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Model-based approach to study the impact of biofuels on the sustainability of an ecological system

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Abstract The importance and complexity of sustainability have been well recognized and a formal study of sustainability based on system theory approaches is imperative as many of the relationships between various components of the ecosystem could be nonlinear, intertwined and non-intuitive. A mathematical model capable of yielding qualitative inferences can serve as an important tool for policy makers as it can be simulated under various important scenarios and also help in evaluating different strategies and technologies. In this article, we consider a simplified ecological food web which comprises a macroeconomic system, an 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 ecosystem either by using a finite, non-renewable energy source or by a combination of non-renewable source and biomass. Many of the components of the ecosystem 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 ecosystem. We have also simulated the model under two commonly foreseen scenarios of population explosion and consumption increase to understand the effect of using biomass for the production of energy on the sustainability of the various components of the system.

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Introduction

Sustainability or sustainable development has been generically defined (Brundtland 1987) as "the development that meets the needs of the present without compromising the ability of the future generations to meet their own needs." From the definition, it can be noted that sustainable development can be achieved (and sustained) only by addressing various diverse issues making the study of sustainability a complex and highly multi-disciplinary concept. In recent times, there has been an exponential increase in the study of sustainability as researchers have been successful in highlighting the enormous stresses exerted by humans activities on the resources of the planet (Raven 2002). The sustained effort of the scientific community has led to the realization that such continued exploitation of the Earth's resources cannot be infinitely sustained and can severely endanger the very existence of many of the species. This has led to a vast mobilization of efforts spanning all strata of the human society. A growing body of research work (Meadows et al. 1992; Bossel 1998; Holling et al. 2002; Scholes et al. 2005; United Nations Environment Programme 2007; Stern 2006) has tried to comprehend the causes of various naturally occurring phenomena and has also attempted to predict the future consequences along with suggesting remedial actions that need to be implemented over a period of time to avoid any catastrophic events. Sustainability is governed by the interactions between various dimensions such as ecology, human society, economics, technology, and many other aspects. Very often, these interactions are nonlinear, intertwined and non-intuitive in nature (Cabezas et al. 2003, 2007a; McMichael et al. 2003; Shastri et al. 2008a, b; Shastri and Diwekar 2006a, b; Cabeza Gutes 1996; Cabezas and Fath 2002; Fath et al. 2003). Coupled with the fact that the effects of many of the current actions manifest over a period of time and there are time-dependent uncertainties make the study of sustainability quite complex and requires a systematic approach.

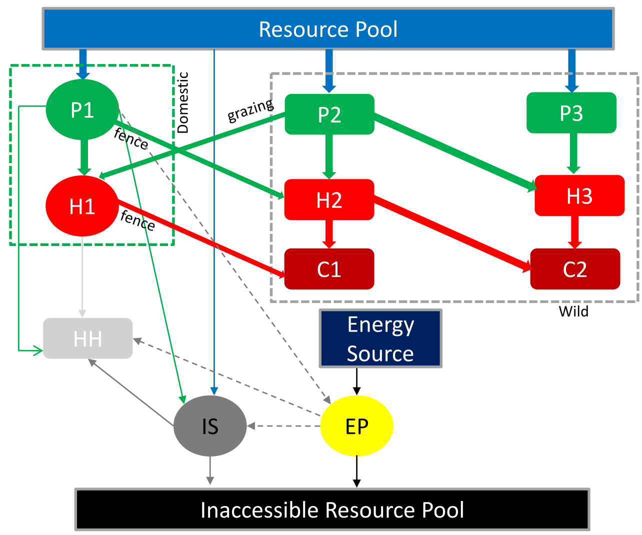
Stable mathematical models featuring the critical components of a real ecosystem can aid in the formal study of sustainability. Models capable of yielding qualitative inferences about the sustainability under various simulated scenarios can help policymakers to evaluate various strategies and technologies. There have been quite a few ecological models which have incorporated varying degree of economic features. Acutt and Mason (1998) and Heal (1998) proposed valuing the various environmental services in an ecosystem in their decision making models. Some of the other works which included largely simplified economic features in their ecological models are the ones developed by Ludwig et al. (2003), Brock and Xepapadeas (2002), Costanza et al. (2002), and Carpenter et al. (1999). Models accounting for processes such as resource extraction, waste assimilation, recycling, and pollution in an integrated ecological economic framework have also been proposed in the literature (van den Bergh 1996). A comprehensive review of some of these models can be obtained from Whitmore et al. (2006). The model proposed by Whitmore and co-workers (2006, 2007b, 2008b) integrated an economy under imperfect competition with a widely used twelve-cell ecological model. Despite the unique features of the model, it had a very limiting assumption as it presumed that an infinite amount of energy was available without any cost to the various components of the ecosystem. This assumption warrants a too cautious approach in extending the qualitative results of the model to a real world ecosystem where it has been seen that factors related to energy not only have geo-political ramifications but also causes enormous stress on certain components of the ecosystem that could even jeopardize the sustainability.

In this study, we have presented an enhanced model which considers various aspects related to the production and utilization of energy from various types of energy sources in an ecological system. In particular, the model can simulate the production of energy just based on a finite, non-renewable energy source or a combination of both non-renewable energy source and biomass. This model is subsequently used to study the sustainability of different components of the ecosystem due to the diversion of a part of biomass for the production of energy. Subsequently, we have used the model to study the sustainability of the ecosystem under various plausible scenarios such as a population explosion and an increase in the consumption levels of humans. The base case as well as both the scenario analysis has been simulated with and without the inclusion of biomass to produce energy and hence help us to evaluate the impact of biofuels on the sustainability of the various components of the system. The article is organized as follows: in the succeeding section, we briefly describe the enhanced integrated ecological–economic model and its features along with the simulation scheme. This section also discusses the base case results and shows the stability of the proposed model and suitability for scenario analysis. This is followed by a discussion on scenario analysis where we present the results for two widely plausible scenarios viz., population explosion and increase in human consumption levels. We finally conclude the article by summarizing the developments in this work and presenting possible future work.

Integrated ecological–economic model

In this section, we will briefly describe the enhanced model and its various features. Additional details of the model can be obtained from the supporting material of this article. The model consists of 14 compartments and represents a simplified ecological food web set (Cabezas et al. 2007a) in a macro-economic framework along with 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), two carnivores (C1 and C2) along with human households (HH). The resource pool (RP) represents a finite nutrient source while the inaccessible resource pool (IRP) represents mass that is not biologically accessible to the rest of the ecosystem. The primary producers feed on RP and make this mass available to the rest of the ecosystem. A small amount of mass from IRP is recycled back into the system by P2 and P3 and symbolizes bacterial actions. All the nine biological compartments recycle mass back to RP through death. The energy source (ES) represents a finite non-renewable energy source. However, the ecological compartments of the system cannot themselves use this ES to produce the energy required by them as the ES needs to be appropriately transformed. The energy producer (EP) is an industry that uses labor to transform the ES into a usable form of energy. This energy is supplied to the HH and the industrial sector (IS). The 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 the HH

Fig. 1 Integrated ecological model



but instead increases the mass of IRP. Similarly, the use of mass by EP to produce energy results in the increase of mass of the IRP and a corresponding decrease in the mass of ES. The biological compartments of the systems can be aggregated as shown in figure into domesticated species with economic value and wild species with no economic value. A legal system assigns property rights to domesticated biological species, the product of the IS, and the non-renewable energy source. Grazing rights are given to H1 to access P2 while the access of H1–C1 is limited as C1 is a protected species. Similarly, the access of P1 by H2 is limited by fencing.

The human workforce can choose to work in any of the four industries (P1, H1, IS, or EP) and the wages are decided by the IS depending on the demand supply gap of the IS product along with the population. The demand of any product (P1, H1, and IS) by the HH also depends on the price and demand of various other products. The demand of a particular product (say P1) decreases with an increase in the price of that product (P1) and the demand increases (of P1) with the 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 would lead to an increase in the supply of energy. In this study, it has been assumed that the price of energy generated from biomass is equal to the price of energy produced from the non-renewable energy source. The growth of 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 to abstractly represent a planet. The food-web is modeled by Lotka–Volterra type expressions (Cabezas et al. 2007a) 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 ecosystem and yet keep it simple enough for a mathematical analysis. Some of the salient features of the model include an organization based on trophic levels with fewer species for higher trophic levels, species specific preferences for food (Whitmore et al. 2006), cyclic variation in the growth of the primary producers (Shastri et al. 2008b; Cabezas et al. 2005), discharge fee on the ISs (Shastri et al. 2008b) and the ability to accommodate both non-renewable and biomass-based energy source to produce energy. Also, the model is flexible enough and allows the variation of the amount of energy produced from biomass. For the results presented in this article, it was assumed that 30 % of the total energy demand by the ecosystem 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 also assumed that there is no surplus or deficit in the energy levels as the EP produces energy as much required by the HH and the IS.

The basic model in a conceptual form is given below.

Food web model equations:

$$\frac{dy_i}{dt} = f(y_k, P_j) \quad (1)$$

where y_i represents the population of each compartment and P_j are the parameters of the model.

Macro-economic model equations:

$$Ec_{l_t} = e(y_k, c_{li}, ds_{lk}), \quad (2)$$

where Ec_{l_t} are the economic parameters of the model, c_{li} are the economic parameters and ds_{lk} are the demand and supply variables.

Apart from the above equations, there are algebraic equations related to factors such as seasonal variations.

Base case simulation

As stated earlier, the basics of the model can be obtained from reference (Cabezas et al. 2007a). However, in this article we made changes to the IS and economic model and added energy sector. This affected the economic model considerably. Therefore, Fig. 2 shows the simulation strategy for this portion of proposed integrated system. The simulation strategy predominantly consists of four major steps namely the determination of wage rates along with the prices and production levels of the various industries, the determination of demands by various parts of the ecosystem, the supply of appropriate amount of material to each of the component of the ecosystem and the determination of the population growth. Having discussed the model and the simulation strategy, we will now focus our attention on the base case scenario. The base case scenario aims to understand the dynamics of the ecosystem under the assumption that there will be no significant changes either in the growth of human population or increase in the levels of human consumption. Though such an assumption may or may not hold true for future, it provides an opportunity to understand the strength and weakness of the current practices in the ecosystem. Since sustainability is a phenomenon evolving throughout the time, it is necessary to have a long time horizon which would enable to understand the broader manifestations in addition to any short-term disturbances. For the results presented in this article, a time horizon of 200 years is assumed. Remember that time is relative in this model. We used the literature values wherever it is available (e.g., mortality rate of humans) for this model and then did the stochastic modeling to obtain initial values of other parameters so that the base case model response is stable. Due to the restrictions on the size of the article, the profiles of only selected compartments are shown. However, a brief description on the dynamics of the other compartments has been included at appropriate places.

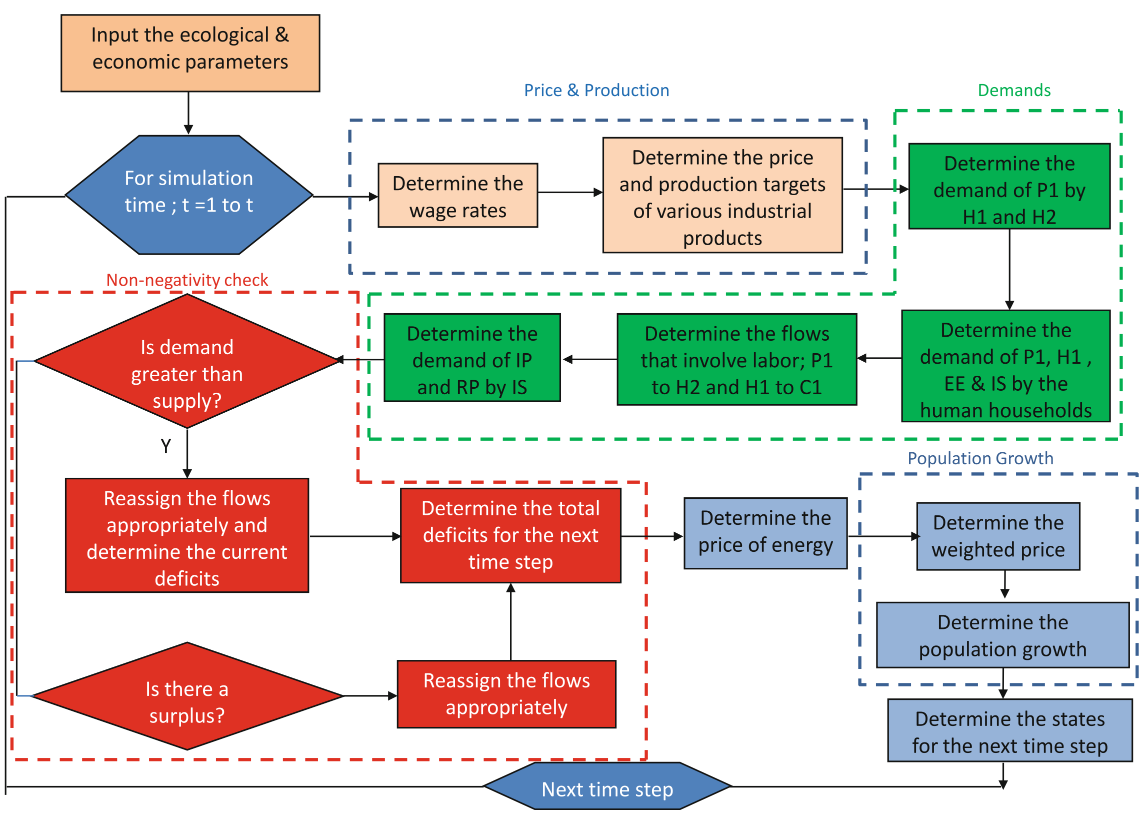


Fig. 2 Simulation strategy

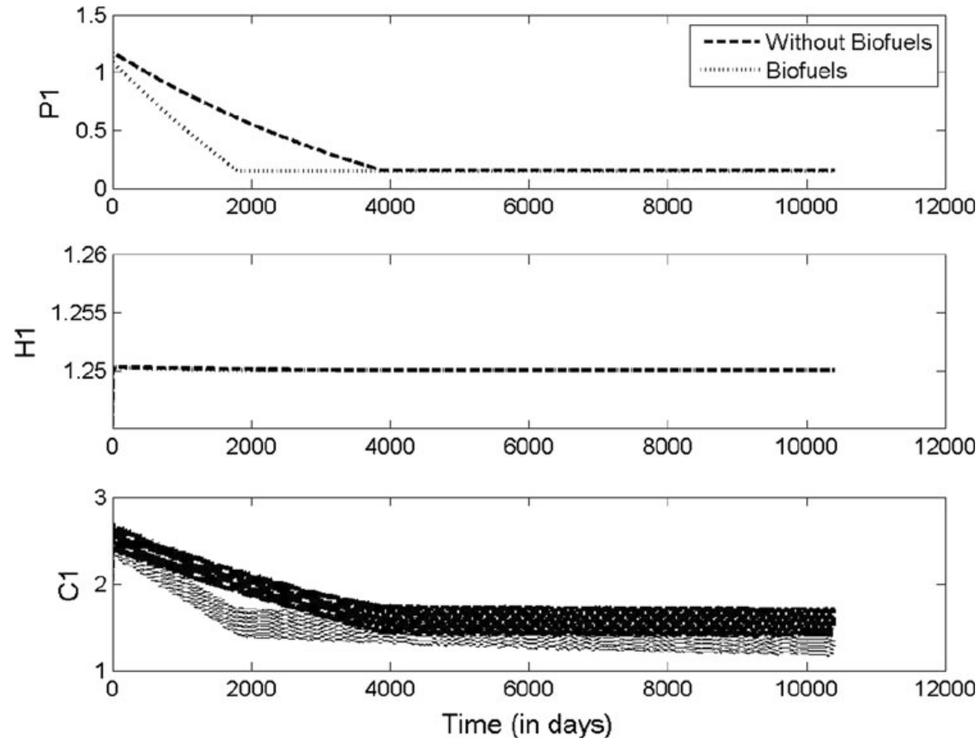


Fig. 3 Profiles of primary producer, herbivore and carnivore (base case)

Figure 3 shows the profiles of the primary producer, herbivores and carnivores. From this figure, it can be seen that the amount of P1 decreases faster if a part of the energy is produced from biomass. This can be attributed to the fact that some of P1s are used as biofuels by the EP to produce energy for the other components of the ecosystem. Though not shown here, there is a marginal decrease in the level of P2 whereas there is no significant change in the level of P3. For herbivores, it can be seen that there is no significant change in the amount of H1. The levels of H2 and H3 are almost similar irrespective of the production of energy using biomass. A marginal drop observed in the levels of H2 can be attributed to the fact that there is a lesser supply of P1 to H2 due to the production of energy using biomass. Figure 3 also shows a drop in the level of C1 if a portion of the energy demand is met using biomass. This can be attributed to the fact that there is a drop in the amount of H2 that is being transferred to the C1 compartment due to a decreased level of H2. Thus, it can be seen that the mass of the C1 compartment drops due to the usage of P1 for producing energy even though C1 does not directly consume P1. Similar observations also hold for C2.

Figure 4 shows the profiles of mass of HH, human population and the wages set by the IS industry. The human mass does not change significantly due to the production of energy using biomass. The slight drop in the human mass due to the production of energy using biomass can be attributed to the fact that a portion of P1 which would be otherwise available for the HH is diverted for the production of energy using biomass. The mass of the HH essentially depends on the mass of P1 and H1. The profiles of the population and the wage rates in figure are essentially the same and are not affected by the production of energy using biomass. Both the population and wage rates are inversely proportional and the absence of any significant dynamics in population would lead to a predominantly static profile of the wage rates. A reduction in human mass along with a constant population is an indicator that the per capita human mass has decreased. Thus, it can be seen that a systematic study of sustainability leads to uncovering the effect of producing energy from biomass on the well being of human population.

Figure 5 shows the profiles related to the energy sector. It can be seen that there is no significant difference in the energy prices due to the production of energy using biomass. This is partly because of the fact that the wages are constant (as shown in Fig. 4). However, it can be seen that the amount of ES is decreasing faster in the absence of production of energy using biomass. This behavior is as expected because the ES is non-renewable and in the absence of energy production using biomass, the complete energy demand by the HH and the IS has to be satisfied by utilizing the non-renewable energy source. This can also be corroborated by the profile of P1 in Fig. 3 where the amount of P1 in the absence of energy production using biomass was higher. Hence, the amount of P1 and the non-renewable energy source are interrelated when energy is produced using biomass. A decrease in the mass of P1

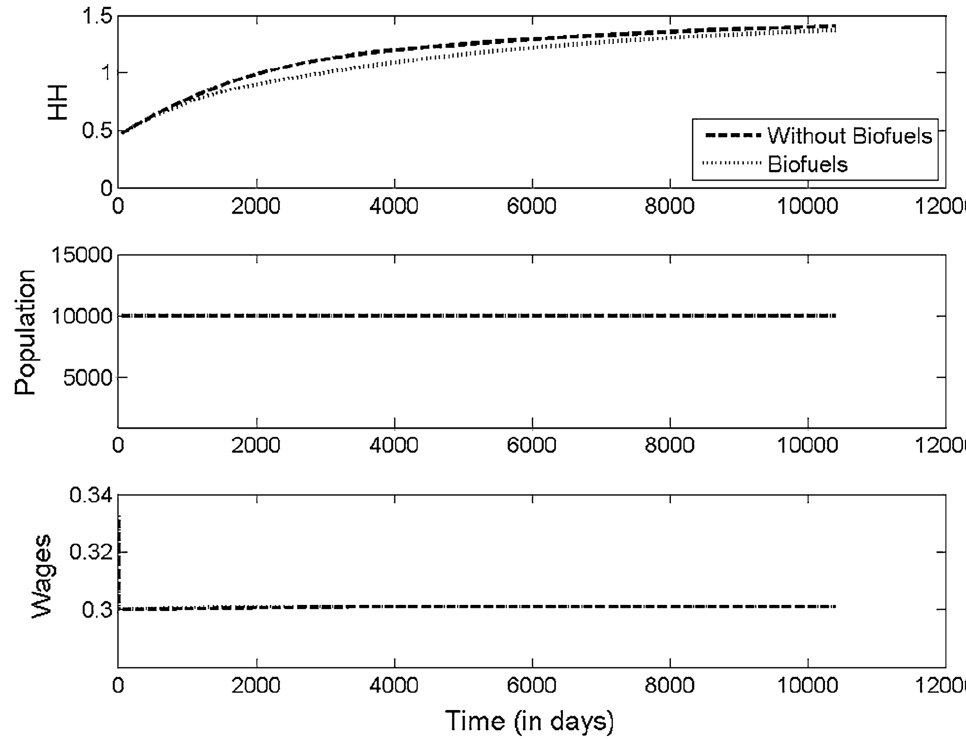


Fig. 4 Profiles of human mass, human population and wages (base case)

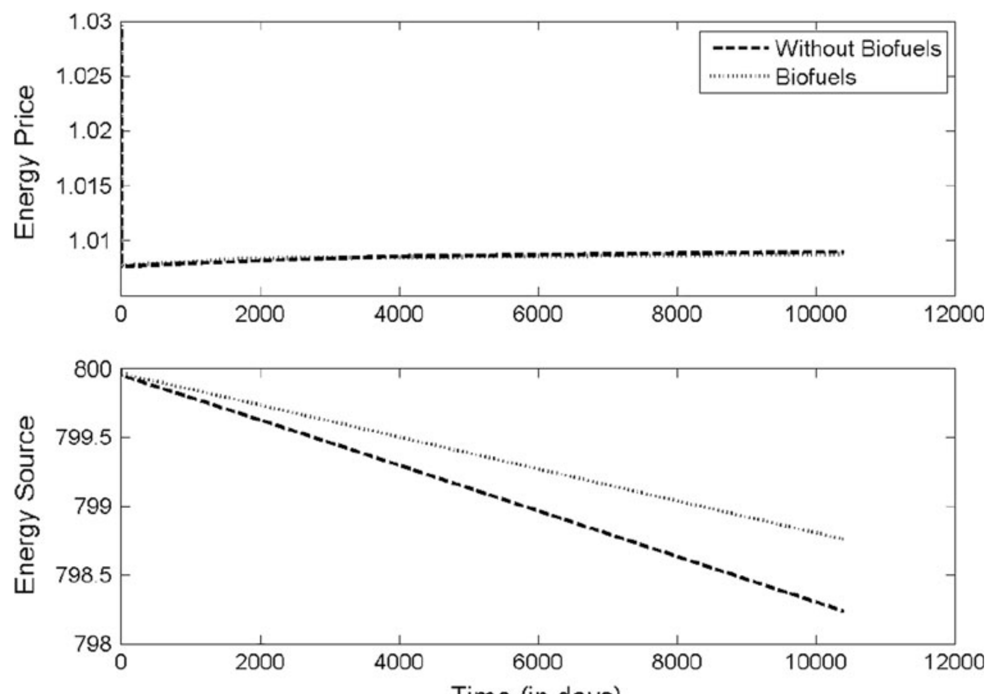


Fig. 5 Profiles of energy prices and ES (base case)

would lead to a slower decrease of the non-renewable energy source. This completes the base case study of the sustainability of the ecosystem. It can be seen that none of the nine biological species goes to extinction due to the production of energy biomass but reach a stable level. The per capita mass of the HH decreases slightly and the model along with the selected parameters is stable. It can also be seen that there are cascading effects and these could be inferred only by a formal study of sustainability. Having developed a stable model, we will now use this model to conduct various scenario analyses and study their implication on the sustainability of the ecosystem.

Scenario analysis

Model-based scenario analysis is an integral part of systems theory and help in understanding the dynamics of a system under various simulated scenarios without disturbing the actual system. Scenarios have been considered as plausible, challenging, and relevant situations about the evolution of the future, which can be described in qualitative as well as quantitative terms (Shastri et al. 2008b; Capistrano et al. 2005). Such analyses have been credited in helping to 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 forecast, projections or predictions about the future as the future need not necessarily evolve based on the scenarios assumed in the scenario analysis. At times, the actual future may involve a combination of different scenarios or even witness happening that were not envisioned as possible scenario. There have been quite a few studies in the literature which are based on scenario analysis. Some of these studies include the works of Meadows et al. (1992), Bossel (1998), and Janssen (2002). A comprehensive series of reports considering various aspects about the ecosystems and human well being has been authored as part of Millennium ecosystem assessment (Hassan et al. 2005; Carpenter et al. 2005; Chopra et al. 2005). These reports include the current state and trends, the various plausible scenarios, policy response and multi-scale assessments. A United Nations sponsored study by Rothman et al. (2015) have discussed the outlook of the global environment in the near future. In this article, we will consider the two scenarios of an increase in human population and an increase in the human consumption levels. This is consistent with the previous studies based on this model (Shastri et al. 2008b).

Scenario analysis: population explosion

Population explosion is one of the common scenarios envisaged by many environmentalists particularly because of the grave dangers posed by such a phenomenon. Their proposition is based on the historical data which shows that the human population has increased from 2.5 billion in 1950 to about 7 billion in 2010. Such an enormous growth of human population has placed severe stress on many of the finite resources and may pose serious concerns on the sustainability of the ecosystem. The prediction of human population is a very complex subject and there are no universal consensuses on the exact numbers. However, it is widely believed that the human population will double its current levels and peak in the next 50–100 years (Capistrano et al. 2005; Cohen 2003). This premise is largely based on the fact that the 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 human population due to an aging population and a decrease in the fertility rates (Shastri et al. 2008b; United Nations 2004; Kolosov 1997). As in previously published studies based on this model (Shastri et al. 2008b), we will modify the mortality and birth rates so as to model the population as explained above. To be specific, the human mortality rate drop is modeled to drop in a piecewise linear manner before settling at a final value while the coefficients in the birth rate function are nonlinearly varied. The following discussion describes the dynamics of the various compartments of the ecosystem.

Figure 6 shows the profiles of the primary producer, herbivore, and carnivore for the population explosion scenario. From Fig. 6, it can be seen that the amount of P1 decreases faster when energy using biomass is produced. This can be attributed to the fact that some of P1s are used by the EP to produce energy for the other components of the ecosystem. Due to an increased amount of RP, 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. 6, it can also be seen that there is a decrease in the level of H1. This is attributed to the fact that the level of P1 also has decreased and hence the amount of mass getting transferred from P1 to H1 also decreases. 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 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 the fact that there is 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. It can be seen that the amount of C1 drops due to the usage of P1 for producing energy even though C1 does not directly consume P1. Similar observations also hold for C2. However, it was observed that the species C1 or C2 do not get extinct due to the production of energy using biomass.

Figure 7 shows the profiles of the mass of the HH, the human population and the wages for the population explosion scenario. It can be seen 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

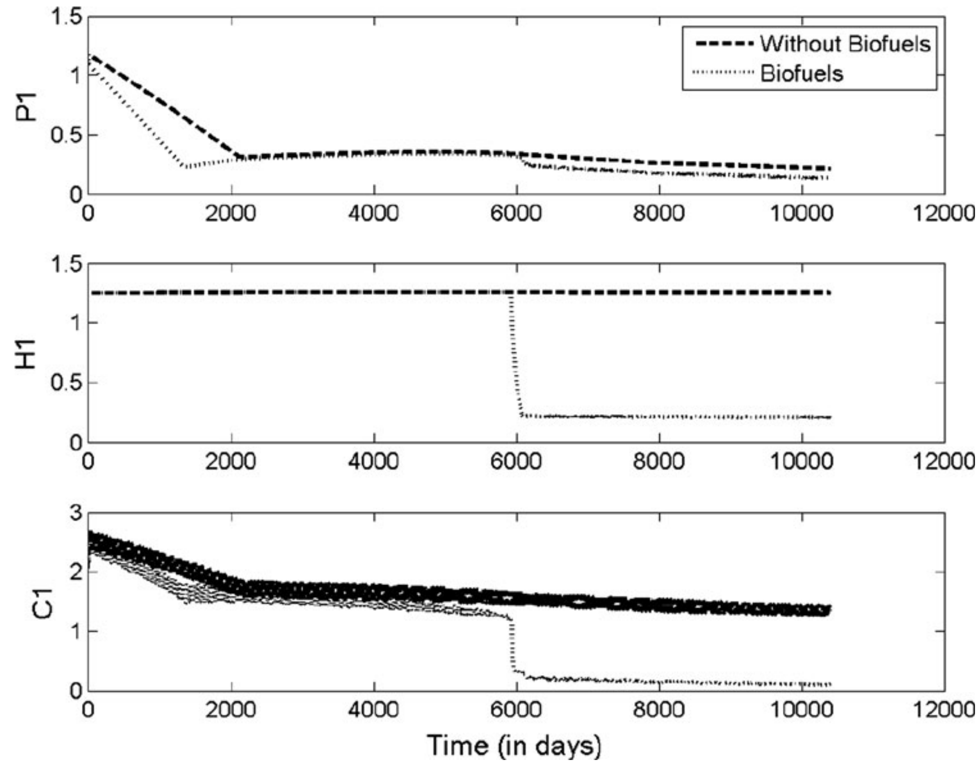


Fig. 6 Profiles of primary producer, herbivore and carnivore (population explosion)

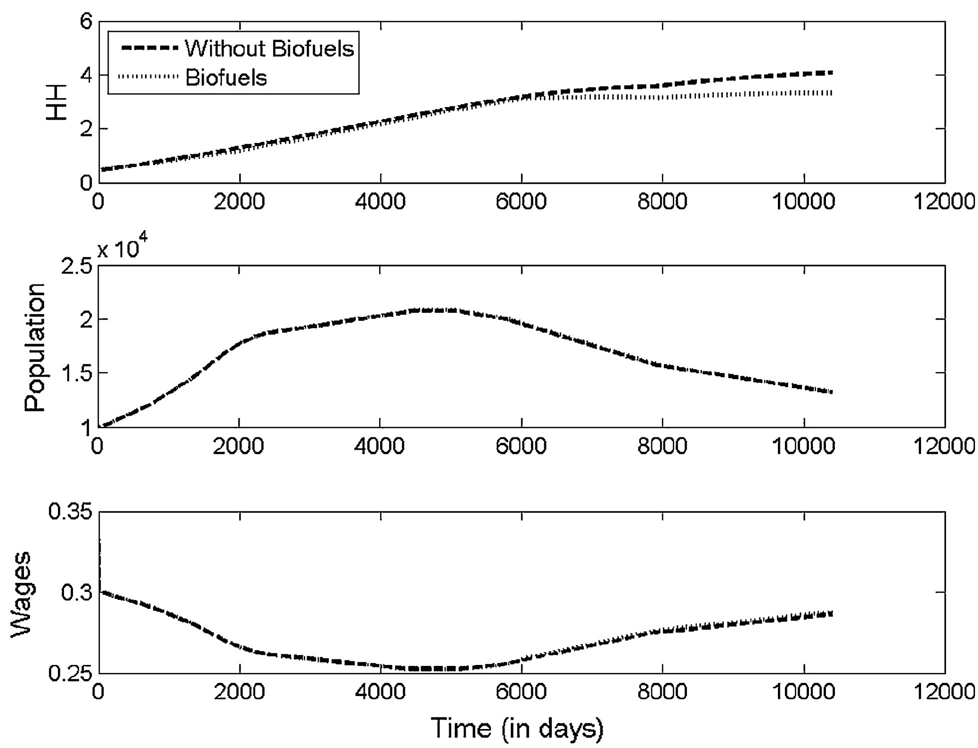


Fig. 7 Profiles of human mass, human population and wages (population explosion)

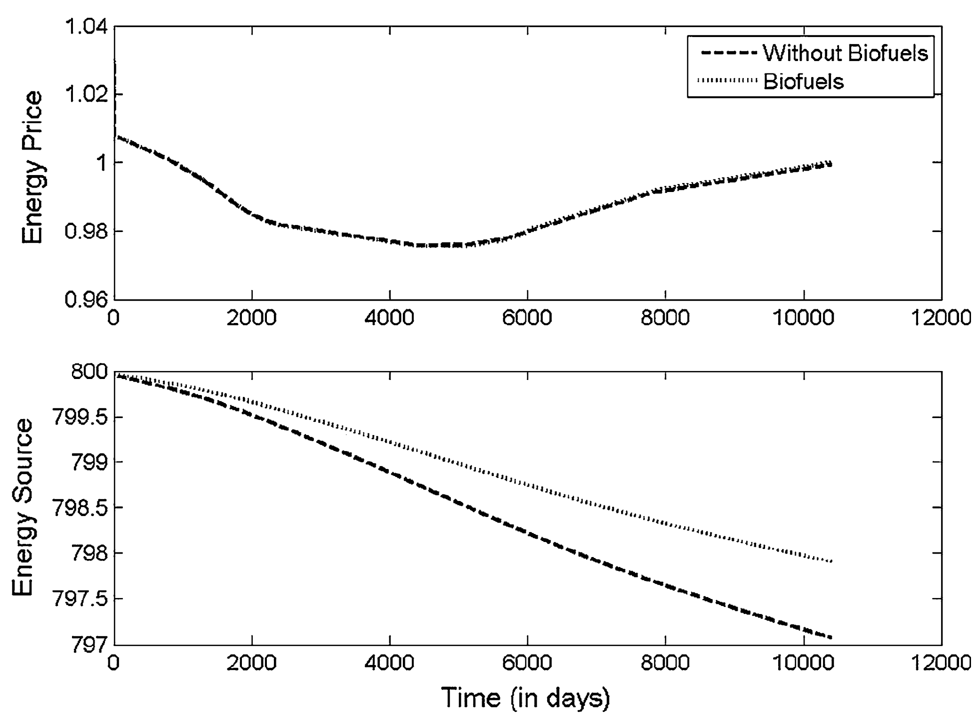
biomass, the amount of P1 decreases and hence the availability of P1–HH decreases thereby causing the drop in human mass. Figure also shows that there is no change in the levels of human population because of the production of energy using biomass. It can also be seen that the drop in the compartmental mass of HH does not get translated into a reduction of the human population. This invariably indicates that the per capita mass of the humans has decreased thereby corroborating both the decrease in human mass and similar levels of human population. Therefore, it can be seen that the use of biomass for producing energy need not necessarily lead to a decrease in the human population but can instead decrease the per capita mass of the human population. Figure also shows the wages paid by all the industries to the human compartment for their labor work. It can be seen that the production of energy using biomass does not lead to an increase in the wages. The wages paid to the HH are inversely proportional to the human population, i.e., an increase in the human population decreases the wages of the HH. Thus, it can be seen that the wages are low when the population is high and increases steadily with an increase in the population levels.

Figure 8 shows the price of energy and the amount of ES available in the ES compartment. It can be seen that the decrease in the amount of 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 for both the cases. This is primarily because the price of energy is dictated by the ES industry which in turn is a function of wages and the amount of fuel. 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 the wages start increasing and this gets reflected in the price of energy. This completes the discussion of the population explosion scenario analysis. We will now discuss the scenario of increase in the consumption levels of the humans.

Scenario analysis: increase in consumption levels

The consumption levels of humans have been estimated to be far higher when compared to any other species on Earth. Many of these resources that humans consume are non-renewable and are finite in nature. The resources which are renewable are consumed at a rate much faster than the time required for its replacement. Such abnormal consumption levels could severely affect the current composition of the ecosystem (Finkelstein and Zuckerman 2008; Arrow et al. 2004; Imhoff et al. 2004). Some studies have suggested that the current levels of human consumption could be up to 40 % higher than the sustainable threshold consumption levels Rothman et al. (2015). Moreover, with increase in per capita income, the quality of life and dispensable income has increased particularly in populated countries and very often leads to an increase in the per capita consumption of both mass and energy. This continuous increase in consumption levels could not only breakdown the ecosystem services but can also endanger the long-term sustainability of the ecosystem. The prediction in the rate of resource consumption is a difficult task primarily due to the large number and varied resources that are present in the ecosystem. However, there have been some studies which have predicted that the consumption levels of most

Fig. 8 Profiles of energy prices and ES (population explosion)



of the resources will increase by an average of about 50 % over the next 50 years (Meadows et al. 1992; Shastri et al. 2008b). 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 of resources. This strategy of modeling consumption increase is similar to the previous published work on this model by Shastri et al. (2008b). We will now present the discussion on the dynamics of various compartments present in the ecosystem under increased levels of consumption.

Figure 9 shows the profiles of the primary producers, herbivore and the carnivore under the scenario of consumption increase. It can be seen from figure that the 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 ecosystem. The level of P2 was also seen to decrease whereas the level of P3 increased due to increased levels of the RP. These changes in the primary producers have cascading effects on the other components of the ecosystem. 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 for the ecosystem 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 levels 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. Hence, it can be seen that the use of P1 to produce energy in an increased consumption level scenario could accelerate the extinction of some of the species.

Figure 10 shows the profiles of the mass of the HH, the human population and the wages for the scenario of increase in consumption levels. 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. Figure also shows that there is a drop in human population towards the end of the simulation horizon. The level of human population is slightly lesser 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 HH and subsequently manifests into a decreased population. Figure also shows the prevailing wages as decided by the 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

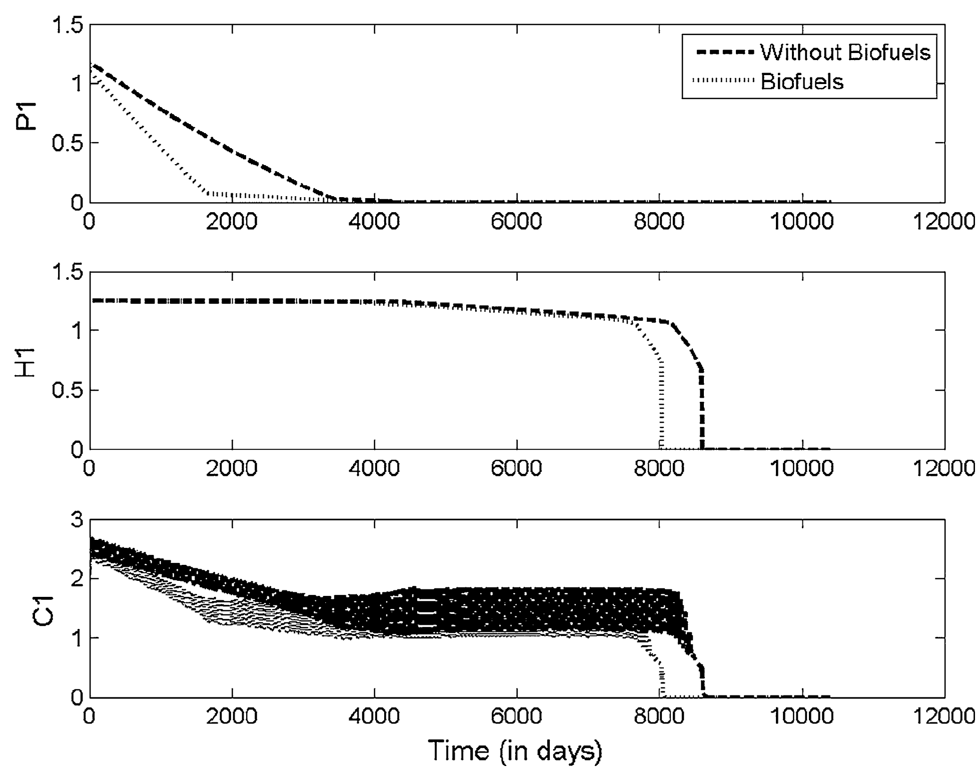


Fig. 9 Profiles of primary producer, herbivore and carnivore (consumption increase)

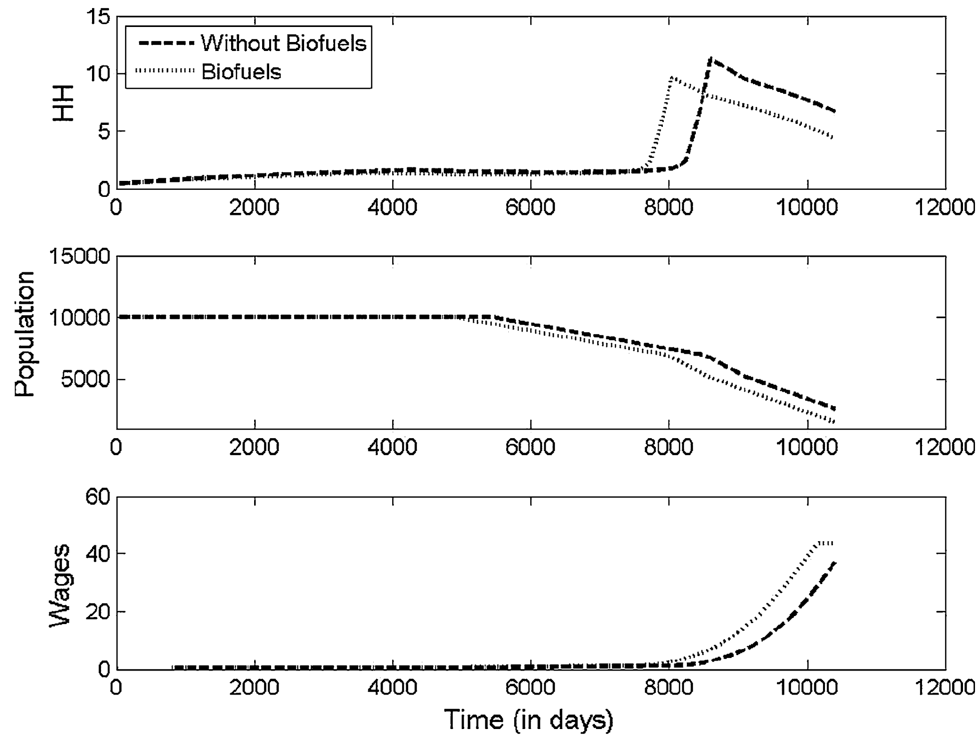


Fig. 10 Profiles of human mass, human population and wages (consumption increase)

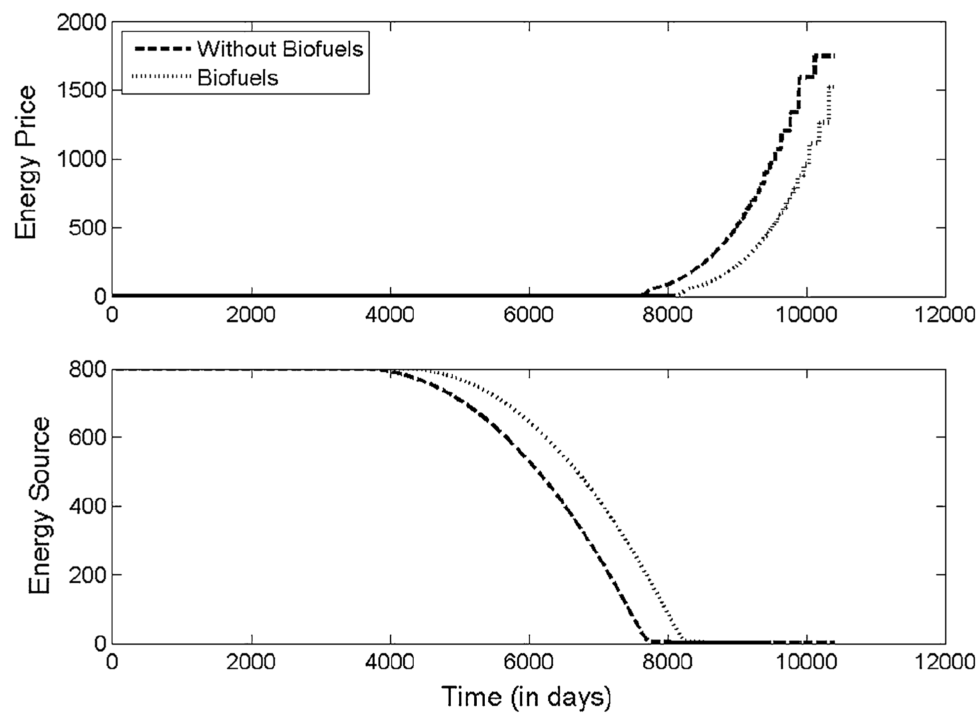


Fig. 11 Profiles of energy prices and ES (consumption increase)

the end due to a decrease in the human population. This is as per the assumptions of the model wherein the wage rate remains constant with a constant population level and starts to increase with a drop in the level of population.

Figure 11 shows the price of energy and the amount of non-renewable energy source available in the ecosystem. As with the base case and population explosion scenario, the decrease in the amount of ES is less if a portion of the energy is produced from biomass. The use of P1 for producing a part of energy decreases the utilization of the non-renewable energy source and hence the decline in it is moderate. However, in both the cases the ES faces decline and the use of biomass for producing energy merely delays the exhaustion of the ES since it is non-renewable. The price of energy is a function of wages and the amount of ES available in the ecosystem. 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 and 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 explosion scenario. This is because the population has come down to very low levels thereby increasing the wage levels. Moreover, the scarcity of energy source also contributes to the increase in the price of energy.

From the results discussed in this section, it can be seen that the study of sustainability of even a simple ecosystem may not be intuitive due to the inter dependency and cascading effects of the various components of the ecosystem. Moreover, the fact that the results of many of the actions get manifested over a period of time reinforces the need for a formal study of sustainability that could provide at least qualitative insight into the possible repercussions. The model proposed in this article could possibly serve as a starting point for developing complex models that could aid in the study of sustainability of the ecosystem.

Conclusions

The importance of sustainability has been well understood and the need for a systematic study of sustainability has been recognized across various disciplines. In this article, we have presented an enhanced 14 compartmental model of the ecosystem which could be used to derive qualitative inferences for various scenarios and aid in the formal study of sustainability. As energy plays a crucial role in a real ecosystem, the proposed model incorporates the generation and utilization of energy in the ecosystem. In particular, we have used this model to study the impact of using biomass for the production of energy on the sustainability of the ecosystem under plausible scenarios such as population explosion and an increase in the human consumption levels. The base case results show that the model presented in this chapter is stable. Under the scenario of population explosion, it was observed that the use of biomass does not decrease the human population but nevertheless leads to a decreased per capita human mass which may be inferred as an indicator for 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 consumption increase, it was observed that the ecosystem cannot 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 expedites 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 evaluate the impact of alternate technologies on the long-term sustainability of an ecosystem. 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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References

Acutt M, Mason P (1998) Environmental valuation, economic policy and sustainability: recent advances and environmental economics. Edward Elgar, Cheltenham

Arrow K, Dasgupta P, Goulder L, Daily G, Ehrlich P, Heal G, Levin S, Mäler K, Schneider S, Starrett D, Walker B (2004) Are we consuming too much? J Econ Perspect 18:147–172

Bossel H (1998) Earth at a crossroads: paths to a sustainable future. Cambridge University Press, Cambridge

Brock W, Xepapadeas A (2002) Optimal ecosystem management when species compete for limiting resources. J Environ Econ Manag 33:189–220

Brundtland G (1987) Our common future; world commission on environment and development. Oxford University Press, Oxford, p 383

Cabeza Gutes M (1996) The concept of weak sustainability. Ecol Econ 17:147–156

Cabezas H, Fath B (2002) Towards a theory of sustainable systems. Fluid Phase Equilib 2:194–197

Cabezas H, Pawlwoski C, Mayer A, Hoagland N (2003) Sustainability: ecological, social, economic, technological, and systems perspectives. Clean Technol Environ Pollut 5:1–14

Cabezas H, Pawlowski C, Mayer A, Hoagland NT (2005) Simulated experiments with complex sustainable systems: ecology and technology. Resour Conserv Recycl 44:279–291

Cabezas H, Whitmore HW, Pawlowski CW, Mayer AL (2007a) On the sustainability of an integrated model system with industrial, ecological, and macroeconomic components. Resour Conserv Recycl 50:122–129

Cabezas H, Whitmore H, Pawlowski C, Mayera A (2007b) On the sustainability of an integrated model system with industrial, ecological, and macroeconomic components. Resour Conserv Recycl 50:122–129

Capistrano D, Samper CK, Lee MJ, Raudsepp-Hearne C (2005) Ecosystems and human well-being: multi-scale assessments, vol

4. In: Millennium ecosystem assessment. Island Press, Washington, DC

Carpenter S, Brock W, Hanson P (1999) Ecological and social dynamics in simple models of ecosystem management. Conserv Ecol 3:4

Carpenter SR, Pingali PL, Bennett EM, Zurek MB (2005) Ecosystems and human well-being: scenarios, vol 2. In: Millennium ecosystem assessment. Island Press, Washington, DC

Chopra K, Leemans R, Kumar P, Simons H (2005) Ecosystems and human well-being: policy responses, vol 3. In: millennium ecosystem. Island Press, Washington DC

Cohen JE (2003) Human population: the next half century. Science 302:1172–1175

Costanza R, Voinov A, Boumans R, Maxwell T, Villa F, Wainger L, Voinov H (2002) Integrated ecological economic modeling of the Patuxent river watershed, Maryland. Ecol Monogr 72: 203–231

Fath B, Cabezas H, Pawlowski C (2003) Regime changes in ecological systems: an information theory approach. J Theor Biol 222:517–530

Finkelstein EA, Zuckerman L (2008) The fattening of America: how the economy makes us fat, if it matters, and what to do about it. Wiley, Hoboken

Hassan R, Scholes R, Ash N (2005) Ecosystems and human well-being: current state and trends, vol 1. In: Millennium ecosystem assessment. Island Press, Washington, DC

Heal G (1998) Valuing the future: economic theory and sustainability. Columbia University Press, New York

Holling C, Gunderson LH, Ludwig D (2002) In quest of a theory of adaptive change. In: Gunderson LH, Holling C (eds) Panarchy: understanding transformations in human and natural systems. Island Press, Washington, DC, pp 3–22

Imhoff ML, Bounoua L, Ricketts T, Loucks C, Harriss R, Lawrence WT (2004) Global patterns in human consumption of net primary production. Nature 429(24):870–873

Janssen MA (2002) A future of surprises. In: Gunderson LH, Holling C (eds) Panarchy: understanding transformations in human and natural systems. Island Press, Washington, DC, pp 241–260

Kolosov G (1997) Size control of a population described by a stochastic logistic model. Autom Remote Control 58:678–686

Ludwig D, Carpenter S, Brock W (2003) Optimal phosphorous loading for a potentially eutrophic lake. Ecol Appl 13:1135–1152

McMichael A, Butler C, Folke C (2003) New visions for addressing sustainability. Science 302:1919–1920

Meadows DH, Meadows LD, Randers J (1992) Beyond the limits:confronting global collapse. Envisioning a sustainable future. Chelsea Green Publishing Company, Post Mills

Raven PH (2002) Science, sustainability and the human prospect. Science 297:954–958

Rothman DS, Agard J, Alcamo J (2007) The outlook-towards 2015 and beyond. The future today. In: Global Environment Outlook GEO 4: environment for development. United Nations Environment Programme, Nairobi

Scholes R, Hassan R, Ash NJ (2005) Ecosystems and human well-being: current state and trends. In: Millennium ecosystem assessment, vol 1. Island Press: Washington, DC

Shastri Y, Diwekar U (2006a) Sustainable ecosystem management using optimal control theory. Part 1 (deterministic systems). J Theor Biol 241:506–521

Shastri Y, Diwekar U (2006b) Sustainable ecosystem management using optimal control theory. Part 2 (stochastic systems). J Theor Biol 241:522–532

Shastri Y, Diwekar U, Cabezas H (2008a) Optimal control theory for sustainable environmental management. Environ Sci Technol 42:5322–5328

Shastri Y, Diwekar U, Cabezas H, Williamson J (2008b) Is sustainability achievable? Exploring the limits of sustainability with model systems. Environ Sci Technol 42:6710–6716

Stern N (2006) The economics of climate change: the stern review. Cambridge University Press, Cambridge

United Nations (2004) World population to 2300. Technical Report ST/ESA/SER. A/236

United Nations Environment Programme (2007) Global environment outlook GEO 4: environment for development, United Nations Environment Programme. Progress Press Ltd., Malta

van den Bergh J (1996) A multisectoral growth model with materials flows and economic-ecological interactions. In: Ecological economics and sustainable development. Edward Elgar, Cheltenham, pp 147–172

Whitmore H, Pawlowski C, Cabezas H (2006) Integration of an economy under imperfect competition with a twelve-cell ecological model. Technical Report EPA/600/R-06/046