A contribution to the qualitative, interdisciplinary modeling of environmental development

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A Contribution to the Qualitative, Interdisciplinary Modeling of Environmental Development

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Abstract. We suggest a simple, interdisciplinary, qualitative, system-theoretical model of long-run environmental development, where the dynamics of environmental quality are determined by the interactions across the political, economic, ecological/natural, and socio-cultural systems. The resulting model is a self-regulating feedback-loop system and can be used to explain the existence and the characteristics of different empirically observable economic/societal development stages (pollution phase and ecological phase) and environmental and economic policy-regime switches consistent with empirical evidence.

Keywords: environmental quality, environmental pollution, long-run dynamics, development, growth, development stages, policy-regime switches, economic, socio-cultural, political, ecological, qualitative, system theory, feedback loop, self-regulation.

JEL-Codes: Q56, O1, A12

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1. Introduction

A large body of literature deals with the long-run development of environmental quality (see Dinda, 2004, and Stern, 2004, for an overview of empirical evidence and theoretical contributions). While the exact dynamics of environmental quality and, in particular, the 'environmental Kuznets curve' are discussed controversially in the literature, it seems that there is a consensus on the fact that environmental quality deteriorates strongly over some earlier stages of development, while at later stages of development, the environmental deterioration at least slows down (where the time points and income levels at which these two phases begin may differ significantly across countries).

Clearly, the analysis of environmental long-run development requires an interdisciplinary approach/model (henceforth, 'PENS model') capturing the relevant interactions across the political (P), economic (E), ecological/natural (N), and socio-cultural (S) systems of a country.[1] One of the major challenges in the analysis of complex social-technological systems such as the PENS model is the fact that *quantitative* modeling of such systems requires strong assumptions regarding the behavior of system elements, which are difficult to support by theory and evidence (particularly due to the social component of social-technological systems) and may lead to odd model results or implications; thus, a *qualitative* analysis focusing on feedback loops in social-technological systems seems advantageous (see Coyle, 2000, for a detailed discussion). Moreover, considering the literature's controversies regarding the *quantitative* aspects of environmental dynamics, a *qualitative* analysis of environmental development seems adequate.

For all these reasons, we focus on the qualitative, interdisciplinary modeling of long-run environmental quality dynamics in our paper. In particular, we build a very simple, qualitative PENS model, where the PENS systems interact via environmental pollution, natural resource use, utility derived from economic standard of living (e.g., via consumption) and environmental quality, societal support of the economic system, economic policy, and social choice of the policy/political regime/leaders. We analyze this model upon existence of feedback loops/cycles among its components. As we show, there are *feedback cycles* in the economic-political-socio-cultural (EPS) subsystem and in the economic-socio-cultural (ES) subsystem. In particular, these cycles lead to a dynamic state of increasing (a) economic activity, (b) socio-cultural support of the economic system and the policy regime, and (c) environmental devastation and resource depletion, which we name 'pollution phase'. However, the feedback cycles that constitute the pollution phase are counteracted/regulated by *half-cycles/mechanisms* in the economic-natural (EN) subsystem, economic-natural-socio-cultural (ENS) subsystem, and the overall PENS system, which reduce economic growth and the socio-cultural support of the economy/policy due to the negative effects of environmental pollution and may lead to a political regime switch entailing a more environment-friendly policy and slower growth, a phase which we name 'ecological phase'. That is, the PENS system is a self-regulating system, where the feedback cycles are regulated/restricted by half-

[1] The PENS system view has been used in the previous literature. Habermas (1973) applies the PENS model in the comparative analysis of economic systems. Wagner (2017, 2018a) discusses, among others, the challenges of the growth strategy of the Peoples Republic of China from the PENS view and notes that, e.g., pollution may endanger the current policy regime. Wagner (2018b) notes the importance of PENS modeling in stability policy (stabilization of macroeconomic short-run fluctuations).

cycles, such that environmental pollution is limited to some extent. The length (and other characteristics) of the pollution phase depend on different factors in our model (among others preferences, technologies, and political stability); thus, it is not surprising that the empirical research discussed at the beginning of this section has difficulties in finding definite income levels at which phase/policy-regime switches occur. If we assume that the marginal utilities of consumption and environmental quality are decreasing (i.e., the second derivatives of the utility function are negative), there occurs a policy-regime switch in general, i.e., the society switches from the pollution phase to the ecological phase. We show that this result can be used (in conjunction with other development literature) to justify a three-stage model of environmental development, while being consistent with the empirical evidence discussed at the beginning of this section.

The primary aim of our paper is to motivate the application and demonstrate the applicability of interdisciplinary, qualitative (feedback-loop) analysis propagated by Coyle (2000) in (economic/societal) development theory and, in particular, in environmental development theory. Thus, we have chosen a relatively simple version of the PENS model. However, as discussed in Section 5, there is large scope for extensions of our basic model, their theoretical foundations, and more complex tools of analysis. In general, the system-theoretical treatise of development phenomena, which is the topic of our paper, seems an interesting complement to the standard approaches used in economic/societal development theory: The latter approaches deal with very specific channels of interactions across very specific variables of the PENS sub-systems (see Stijepic, 2018, for a discussion), while the system-theoretical approach provides rather an overview of the different channels. Beyond its methodical contribution (application of qualitative system-theoretical analysis), our paper contributes to the development literature dealing with stages of economic/societal development (e.g., Fourastié, 1949, and Rostow, 1978) and to the structural change literature dealing with industrialization and de-industrialization (e.g., Kongsamut et al., 2001, Schettkat and Yocarini, 2006, Krüger, 2008, Stijepic, 2015, 2017, and van Neuss, 2018). Moreover, obviously, it is a contribution to the empirical and theoretical literature on environmental development discussed at the beginning of this section.

The next section discusses the model assumptions. Section 3 explains the model results (feedback cycles, regulatory half-cycles, characteristics of the phases, and their determinants). The implications of these results for a three-stage model of environmental development are discussed in Section 4. Concluding remarks are provided in Section 5.

2. Assumptions

Our model is based on four indices: political regime index (p), economic activity index (e), environmental quality index (n), and socio-cultural index (s), all of which are real-valued. We assume that these indices do not only depend upon each other but also on other/exogenous variables, which we will not state here explicitly. Moreover, to avoid complex notation, e.g., the usage of differential equations and integrals, we express only the tendencies regarding the effects of indexes on each other. For doing so, we use the following notation: If there is a relation between two or more indexes, this relation is expressed by an arrow, where the variables that are listed at the tail of the arrow (and separated by commas) have an impact on the variable that is located at the tip of the arrow. The index (+) associated with a variable

listed at the tail of an arrow indicates that this variable has a positive effect on the variable located at the tip of the arrow. Analogously, the index (–) indicates that the variable has a negative effect on the variable located at the tip of the arrow. The model assumptions can, then, be summarized as follows.
Economic activity (*e*) has a negative impact on the environmental quality (*n*) via, e.g., the environmental pollution caused by industrial production and transport.

(1) $e^{(-)} \rightarrow n$

The socio-cultural index (*s*) expresses the satisfaction of the society with the current state (of society, economy, and politics). We assume that the society draws utility from economic activity (*e*) via, e.g., consumption of goods, and from environmental quality (*n*). Thus, the greater *e* and *n* are, the greater the satisfaction *s* is.

(2) $e^{(+)}, n^{(+)} \rightarrow s$

The satisfaction of the society is deciding for its support of the policy regime. We assume that in the initial state, policy regime π_2 is established. If the satisfaction of the society (*s*) falls below a certain level (σ), then the society enforces a policy regime change, i.e., policy regime π_2 is replaced by policy regime π_1, where $\pi_2 > \pi_1$.

(3) $(p = \pi_2 \text{ if } s > \sigma)$ and $(p = \pi_1 \text{ if } s < \sigma)$

The economic activity index (*e*) is influenced by the other indexes along three channels. First, we assume that the policy regime π_2 is supportive of quick expansion of economic activity, while the policy regime π_1 allows for only relatively slow expansion of economic activity due to stronger environmental protection. Thus, the greater *p* is, the greater *e* is. Second, societal satisfaction (*s*) has a positive effect on economic activity (*e*). This is a lesson from economies plagued by crises, poor economic conditions, or, more generally, dissatisfaction with the current economic (and political) system, where full commitment (of capital and labor) in (legal) economic activities is depressed and incentives for rent seeking (e.g., economic crimes, corruption) and black market formation are increased. In general, this impact channel (of social satisfaction on economic activity) may not exist at all stages of development; however, it seems worthwhile being considered. Third, following Arrow et al. (1995) and Stern (2004), we assume that environmental damage has negative feedbacks on the economic system, i.e., the lower *n* is, the lower *e* is.

(4) $p^{(+)}, s^{(+)}, n^{(+)} \rightarrow e$

We turn now to the implications of the model described in this section.

3. Results

Figure 1 summarizes the model described Section 2, where the Arabic numbers (1)-(4) refer to the assumptions (1)-(4) introduced in Section 2, and the arrows and signs (+ and –)

indicate the effects of variables on each other following the convention introduced in Section 2.

Figure 1

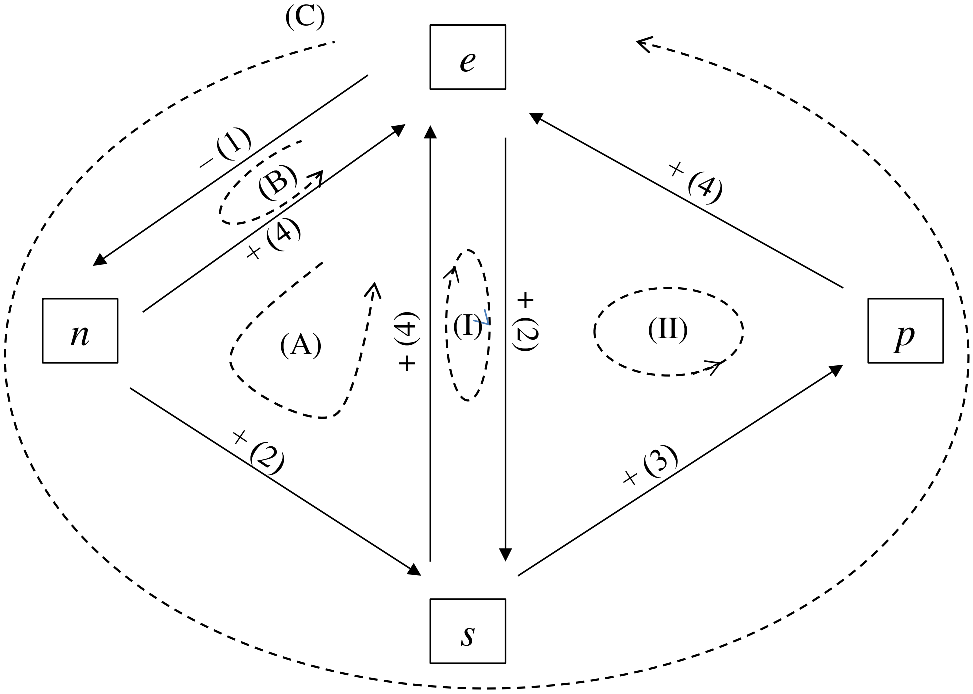

Figure 1 highlights that our assumptions imply that there are two feedback loops/cycles (denoted by dashed, closed curves and the Roman numbers (I) and (II)) and three regulatory half-cycles/mechanisms (denoted by dashed, open curves and the letters (A), (B), and (C)). We explain them in the following.

Feedback loop (I) arises due to the interaction between the economic and social-cultural systems. According to (2), a (significant) increase in economic activity (*e*), may increase the satisfaction (*s*) of the society with the current system (e.g., via increased consumption and investment possibilities) and, thus, may increase the efforts/commitment of the society members when engaging in (legal) economic activities (cf. Section 2), which has a positive effect on economic activity via (4). Thus, we have a feedback loop, such that increases in *e* and *s* can go on for some time ceteris paribus. As noted in Section 2, the effect of *s* on *e* may be of relevance only at some specific development stages (or only in some countries with specific socio-economic conditions, e.g., (post-)socialist countries). Thus, the feedback loop (I) may generate only transitory growth effects. However, even transitory processes can be prolonged and can have strong cumulative effects. Thus, they are not necessarily neglectible.

Feedback loop (II) states that, if a policy regime that is supportive of economic expansion (via (4)) is established (i.e., $p = \pi_2$; cf. (3)), then the satisfaction of the society (*s*) grows via (2) and, thus, the support of the policy regime (*p*) grows via (3). That is, a growth supporting policy regime (π_2) will not be replaced ceteris paribus; once it is established, it lasts forever (unless the regulatory cycles discussed below intervene). However, even this feedback loop may generate only transitory dynamics depending on the assumptions. Exactly speaking, whether the feedback loop (II) is able to generate permanent growth (when neglecting the regulatory cycles discussed below) depends on the nature of the economic system (*e*) and the effectiveness of the policy system (*p*) as a driver/supporter of economic growth. For example, endogenous (economic) growth theories (e.g., Romer, 1994) imply that permanent growth can exist under good institutional/political conditions (if environmental effects, i.e., the regulatory cycles discussed below, are neglected), while other theories (e.g., the classical political economy) are pessimistic about the (very) long-run growth prospects of (capitalist/market) economies. Needless to say that the whole economic growth theory deals with the topic of the possibility of permanent growth under 'good' political support (see, e.g., Barro and Sala-i-Martin, 2004, for an overview).

We can see that feedback loops (I) and (II) are not working against each other but are supporting each other. In particular, the increases in *s* generated by loop (I) help to support policy π_2 and, thus, support loop (II). The latter generates an increase in *e*, which supports loop (I). This mutually supporting behavior of the two loops is geometrically manifested in Figure 1 by the fact that the two neighboring loops (I) and (II) on the graph depicted in Figure 1 describe cyclical dynamics with different directions (clockwise vs. counterclockwise), which is a property of orientable graphs/complexes (see Figure 1).

The increases in economic activity (*e*) generated by feedback loops (I) and (II) generate decreases in quality of environment (*n*) via (1). This gives rise to three regulatory mechanisms of development and pollution, which counteract/regulate the feedback loops (I) and (II) via negative feedbacks, as depicted by Figure 1: *Regulatory half-cycle (A)* works within the economic-environmental/natural-socio-cultural (ENS) subsystem of the PENS model: economic activity (*e*) reduces environmental quality (*n*) via (1) and, thus, social satisfaction (*s*) via (2) and, thus, economic activity via (4). *Regulatory half-cycle (B)* works within the economic-environmental/natural (EN) subsystem of the PENS model: economic activity (*e*) reduces environmental quality (*n*) via (1), which has a negative feedback on economic activity via (4). *Regulatory half-cycle (C)* works over the whole PENS system: economic activity (*e*) reduces environmental quality (*n*) via (1) and, thus, social satisfaction (*s*) via (2) and, thus, endangers the policy regime (*p*) via (3) that drives economic activity via (4).

Note that the regulatory cycle (C) may take a lot of time before taking effect, since the policy system (*p*) has homeostatic characteristics: The social satisfaction (*s*) may be declining over long periods without changing the policy regime (*p*). However, as soon as the environmental quality and, thus, the satisfaction falls below a certain satisfaction level (σ), the policy regime is changed. That is, the growth enhancing regime may be prolonged.

The three regulatory cycles (A)-(C) have the same (counterclockwise) orientation, i.e., they are supportive of each other. Each of the cycles (A)-(C) arises due to the fact that economic activity (*e*) has a negative impact on environmental quality (*n*), and each of the cycles (A)-(C) feeds back to the economic system (by reducing the rate of economic expansion). That is, the economic system is not only the source but also the target/destination of the regulatory cycles (A)-(C). The environmental/natural system determines the sign of the effect transported via the half-cycles (A)-(C): as we can see in Figure (1), in each of the three cycles (A)-(C), the connection to the environmental/natural system has a negative sign, while all other connections have positive signs. While the cycle (B) immediately loops back from the environmental/natural system to the economic system, cycle (A) has the socio-cultural system as an (additional) intermediary, and cycle (C) has the socio-cultural and political systems as (additional) intermediaries.

By now, our discussion shows that, if the society establishes the policy regime π_2, it enters a phase of economic expansion and decreasing environmental quality due feedback loops (I) and (II). We name this phase *pollution phase.* The feedback loops (I) and (II) are counteracted by the regulatory mechanisms/half-cycles (A)-(C), such that, in general, the pollution phase comes to an end and a new phase, which we name *ecological phase*, is initiated by the replacement of policy π_2 by policy π_1, where the latter is characterized by weaker economic expansion and weaker environmental deterioration. The high rate of economic expansion during the pollution phase is reduced by the negative effects of decreasing environmental quality and decreasing social satisfaction on economic activity (half-cycles (B) and (A)). Moreover, a policy regime change and, thus, an end of the pollution phase may be initiated by increasing social dissatisfaction (half-cycle (C)) as explained above.

The characteristics of the pollution phase depend on the relative strength of the regulatory mechanisms (A), (B), and (C) among others. In particular, it can happen that due to regulatory mechanisms (A) and (B), the rate of economic expansion decreases over a long period of time (while the environmental quality decreases as well) before a policy regime switch (to the environment-friendly policy π_1) occurs via mechanism (C). On the other hand, if mechanism (C) is relatively strong, the society may switch relatively quickly to the ecological phase.

At this place, the question about the exact determinants of the length of the pollution phase arises. To answer this question, we specify the assumptions made in Section 2 by assuming that (a) the society seeks to maximize the concave utility function (u) as stated by (5) and (b) the societal satisfaction depends positively on this utility as stated by (6).

(5a) $\max_{(e,n)} u$

(5b) $u: \mathbb{R}\times\mathbb{R}\to\mathbb{R}$

(5c) $u = u(e, n)$

(5d) $\partial u/\partial e > 0$

(5e) $\partial u/\partial n > 0$

(5f) $\partial^2 u/(\partial e)^2 < 0$

(5g) $\partial^2 u/(\partial n)^2 < 0$

(6a) $s: \mathbb{R}\to\mathbb{R}$

(6b) $s = s(u)$

(6c) $ds/du > 0$

Assumptions (5) and (6) allow us to explain the switch from the policy π_2 and the pollution phase to the policy π_1 and the ecological phase by using standard economic arguments: Neglect for a moment the mechanisms (A)-(C), which are, anyway, supportive of the following argumentation. Then, under policy π_2, e grows quickly, and n decreases quickly. This implies in conjunction with (5) (and, in particular, with the *concavity assumption* (5d)-(5g)) that the marginal utility of n increases quickly and the marginal utility of e decreases quickly, such that at some point of time, the utility *u* (cf. (5)) begins to decrease (unless it is already decreasing) and, thus, *s* begins to decrease (cf. (6)). This process of declining *u* and *s* continues until $s < \sigma$. Then, the society enforces a policy regime switch, i.e., policy π_1 is established (cf. (3)), which means slower economic growth and more environmental protection (cf. Section 2). In other words, the ecological phase is initiated. In a model of a rational representative household with perfect foresight, the policy regime switch may happen even earlier, since the household foresees that *n* and, thus, the utility may continue decreasing even after the regime switch. However, the assumption of a rational representative household with perfect foresight seems highly questionable in the context of collective environmental decision making, which is characterized by externality (free rider) and public choice problems. Thus, our rather crude model of Section 2 and the argumentation via cycles (A)-(C) seem preferable. Nevertheless, the utility and representative-household related argumentation highlights one important fact: If we want to ensure that a policy switch occurs, we have to assume that policy π_1 is not only environment-friendlier than policy π_2 but also ensures a certain economic wellbeing since the society requires both, economic and environmental wellbeing.

This discussion shows that decreasing marginal utilities of economic activity (*e*) and environmental quality (*n*) can ensure a switch of the policy regime, i.e., an end of the pollution phase and the beginning of the ecological phase. Moreover, if

(a) the expansion of economic activity (*e*) is relatively weak,

(b) the deterioration of environmental quality (*n*) is relatively strong,

(c) the utility function is such that the marginal utilities decrease strongly (cf. (5)), or

(d) the policy regime π_2 does not, anyway, have a strong support in the society, i.e., *s* is close to σ (cf. (3)),

then the pollution phase is relatively short ceteris paribus. Thus, the length of the pollution phase depends not only on utility parameters (cf. (c)) and the general stability of the policy regime (cf. (d)) but also on the technology(-policy). In particular, if the economic policy π_2 supports an inferior technology that generates relatively slow economic expansion or a relatively strong degradation of environmental quality (cf. (a) and (b)), then the pollution phase ends very quickly. The same is true if the chosen technology is not (only) the result of policy decision but (also) of poor technological possibilities (as in many developing countries). These facts are potential explanations of the cross-country differences regarding the time-points and income levels at which the ecological phase begins.

The same arguments apply as well to the effectivity of regulatory mechanisms (A)-(C), i.e., to the question of how quickly the regulatory mechanisms (A)-(C) enforce the beginning of the ecological phase. The effectiveness of the regulatory mechanism (A) is not only determined by the points (a)-(d) but also by the strength of the effect of *s* on *e* via (4), i.e., on the strength of the direct dependency of economic activity on socio-cultural support discussed in Section 2. Similarly, the effectiveness of regulatory mechanism (B) depends on the elasticity of economic activity with respect to natural quality changes via (4) (cf. Section 2) in addition to the points (a)-(d). The effectiveness of regulatory mechanism (C) depends primarily on the points (a)-(d).

Overall, our results imply that the cross-country differences in the time-points and income levels at which the ecological phase is initiated can be explained by cross-country differences regarding:

(i) preferences (particularly, the degree of concavity of the societal utility function),

(ii) technology frontiers (particularly, the feasibility of the technology to generate quick economic expansion or low environmental impact (clean vs. dirty technology)),

(iii) technological proficiency/efficiency of the political system (particularly, the question of whether the political system chooses/supports a technology that is at the technology frontier or a technology that is inferior regarding the economic growth potential and environmental pollution),

(iv) general support of the political regime (particularly, the question of whether the regime is close to an overthrow for reasons other than economic and ecological ones),

(v) the direct dependency of economic expansion on societal support/satisfaction, i.e. the dependency of economic system well-functioning on the commitment of the society members to (legal) economic activity (cf. (4) and Section 2), and

(vi) the direct dependency of economic expansion on environmental quality à la Arrow et al. (1995) (cf. (4) and Section 2).

Now, we apply these results in a three-stage model of environmental development.

4. A three-stage model of environmental development

The model developed in the previous sections can be used in conjunction with other theories of economic development to establish a three-stage model of environmental quality. As we will see, the advantage of this model in comparison to the environmental Kuznets curve concept is that it is consistent with the empirical evidence contradicting the environmental Kuznets curve discussed in Section 1.

Let the first stage be the *pre-industrial revolution phase*, where the population engages primarily in agriculture (using primitive techniques) and its ecological impact is relatively low such that the environmental quality is relatively high (except in the few larger cities, where the pollution may be high due to sewage and primitive industry, e.g., tanning). Assume that, then, by some endogenous or exogenous impulse, the country starts to develop. In general, this development is manifested by industrialization (as was the case in the early phases of development of the today's highly developed countries) or increasing intensity and modernization of agriculture (as was/is often the case in the today's developing countries). Both ways of development are accompanied by increasing pollution, i.e., decreasing environmental quality. That is, due to the endogenous or exogenous impulse, the country enters the *pollution phase* (cf. Section 3). Note that the standard economic development theories discuss different endogenous/exogenous development impulses. For example, Galor (2011) discusses endogenous impulses, where the primitive economy starts to grow significantly when certain endogenous accumulation processes (e.g., the interaction across technology, population growth, and human capital) allow it to escape from the Malthusian development trap. An example of the exogenous impulses that may initiate a phase of fast economic growth is colonialization as discussed by Acemoglu et al. (2001).

The characteristics of the pollution phase are described in Section 3: depending on technology, preferences, and the political system quality/stability, it may be a period of prolonged and strong (but decreasing) economic growth and decreasing environmental quality or a relatively short period where the high economic growth rate decreases quickly due to the negative effects of strong pollution and increasing social dissatisfaction. Many transitional economies seem to display the latter (short) type of the pollution phase.

Finally, as discussed in Section 3, the country enters the *ecological phase* due to the negative effects of pollution on the economic and socio-cultural systems. In particular, the society enforces a switch in the policy regime and establishes a policy that is more environment-friendly (and, potentially, less supportive of economic growth). The ecological phase is not necessarily characterized by an increasing environmental quality; at least, it is characterized by a lower rate of environmental quality degradation.

5. Concluding remarks

The long-run dynamics of environmental quality are determined by the interactions across the political, economic, environmental/natural, and socio-cultural systems and, thus, require an interdisciplinary treatment. By using a relatively simple model structure depicting the interactions across these systems and a qualitative modeling approach, we have shown that the long-run environmental quality dynamics can be understood in terms of a feedback-loop system with self-regulation mechanisms (half-cycles). This system can

(1.) explain the existence of (long) phases of environmental pollution and the switch to a more environment-friendly ecological phase,

(2.) be used to elaborate the determinants of the characteristics of the pollution phase and to (theoretically) explain the observable cross-country differences in these characteristics (see the end of Section 3 for a summary), and

(3.) serve as a basis for a three-stage model of environmental development (see Section 4).

The mere existence of the environmental-pollution-regulatory mechanisms (A)-(C) derived in Section 3, does *not* imply that (a) the society and the environment will not be devastated by environmental pollution and ecological changes and (b) intense social/political efforts are unnecessary to stop the destruction of the environment and the ecological system. In particular, our paper does not imply that the regulatory mechanisms (A)-(C) are efficient or socially optimal (social-welfare maximizing).[2] Rather, our model describes the whole socio-economic-technological-natural complex within which the society destructs the environment and tries to restrict this destruction. That is, our model covers all the possible outcomes of environmental pollution and identifies the aspects of the system that can create outcomes that are characterized by a very slow reaction of the system to environmental degradation and, thus, high environmental destruction. Moreover, while the environmental Kuznets curve has been criticized heavily for its implication that the environmental destruction can be reversed (to some extent) our model does neither require nor imply this possibility (but can be consistent with it if required).

While our paper is devoted to the propagation of PENS-system modeling in conjunction with the qualitative feedback loop analysis emphasized by Coyle (2000) and, thus, our model is relatively simple (yet comprehensive), it can be expanded along different dimensions:

[2] For example, the model-endogenous switch to the environment-friendly policy π_1 may occur too late such that the environmental degradation (and climate change) cannot be stopped or reversed anymore and, thus, the society is captured in low levels of satisfaction.

1.) The interconnections between the four PENS systems (cf. Figure 1) could be discussed in more detail or even complemented by further interconnections (provided that there is theoretical and empirical support for these complements). Two examples may clarify this aspect. First, we have not discussed the possibility that the policy regime tries to support itself (i.e., to prevent a change from policy π_2 to policy π_1) via marketing, propaganda, or even violence/suppression. In this case, there would be an arrow from the political to the socio-cultural system in Figure 1, and π_2 may then persist even if $s < \sigma$ (cf. (3)). That is, political stability would be ensured via this channel. The decision for the ecological phase is, then, not made in the socio-cultural system but in the political system, which may delay the ecological phase in some cases. Second, in many democratic regimes, industrial organizations have a significant effect on policy and society and may be interested in preventing the ecological phase. In this case, we would have to draw arrows from the economic system to the political and socio-cultural systems. The impact on the political system is not relevant in this context (the policy regime would be replaced when $s < \sigma$ irrespective of the opinion of the economic system) unless the political regime has the already mentioned possibilities to enforce its stability via marketing, propaganda, or suppression/violence. However, the marketing from the economic to the socio-cultural system can be effective in this context, i.e., it may prolong the pollution phase.

2.) Each of the four PENS systems could be modeled in more detail. In particular, we have chosen for each of them only one (real-valued) indicator. In contrast, each of the systems is more adequately described by several variables. For example, the economic system could be described by a vector of indices covering not only an activity index (e.g., GDP) but also a personal-income inequality index. The environmental/natural system could distinguish between local and global (i.e., ecological) effects of environmental pollution as well as different forms of resource depletion (renewable vs. non-renewable resources). This extension would not only specify more exactly the connections between the (different indices of the) four PENS systems but also allow for consideration of intra-system interconnections and dynamics.

3.) A more detailed study of the time structure of the model seems interesting as well. The model presented in this paper is already characterized by reaction lags. In particular, the (discrete) policy change (from π_2 to π_1) as a reaction to economic and natural system dynamics occurs with a lag due to the homeostatic nature of the political system (cf. (3)). A further study of the possible lags and velocity of dynamics of different (variables of the) systems seems interesting. Such a study requires profound (interdisciplinary) knowledge (of theory and empirics) of the different systems and could yield models in which qualitative simulation methods (cf. Kuipers, 1986) could be applied more rigorously.

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