Exploring the sustainability of industrial production and energy generation with a model system

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Abstract: The importance and complexity of sustainability has been well recognized and a formal study of sustainability based on system theory approaches is imperative as many of the relationships between the various components of the system could be non-linear, intertwined, and non-intuitive. A mathematical model capable of yielding qualitative inferences can serve as an important tool for policy makers to: (1) explore various simulated important scenarios, and (2) evaluate different strategies and technologies. In this article, we consider a simplified ecological food web with an integrated macro-economic system, industrial production sector, an energy generation sector, and elements of a human society along with a rudimentary legal system. The energy sector is designed to supply energy to the other components of the system either by using a finite, non-renewable energy source or by a combination of a non-renewable source and biomass. Many of the components of the system depend directly or indirectly on the biomass used for energy production. Subsequently, this model is used to study the impact of using biomass for the production of energy on the sustainability of other components of the system under different scenarios such as population increases and per capita consumption increase.

Keywords: *Sustainability, Energy, Ecological Model, Scenario, Ecosystem*

1. Introduction

Sustainability or sustainable development has been generally defined (1) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." From this definition, it can be noted that sustainable development can be achieved (and sustained) only by addressing various diverse issues making the study of sustainability an inherently complex and highly multi-disciplinary concept. The sustained effort of the scientific community has led to the realization that continued exploitation of the Earth's resources cannot be infinitely sustained and can severely endanger the existence of many of the biological species (2). This has led to a vast mobilization of efforts spanning all strata of human society including the scientific, political, and social. A growing body of research has been reported in literature (3-8). It has tried to comprehend the causes of various naturally occurring phenomena and attempted to predict some future consequences, along with suggesting remedial actions that need to be implemented over a period of time to avoid catastrophic events. It should be noted that sustainability is not a goal but a path or corridor through time, which has to be continuously followed and monitored. Sustainability is dependent on the interactions between the various dimensions of the system such as ecology, human society, economics, technology, and other aspects. Often, these interactions are nonlinear, intertwined, and non-intuitive in nature (7, 8). Additionally, the effects of many current actions manifest over a long period of time making the study of sustainability quite complex, requiring a systematic approach.

Stable mathematical models featuring the critical components of a real system can aid in the formal study of sustainability. Models capable of yielding qualitative inferences about sustainability under various simulated scenarios can assist policymakers when evaluating various strategies and technologies. A comprehensive review of some of these models can be obtained from Whitmore et al. (5). The model proposed by Whitmore et al. (5, 6) integrated an economy under imperfect competition with a twelve-cell ecological model. Despite the unique features of the model, it had a limiting assumption as it presumed that an infinite amount of energy was available without any cost to the various components of the integrated system. This assumption warrants a cautious approach when extending the qualitative results of the model to any real world system, where it has been seen that factors related to energy not only have geo-political ramifications but also cause enormous stress on certain components of the system that could jeopardize sustainability.

An enhanced model, which considers various aspects, related to the production and utilization of energy from various types of energy sources in an integrated system has been presented in this article (8). This model can be used to simulate the production of energy based on a finite, non-renewable energy source or a combination of both a non-renewable energy source and biomass. The model is subsequently used to study the sustainability of different components of the integrated system due to the diversion of a part of biomass for the production of energy. Finally, we have used the model to study the sustainability of the integrated system under various plausible scenarios such as a population increases and an increase in the per capita material consumption levels of humans.

2. Integrated Ecological-Economic Model

The model consists of 14 compartments and represents a simplified ecological food web set in a macro-economic framework with farming, livestock raising, industrial production, energy generation, and a rudimentary legal system. The model shown in Fig. 1 consists of three primary producers (P1, P2 and P3), three herbivores (H1, H2 and H3), and two carnivores (C1 and C2) along with human households (HH). The Resource Pool (RP) represents a generic finite nutrient source while the Inaccessible Resource Pool (IRP) represents mass that is not biologically accessible to the rest of the system. The primary producers feed on RP and use energy from the Sun to make this mass available to the rest of the integrated system. A small amount of mass from IRP is recycled back into the system by P2 and P3, which symbolizes degradation by the actions of microorganisms. All nine biological compartments recycle mass back to RP through death. The Energy source (ES) represents a finite non-renewable energy source. The Energy Producer (EP) is an industry that uses labor to transform the energy source into a usable form of energy. This energy is supplied to HH and IS. EP is also capable of producing energy using P1, and this would represent the production of energy using biomass. The IS produces products valuable to HH using P1 and RP. The use of the IS products does not increase the mass of HH, but it instead passes through as this is used to increase the mass of IRP. Similarly, the use of mass by the EP to produce energy results in the increase of the mass of the IRP and a corresponding decrease in the mass of ES. The biological compartments of the system can be aggregated as shown in Fig. 1 into domesticated species that have economic value and wild species that have no economic value. A legal system assigns property rights to domesticated biological species, the product of the industrial sector, and the non-renewable energy source. Grazing rights are given to H1 to access P2, while the access of C1 to H1 is limited. Moreover, C1 is a protected species and cannot be hunted or consumed by other components of the integrated system. Similarly, the access of P1 by H2 is limited by using capital and labor, i.e. erecting barriers or “fences.”

The human workforce can choose to work in any of the four industries (P1, H1, IS or EP) and the wages are set by IS depending on the demand supply gap of the IS product along with the population, i.e. IS dominates the labor market. The demand for any product (P1, H1, and IS) by HH also depends on the price and demand for various other products. The demand for a particular product (say P1) decreases with an increase in the price of that product (P1) and the demand increases (for P1) with an increase in the price of other products (like H1 and IS). The prices of the products depend on the wages paid for labor and the demand supply gap of that particular product. An increase in the wage levels or demand supply gap increases the price of the product. The price of energy depends on the labor and the amount of fuel that is available at the given point of time. An increase in labor cost increases the price of energy whereas a decrease in the amount of energy source would lead to an increase in the price of energy. The growth of the human population depends on the per capita human mass, the birth rate, and the mortality. The human birthrate in turn is assumed to be a negative function of the real wage as it represents the opportunity cost of opting to remain outside the labor force for the purpose of rearing children. The complete system is closed to mass so that it abstractly represents a planet. The food web is modeled by Locka-Volterra type expressions whereas the economy is represented by a price-setting model wherein firms and HH attempt to maximize their well-being. The aim of this model is to represent the critical elements of a real world system while keeping it simple enough for tractable mathematical analysis. Some of the salient features of the model include an organization based on trophic levels with fewer species and lower total mass for higher trophic levels, species specific preferences for food, cyclic variation in the growth of the primary producers, discharge fee on the industrial sectors and the ability to accommodate both non renewable mass and biomass to produce usable energy. Also, the model is flexible enough to allow for variation of the amount of energy produced from biomass. For this article, it was assumed that 30% of the total energy demand by the integrated system is being provided by the biomass. If sufficient amount of biomass is not available, the maximum available biomass is used for the production of energy and the remaining energy is produced from the non-renewable energy source. Moreover, it was assumed that there is no surplus or deficit in the energy levels as the EP produces as much energy as required by HH and IS. The dashed lines in Fig. 1 indicate mass flows that occur under anthropogenic influence. The dotted lines indicate the flow of energy from EP to HH and IS. The square dotted line between P2, P3, and IRP indicate slow transfers of mass as a result of microbial activity. For the sake of brevity, the complete mathematical model is not presented here and details including the base case results can be found in Kotecha *et. al.* (8)

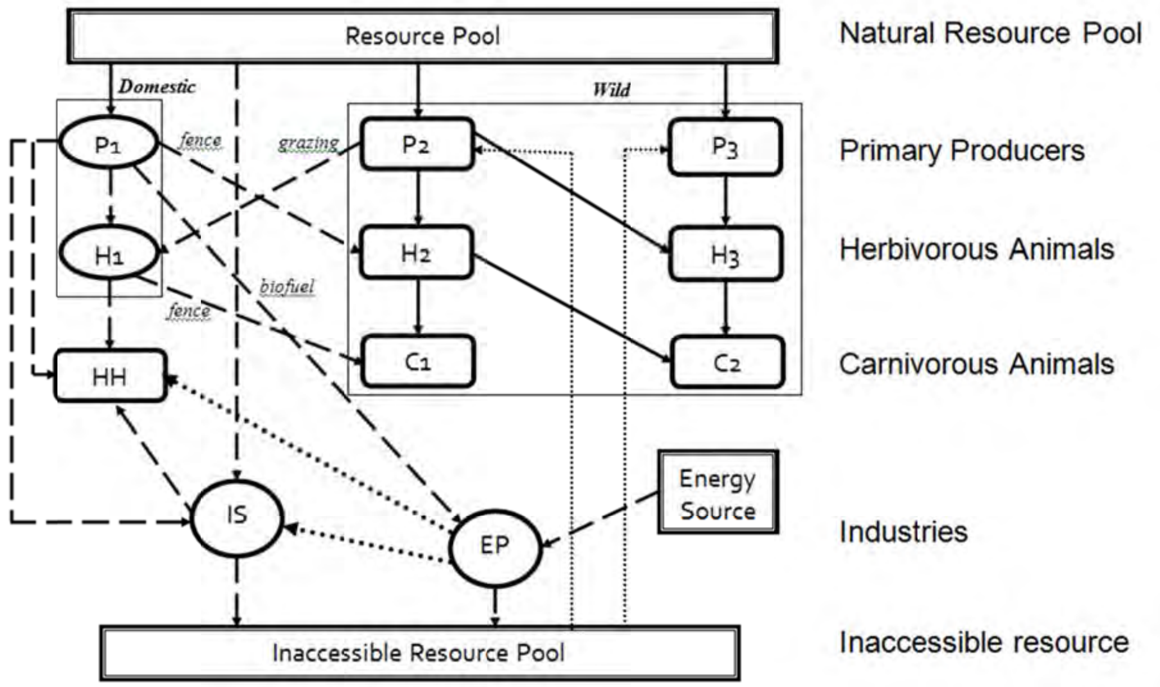

Fig. 1. Integrated Ecological Model

3. Scenario Analysis

Model based scenario analyses are an integral part of systems theory and help in understanding the dynamics of systems under various simulated scenarios without disturbing any actual system. Such analyses have been credited with helping make informed and rational decisions by their ability to offer insights into ramifications of current and possible future actions. However, the results of the scenario analysis should not be mistaken for actual forecasts, projections or predictions of the future as the future need not necessarily evolve based on the assumptions underlying the scenario analysis. At times, the actual future may involve a combination of different scenarios or even witness happenings not envisioned as possible scenarios. There have been a number of studies, which are based on scenario analysis and have been discussed in the literature (7, 8). We will consider here the two scenarios of an increase in human population and an increase in the per capita human consumption levels. For the sake of brevity, profiles of only the most important compartments have been provided.

3.1. Population Increase

Rapid population increase is one of the scenarios commonly envisaged by many environmentalists. The enormous growth of the human population has already placed severe stress on many finite resources of the Earth and may pose serious concerns on the sustainability of its ecosystem. It is widely believed that the human population will double from its current level and peak in the next 50-100 years (9, 10). This premise is largely based on the fact that mortality rates will be dropping due to better health care facilities whereas the birth rate will also get lowered due to better education of women and increased awareness of birth control techniques, particularly in the under developed countries. This period will be followed by a steady decline in the human population due to aging and a decrease in fertility rates (7, 8). As in previous published studies based on this model (7), the human mortality rate drop is modeled in a piecewise linear manner before settling at a final value while the coefficients in the birth rate function are nonlinearly varied. The issue of population is included here to provide a complete description of the system, but addressing it is well outside the purview of the U.S. EPA. This work should, therefore, not be construed as providing any guidance on population issues. The following discussion describes the dynamics of the various compartments of the integrated system.

From Fig. 2, it can be seen that the amount of P1 decreases faster initially when energy is produced using biomass. The price of P1 is initially higher for the scenario where bioenergy is used. Although, P1 is used for bioenergy, it does not decrease beyond a certain point because of market equilibrium. Due to an increased amount of resource pool mass, the amount of P3 increases with time whereas the amount of P2 declines due to an increase in the growth of H3. The increase in the growth of H3 is essentially due to an increased level of P3. From Fig. 2, it can be seen that there is a sudden decrease in the level of H1, and H1 never recovers. This sudden decrease occurs at the point where population growth is highest. At this stage, the resources for H1 to consume became limited due to consumption of P1 by humans as well as for its use for bioenergy. However, the level of H2 increases because the decrease in H1 leads to a decrease in the levels of C1, which in turn decreases the consumption of H2, and hence increases the compartmental mass of H2. From the figure, it can be seen that there is a drop in the level of C1 if a portion of the P1 is used for producing energy. This can be attributed to a drop in the amount of H1 that is being transferred to the C1 compartment due to a decreased level of H1, because of the production of energy using biomass. The amount of C1 drops due to the usage of P1 for producing energy even though C1 does not directly consume P1. Another important thing to notice is that though C1 is a protected species, its mass drops significantly because of the economics of P1. Similar observations also hold for C2. However, it was observed that the species C1 or C2 do not become extinct due to the production of energy using biomass.

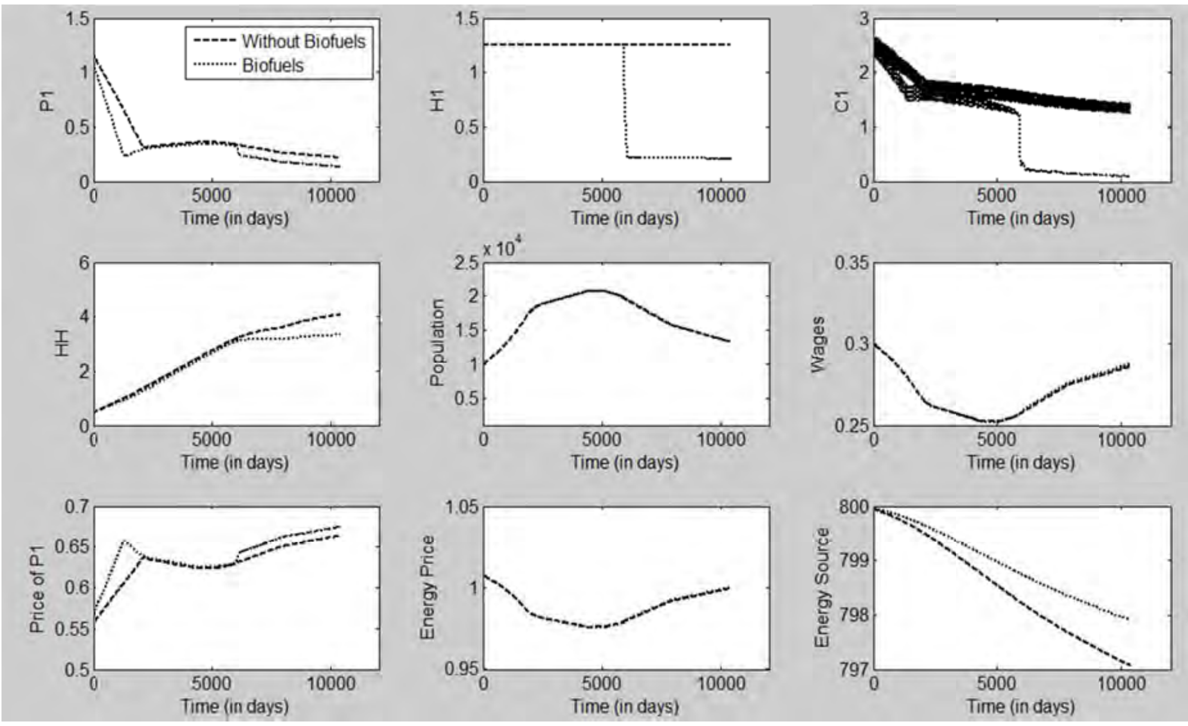

Fig. 2. Profiles of compartmental mass and price (population increase)

Figure 2 shows that the amount of human mass has slightly decreased due to the production of energy using biomass. The amount of human mass is directly dependent on the amount of P1 transferred to the HH compartment. Due to the production of energy using biomass, the amount of P1 decreases and hence the availability of P1 to feed HH decreases thereby causing the drop in human mass. Figure 2 also shows no change in the level of human population because of the production of energy using biomass. It can also be seen that the drop in the compartmental mass of human households is not translated into a reduction of the human population. This invariably indicates that the per capita mass of humans has decreased thereby corroborating both the decrease in human mass at similar levels of human population. Figure 2 shows that the production of energy using biomass does not lead to an increase in wages. Wages paid to human households is inversely proportional to the human population i.e., an increase in the human population decreases the wages of the human households. Thus, the wages are low when the population is high and increase with a decrease in the population.

Figure 2 shows that the decrease for ES is less if a portion of the energy is produced from biomass. This is because in the production of energy using biomass, P1 is used for producing energy and hence the non-renewable energy source is not used for that portion of energy thereby leading to a slower decrease in the amount of ES. The price of energy is similar in both cases. The price of energy initially decreases because the human population is increasing and leads to lower wages. Subsequently, the human population starts to decrease and wages start increasing as this gets reflected in the price of energy. This completes the discussion of the population scenario analysis, and we will now discuss the scenario of increase in the consumption levels of the humans.

3.2. Consumption Increase

Many of the resources that humans consume are non renewable and are finite in nature, and the resources which are renewable are often consumed at a rate much faster than the rate of replacement. Such abnormal high consumption levels could severely affect the current composition of the ecosystem (11, 12). Moreover, with an increase in per capita income, the quality of life and disposable income have increased often leading to an increase in per capita consumption of both mass and energy. This continuous increase in consumption levels could not only exceed the capacity of the ecosystem to provide services, but endanger the longer-term sustainability of the system. For the model under study in this article, the increase in the consumption level of humans is modeled by linearly varying the constant coefficients involved in the estimation of per capita demand for resources. This strategy of modeling consumption increase is similar to the previous published work on a similar model by Shastri et al. (13). We will now present the discussion on the dynamics of various compartments present in the integrated system under increased levels of per capita consumption.

Figure 3 shows that increase in the consumption levels of humans leads to a decrease in the levels of P1, H1, and C1. The magnitude of decrease is more prominent when energy is produced using biomass. This is because a part of P1 is being used for the production of energy, and, thereby, is not available to the rest of the system. The increase in the price of P1 leads to a lower consumption of P1 by the H1 compartment. The level of P2 was also seen to decrease whereas the level of P3 increased due to increased levels of the resource pool. These changes in the primary producers have cascading effects on the other components of the integrated system. The herbivore H1 preys on P1 and a rapid decline in the levels of P1 leads to a rapid decline in the levels of H1. Similarly, the level of H2 falls rapidly when P1 is used for producing energy, since the levels of P1 and P2 are lower. However, the level of H3 remains the same in both the cases as it depends on the level of P3. The level of C1 and C2 in both cases decreases to significantly lower levels due to a decrease in the levels of H1 and H2. However, their decline is more rapid when P1 is used for the production of energy. For the case of population increase, the amount of C1 and H1 had also decreased but in the case of consumption increase, the mass of these two compartments not only decreases, but they become extinct. It should be noted that the extinction of C1 occurs despite the fact that it is a protected species. This is an example of the complex interaction between the various dimensions of sustainability, and how one or more dimensions can dominate the others. In this case, the economic dimension dominated the legal dimension, and this resulted in the extinction of the C1 species. It can be seen that the use of P1 to produce energy in an increasing consumption level scenario could accelerate the extinction of some species.

From Figure 3, it can be seen that the amount of human mass has increased substantially due to an increase in the consumption of P1 and H1. However, the use of P1 to produce energy leads to a lower increase in the mass of the human compartments. The figure shows that there is a drop in human population towards the end of the simulation horizon. The level of human population is slightly less when P1 is used as a source of energy for producing energy. This can be attributed to the fact that the non-availability of P1 leads to a decrease in the compartmental mass of the human households and subsequently manifests into a decreased population. The figure shows the prevailing wages as decided by the Industrial Sector (IS). The difference in the wage levels is a reflection of the difference in the population level for the two cases. Since the population is slightly lower when P1 is used for producing energy, the wage rates for this case are higher. The wage rates are constant for a considerable period of time and start to increase towards the end due to a decrease in the human population. This is consistent with the assumptions of the model wherein the wage rate remains constant with a constant population level and increases with a drop in the population.

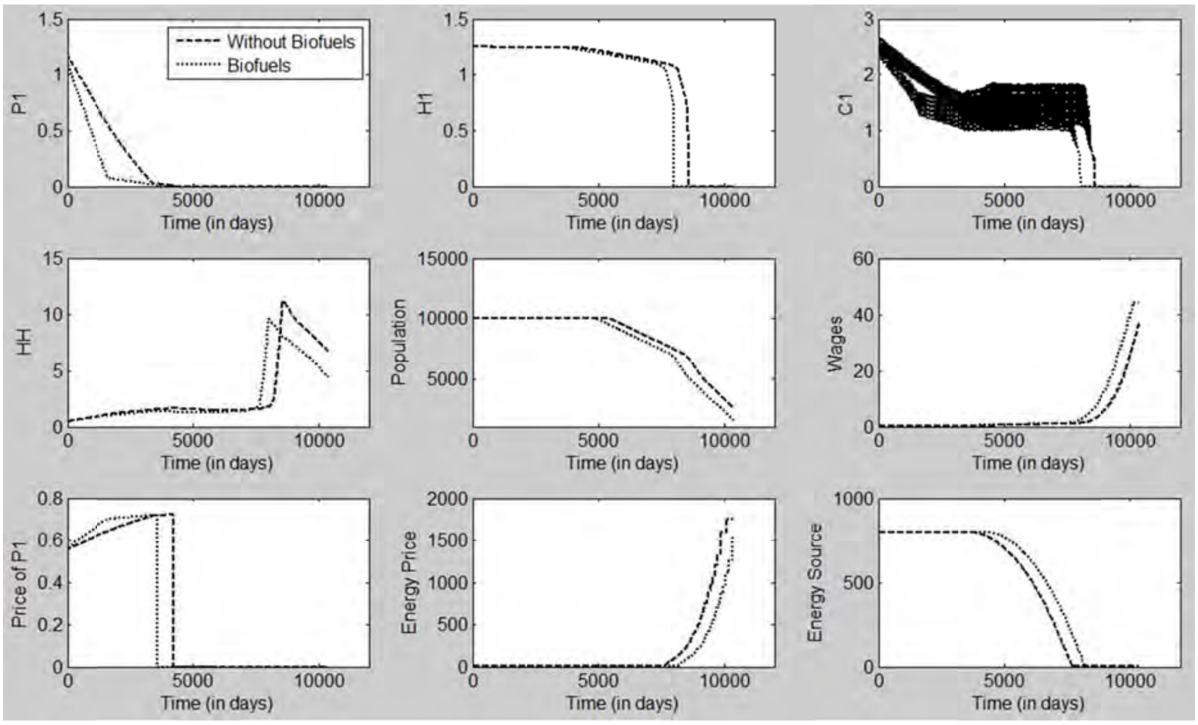

Fig. 3. Profiles of compartmental mass and price (consumption increase)

Figure 3 shows the price of P1 and energy along with the amount of non-renewable energy source available in the integrated system. As with the base case and the population increase scenario, the decrease for ES is less if a portion of the energy is produced from biomass. The use of P1 for producing a part of the energy decreases the utilization of the non-renewable energy source and hence the decline in it is moderated. However, in both the cases, the energy source faces decline, and the use of biomass for producing energy merely delays the exhaustion of the non-renewable energy source. The price of energy is a function of wages and the amount of energy source available in the system. Irrespective of the use of biomass to produce energy, the energy prices keep increasing. However, the use of biomass for producing a portion of the energy seems to lower the cost of the energy for this particular scenario of increasing consumption. This is because of the fact that the use of biomass helps in maintaining a higher level of the non-renewable energy source longer, and this, thereby, leads to a relatively lower cost of energy. It can be seen that the price of energy is significantly higher in the scenario of consumption increase than either the base case or population increase scenario. This is because the human population has decreased to very low levels thereby increasing the wage levels. Moreover, the scarcity of the energy source contributes to the increase in the price of energy.

4. Conclusions

An enhanced 14 compartmental model for an integrated system incorporating the generation and utilization of energy has been developed to aid in the formal study of sustainability and to derive qualitative inferences for various scenarios. Under the scenario of population increase, the use of biomass does not decrease the human population, but leads to a decreased per capita human mass, which may be inferred as an indicator for the quality of life. Moreover, the use of biomass for producing energy only delays the inevitable exhaustion of the non-renewable energy source and does not significantly impact the energy prices. For the scenario of per capita consumption increase, it was observed that the integrated system could not sustain high levels of human consumption. It was observed that the use of biomass for the production of energy delays the exhaustion of the non-renewable source, but can expedite some of the catastrophic events such as the extinction of protected species and human well-being. The proposed model can be used to explore strategies, policies, and to evaluate the impact of alternate generic technologies on the long-term sustainability of the system. The inherent assumptions of the model have to be borne in mind, and a cautious and conservative approach should be practiced while extending these model inferences to reality.

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