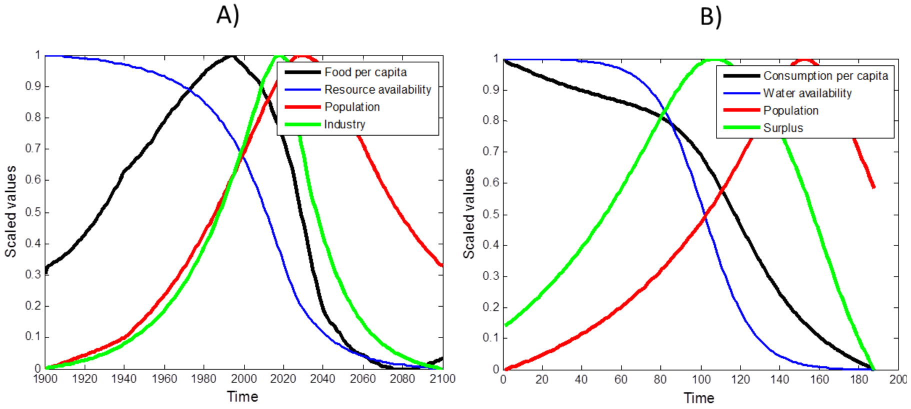

Fig. 3. (A) World3 model output for business as usual scenario (Hayes, 2012). **(B)** Output of the endogenous technological change model presented here. All the variables in both the figures have been scaled between 0 and 1 by subtracting the minimum and dividing by the range. Variables "food per capita", "resource availability" and "industry" in **(A)** are equivalent to "consumption per capita", "water availability" and "surplus" in **(B)**.

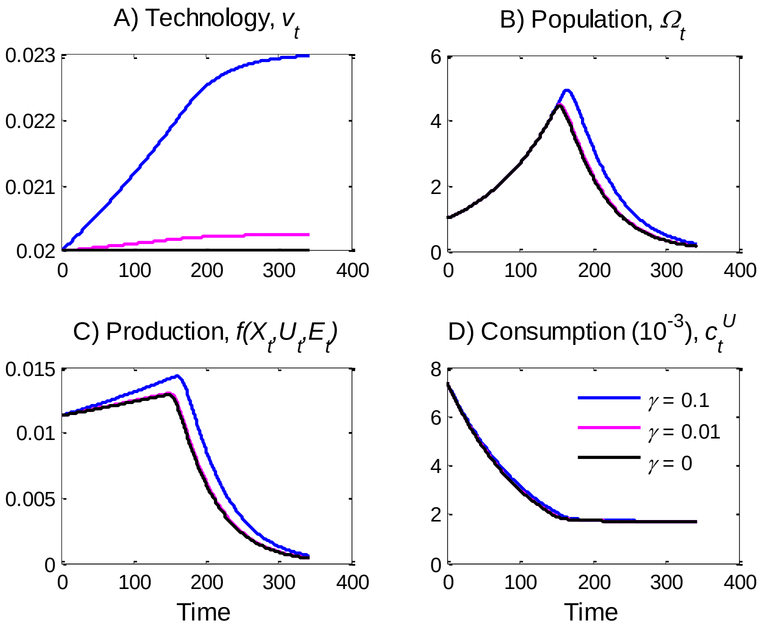

Fig. 4. The co-evolution of technology, population, production and consumption per capita under modest rate of success ($\gamma = 0.10, 0.01$) and no technological change ($\gamma = 0.00$). The population growth rate threshold $\eta = 0.25$. No randomness in technological rate of success is assumed, i.e. $\gamma = \overline{\gamma}$.

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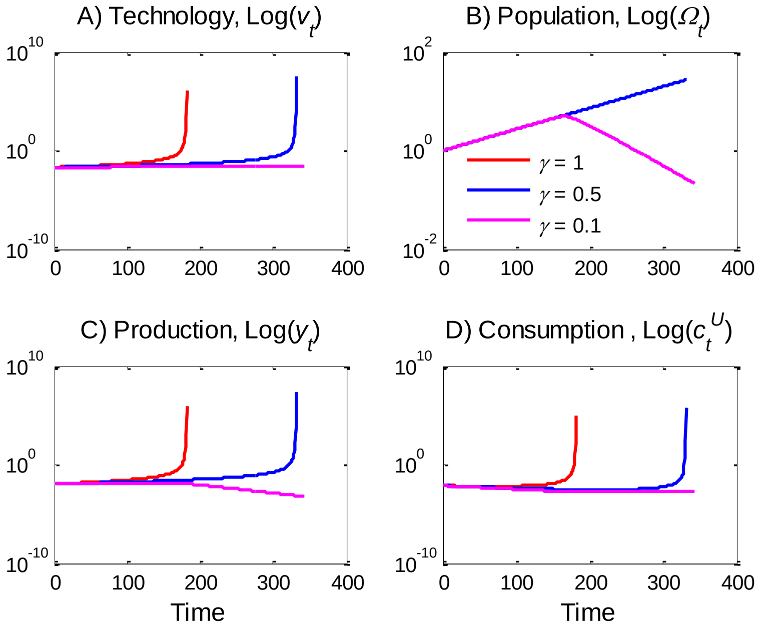

Fig. 5. Technological singularity: the coevolution of technology, population, production and consumption per capita under high rates of success ($\gamma = 0.50, 1.00$) and modest rates of success ($\gamma = 0.10$). The population growth rate threshold $\eta = 0.25$. No randomness in technological rate of success is assumed, i.e. $\gamma = \overline{\gamma}$.

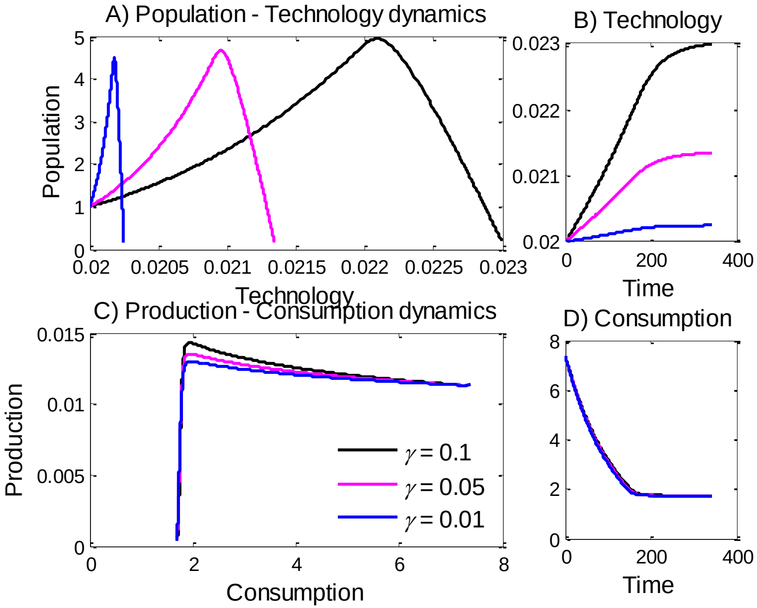

Fig. 6. Population-technology and production-consumption dynamics: the relationship itself evolves over time and varies for different rate of success, $\gamma = \{0.1, 0.05, 0.01\}$ considered. Note that consumption per capita declines even when aggregate production is rising before its eventual decline. The population growth rate threshold is $\eta = 0.25$. No randomness in technological rate of success is assumed, i.e. $\gamma = \overline{\gamma}$.

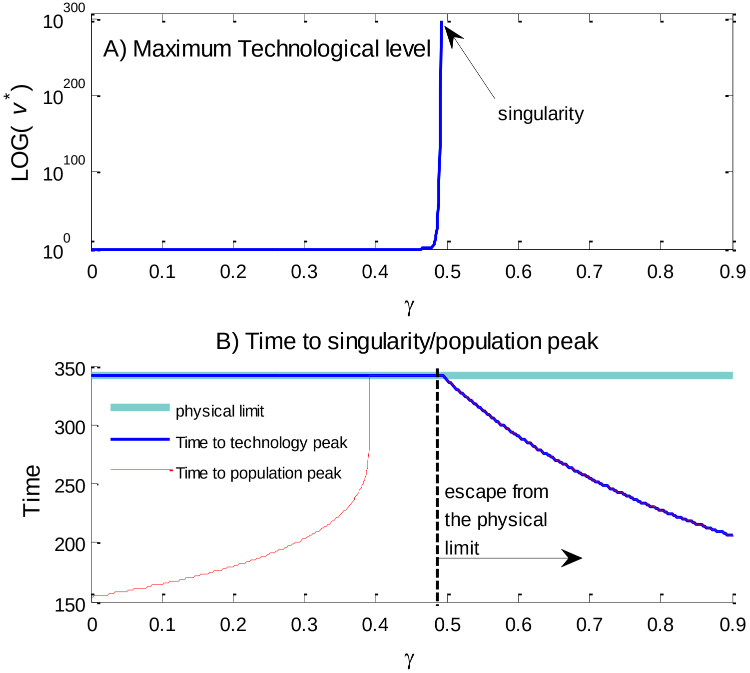

Fig. 7. **(A)** The asymptotic technological level is super-exponential in the rate of success. **(B)** The escape of society from the physical limit beyond the critical rate of success γ_c, when technological singularity appears. Note that for $\gamma < \gamma_c$, the population decline appears before the physical limit of water resource availability is reached, while for $\gamma \geq \gamma_c$, population explosion to infinity (hence its peak) at the same time when technological singularity appears.