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Abstract

This paper derives some possible implications of changing carrying capacity and environmental concerns for human survival. It proposes that even in the absence of any further technological, healthcare, social and international progress, diminishing complacency embarks the global environment and its human population on a course leading to an interior steady state. Therefore, convergence to extinction is not a likely course for a population that, in addition to displaying diminishing complacency toward deteriorating environmental conditions, generates improvements in technology, healthcare and social and international affairs.

1. Introduction

Studies of wildlife population's survival and management typically employ growth functions embodying fixed, exogenously determined carrying capacity (cf., Clark, 1976; Berck, 1979; Berck and Perloff, 1984; Horan and Bulte, 2004). Unlike wildlife, the aggregate footprint of human beings on Earth's environment is large and widespread. The Earth's environment does not have the property of exclusivity. Being an open access resource, it is exploited by human beings beyond its natural regeneration level. The excessive exploitation decreases Earth's carrying capacity, but also evokes concerns for the state of the environment and human beings' survival. Whether the conflict between the environmentally damaging utilitarian activities and the concerns for the environment is resolved in survival, or extinction, of human beings is the subject of this paper.

In their *Limit to Growth*, Meadows, Meadows, Randers and Behrens (1972) come to the conclusion that output-growth would likely not be impeded by lack of resources before it was impeded by severe pollution. Absent in their simulation model of the world is a link between pollution and pollution prevention. The rationale for such a link is growing concerns. Indeed, analyses of the Health of the Planet Survey, the World Values Survey and the International Social Survey Program indicate that during the last twenty years environmental concerns have not only risen in rich countries as advocated by the affluence hypothesis (Diekmann and Franzen, 1999; Franzen, 2003), but also in poor ones (Inglehart, 1995, 1997; Dunlap, Gallup and Gallup, 1993; Dunlap and Mertig, 1997). Supporting arguments and evidence of rising environmental concerns are also given by studies of the Environmental Kuznets Curve including Shafik and Bandyopadhyay (1992), Selden and Song (1994), Grossman and Krueger (1995), Arrow et al. (1995), Chaudhuri and Pfaff (1998), Andreoni and Levinson (2001) and Chavas (2004).

In his *A Question of Balance*, Nordhaus (2008) provides an integrated assessment model for global warming. Unlike Meadows et al.'s *Limit to Growth* (1972), his DICE model has a feedback loop between the atmospheric carbon dioxide and abatement activities. Optimal aggregate feedback is assumed and, in view of the modest abatement costs estimated in the Intergovernmental Panel on Climate Change's Assessment Reports, environmental catastrophe is not predicted. However, optimal aggregate feedback is too strong an assumption. Lack of exclusivity encourages free riding in sharing the costs of abatement activities. The larger the costs of abatement activities the stronger the inclination to free ride. Recalling Mendelsohn's (2008) arguments, the full costs of abatement activities are not modest. In which case, the real system of the environment and human population is likely to have a suboptimal feedback.

We conduct a theoretical investigation of the possible joint course of the environment and human population and its implications for survival within a deterministic environment and population (E-P) model. Shocks (solar plasma bursts, volcanic eruptions, meteor collision and nuclear accidents) are ignored. We treat the whole biosphere as an open access resource and consider a Lotka (1925)-Volterra (1931) type of *ad hoc* feedback mechanism. In our E-P model, Earth's carrying capacity declines as the environment deteriorates and the intensity of the feedback is associated with the human population's aggregate level of environmental concerns. Exposure to environment that is different from a complacency threshold state changes awareness of the looming environmental-population mutual destruction and, consequently, the aggregate level of environmental concerns.

2. E-P model with changing carrying capacity and environmental concerns

Our E-P model comprises the motion equations of the physical environment and human population. While the size of Earth's physical environment is (roughly) fixed, the quality of Earth's environment (defined as the suitability of Earth's environment for human life) may vary over time. We denote Earth's quality adjusted physical environment by $E \in \mathbb{R}_+$ and the population of human beings by $P \in \mathbb{R}_+$.

We assume that the physical environment is naturally improved at any instance *t* in a manner that can be approximated by the following regeneration logistic function:

$$G_e(t) = g_e E(t)\left(1 - \frac{E(t)}{E_{\max}}\right) \tag{1}$$

where g_e and $E_{\max}$ are positive scalars representing the environment's intrinsic improvement (recovery) rate and the maximal quality adjusted physical environment, respectively.

We further assume that the weaker the humans' concerns for the physical environment, *ceteris paribus*, the larger their production and consumption footprints on the physical environment. We consider humans to be quality responsive: as the environment deteriorates, awareness of, and, in turn, concerns for, the state of the environment are intensified. These assumptions are displayed by the incorporation of a complacency threshold: a quality adjusted physical environment, E_{comp} ($E_{comp} < E_{\max}$), above (below) which the individual footprint (IFP) on the environment is larger (smaller) than a positive scalar β. We refer to β as the footprint-complacency coefficient. This feedback is represented by the following *ad hoc* behavioral rule:

$$IFP(t) = \beta \frac{E(t)}{E_{comp}}. \tag{2}$$

Since there are P people (identical, for tractability), each detracting IFP from the environmental stock, the change of the quality adjusted physical environment is:

$$\dot{E}(t) = G_e(t) - IFP(t)P(t) = g_e E(t)\left(1 - \frac{E(t)}{E_{\max}}\right) - \beta \frac{E(t)}{E_{comp}} P(t). \tag{3}$$

Due to the fixed size of Earth's physical environment, a carrying capacity is incorporated into the formalization of the human population growth. We assume that humans cannot prevail in a quality adjusted physical environment lower than E_{ext}. We refer to E_{ext} as the extinction threshold. We further assume that at any point in time the physical environment's carrying capacity of human population ($\hat{P}(t)$) rises with the current deviation of the quality adjusted physical environment from the extinction threshold, and that the rise is amplified by improvements in technology, healthcare, social interaction and international relations. For instance, higher environmental quality in the form of lower greenhouse-gas concentrations results in higher potential food production, which is further increased by improvements in cultivation methods, in farmers' information, cooperation, healthcare and property rights, and in national and international security and marketing opportunities. Consequently, we specify the physical environment's capacity to carry humans as:

$$\hat{P}(t) = (\alpha + \gamma t)[E(t) - E_{ext}] \tag{4}$$

where $\alpha > 0$ and $\gamma \geq 0$ are scalars. The term $(\alpha + \gamma t) > 0$ is the inverse of the stock of the extra (beyond the extinction threshold) quality adjusted environmental resources required for sustaining a human being. We assume that improvements in technology, healthcare, social capital and international cooperation reduce this per capita environmental stock. Hence, a continuous overall technological, healthcare, social and international cooperation progress is depicted by $\gamma > 0$, whereas stagnation is represented by $\gamma = 0$. Though not consider in this paper, $\gamma < 0$ is possible. In particular, international relations might deteriorate to a destructive conflict that more than offset the carrying-capacity gains from improvements in production and healthcare technologies. The positive scalar α can be interpreted as the inverse of the stock of the quality adjusted extra environmental resources required for sustaining a human being under a perpetual stagnation. The multiplicative specification reflects that, even in the presence of a continuous combined technological, healthcare, social and international relation progress, the carrying capacity of Earth might decline as the physical environment deteriorates and vanishes when the extinction threshold is reached.

By incorporating the said specification of the carrying capacity into a logistic growth function, the motion-equation of the human population is:

$$\dot{P}(t) = g_p P(t)\left(1 - \frac{P(t)}{(\alpha + \gamma t)[E(t) - E_{ext}]}\right) \tag{5}$$

where g_p is a positive scalar indicating the human population's intrinsic growth rate.

The motion equations (3) and (5) constitute our E-P model. The implications of this model for the joint dynamics of the environment and human population are investigated in the following sections.

3. Unique, interior steady state in the absence of progress

A continuous combined process of technological, healthcare, social and international relation improvements ($\gamma > 0$) renders the differential equation-system (3) and (5) non-autonomous and hence precludes interior steady states in the E-P model. We ask whether such a multi-facet progress also prevents the E-P model from having a corner steady state – inhabitable planet. We claim that coupled with diminishing complacency it does. We support this claim by demonstrating that even in the absence of future technological, healthcare, social and international cooperation changes ($\gamma = 0$), the quality adjusted physical environment does not converge to E_{ext} and the human population is not driven to extinction, but rather converges to an interior steady state.

Recalling equations (3) and (5) and assuming that $\gamma = 0$, the isocline $\dot{E} = 0$ is given by $E = E_{\max} - [(\beta E_{\max})/(g_e E_{comp})]P$ and the isocline $\dot{P} = 0$ by $E = E_{ext} + (1/\alpha)P$. Since the intercept of the negatively sloped isocline $\dot{E} = 0$ is larger than the intercept of the positively sloped isocline $\dot{P} = 0$ these linear isoclines intersect one another once, and their intersection point is in the positive orthant of the $P - E$ plane. That is, in the absence of further technological, healthcare, social and international progress, or regression, there exists a unique, interior steady state.

The distance between the stationary quality adjusted physical environment and the extinction threshold is:

$$E^* - E_{ext} = \frac{1}{\alpha}\left(\frac{E_{\max} - E_{ext}}{\frac{1}{\alpha} + \frac{\beta E_{\max}}{g_e E_{comp}}} \right). \tag{6}$$

The stationary human population is:

$$P^* = \frac{E_{\max} - E_{ext}}{\frac{1}{\alpha} + \frac{\beta E_{\max}}{g_e E_{comp}}}. \tag{7}$$

Equations (6) and (7) suggest that as long as the lack of progress is not accompanied by absolute complacency ($E_{comp} = 0$) the stationary quality adjusted physical environment is better than the extinction threshold (E_{ext}) and, consequently, the stationary human population is not nil. The higher the population's complacency threshold (E_{comp}), the more distant the stationary quality of the physical environment from the extinction threshold and, due to a greater carrying capacity, the larger the stationary population of human beings. These equations also suggest that the stationary population and the stationary quality adjusted physical environment increase with the environment's intrinsic recovery rate (g_e) and the maximal quality adjusted physical environment ($E_{\max}$), and decrease with the footprint-complacency coefficient (β). The stationary population also decreases with the extinction threshold (E_{ext}). The stationary population further decreases with the stock of the quality adjusted extra environmental resources required for sustaining a human being under perpetual stagnation ($1/\alpha$). As the subsequent positive effect of the population decline on the stationary quality of the environment can be dominated by the larger per capita requirement of environmental stock, $\partial(E^* - E_{ext}) / \partial(1/\alpha) = \{1 - 1/[1/\alpha + \beta E_{\max} / g_e E_{comp}]\} P^*$ is not necessarily positive.

4. Is there convergence to the unique, interior steady state?

In order to answer this question we evaluate the Jacobian of the E-P model's motion equations (3) and (5) with $\gamma = 0$ in the steady state indicated by (6) and (7):[1]

$$J = \begin{bmatrix} \partial \dot{E}(*) / \partial E & \partial \dot{E}(*) / \partial P \\ \partial \dot{P}(*) / \partial E & \partial \dot{P}(*) / \partial P \end{bmatrix} = \begin{bmatrix} [g_e - 2\dfrac{g_e}{E_{\max}} E^* - \beta \dfrac{P^*}{E_{comp}}] & -\beta \dfrac{E^*}{E_{comp}} \\ \alpha g_p & -g_p \end{bmatrix}. \quad (8)$$

The characteristic roots of this Jacobian are:

$$\lambda_{1,2} = 0.5\{g_e - [g_p + 2\frac{g_e}{E_{\max}} E^* + \beta \frac{P^*}{E_{comp}}]$$
$$\pm \sqrt{\{g_e - [g_p + 2\frac{g_e}{E_{\max}} E^* + \beta \frac{P^*}{E_{comp}}]\}^2 + 4 g_p [g_e - 2\frac{g_e}{E_{\max}} E^* - \beta \frac{P^*}{E_{comp}}] - 4\beta \frac{E^*}{E_{comp}} \alpha g_p} \quad .(9)$$

A priori, the signs of these characteristic roots are not clear. Yet insight about the possibility of convergence to steady state can be gained from inspecting the off-diagonal elements of the Jacobian. As $\partial \dot{E}(*) / \partial P = -\beta E^* / E_{comp} < 0$, the vertical arrows in the phases above (below) the isocline $\dot{E} = 0$ point downward (upward). As $\partial \dot{P}(*) / \partial E = \alpha g_p > 0$, the horizontal arrows point rightward (leftward) in the phases above (below) the isocline $\dot{P} = 0$. The directions of the horizontal and vertical arrows imply convergence to the steady state from any initial combination of population and quality adjusted physical environment, possibly along a clockwise spiraling trajectory, as displayed in Figure 1. In order to explore this possibility, note that the discriminant in equation (9) can be expressed as:

$$\Delta = (trJ)^2 + 4g_p(trJ + g_p) - 4\alpha\beta g_p(E^* / E_{comp})$$
$$= (trJ + 2g_p)^2 - 4\alpha\beta g_p(E^* / E_{comp}). \quad (10)$$

A converging spiral trajectory exists when $\Delta < 0$ and $trJ < 0$. From equation (10), $\Delta < 0$ as long as:

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[1] Recalling that $E^* = E_{ext} + (1/\alpha)P^*$, $\partial \dot{P} / \partial E = \alpha g_p P^{*2} / [\alpha(E^* - E_{ext})]^2 = \alpha g_p$ and $\partial \dot{P} / \partial P = g_p - 2g_p P^* / [\alpha(E^* - E_{ext})] = -g_p$.

$$\frac{E^*}{E_{comp}} > \frac{(trJ + 2g_p)^2}{4\alpha\beta g_p}. \qquad (11)$$

Recalling that

$$trJ = g_e - \left[g_p + 2g_e \frac{E^*}{E_{\max}} + \beta \frac{P^*}{E_{comp}} \right] \qquad (12)$$

then $trJ < 0$ as long as

$$\frac{g_p}{g_e} > 1 - \left[2\frac{E^*}{E_{\max}} + (\beta / g_e) \frac{P^*}{E_{comp}} \right]. \qquad (13)$$

In a world where the human population's intrinsic growth rate is larger than the environment's intrinsic recovery rate, $trJ < 0$. More generally, $trJ < 0$ in a world where the human population's intrinsic growth rate is larger than $[1 - 2E^* / E_{\max} - (\beta / g_e) P^* / E_{comp}] g_e$.

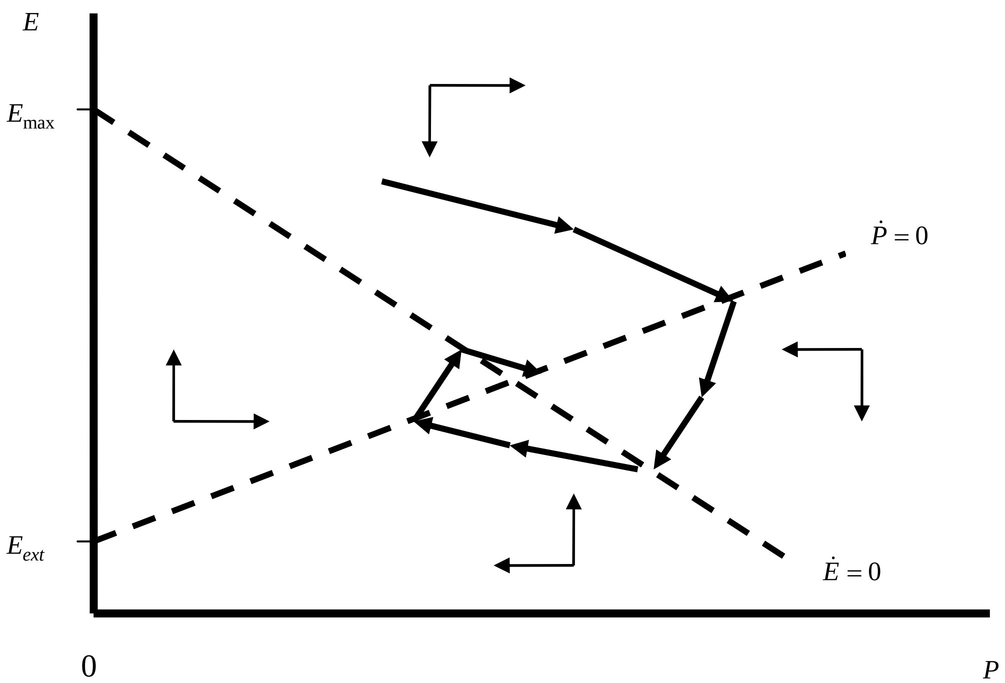

Figure 1. Population and the environment in the absence of progress

5. Conclusion

This paper derives the implications of the opposing endogenously generated phenomena – declining carrying capacity due to excessively damaging production and consumption activities and growing aggregate concerns – for the dynamics of the environment and human population. It proposes that even in the absence of any further technological, healthcare, social and international cooperation improvements, the resultant autonomous ecological system comprising an environment with sensitive carrying capacity and inhabitants with decreasing environmental complacency has a unique, interior, asymptotically stable steady state. It further proposed that if $E^* / E_{comp} > (trJ + 2g_p)^2 / 4\alpha\beta g_p$ and $g_p > [1 - 2E^* / E_{\max} - (\beta / g_e)P^* / E_{comp}]g_e$, the converging joint course of the human population and the environment is displayed by a clockwise spiraling trajectory. These propositions can be subjected to empirical test if a sufficiently long time-series of the world's population and environment exists.

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