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A Novel Integrated Ecological Model for the study of Sustainability

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Abstract: In recent years, there has been a growing interest among various sections of the society in the study of sustainability. Recently, a generalized mathematical model depicting a combined economic-ecological-social system has been proposed to help in the formal study of sustainability. This model was based on an assumption of non-limiting supply of energy thereby limiting its applicability to real-world scenarios in which energy plays a very crucial role. In this work, we propose an enhanced model which considers various factors related to energy in an integrated economic-ecological-social framework. As a preliminary use of the proposed model, it has been used to conduct various scenario studies to help understand the complex dynamic relationships between the different entities of the ecosystem and to identify any potential catastrophes or trends.

Keywords: Sustainability, Energy models, Ecological economic models, Integrated models

1. INTRODUCTION

The interest of almost every community in sustainability has been tremendously increasing as it has become obvious that the biological systems of the Earth cannot indefinitely support current rates of human population growth and resource consumption. Sustainability or sustainable development has been generically defined as "the development that meets the needs of the present without compromising the ability of the future generations to meet their own needs." Hence, sustainability is considered to be not a goal to be reached but more of a path or corridor that needs to be maintained throughout time. A substantial amount of recent literature that is focussed on sustainability issues has been cited by Shastri & co-workers (Shastri et. al., 2008a & Shastri et. al., 2008b). A number of existing Computable General Equilibrium have also been reviewed by Conard (Conard, 2002) and are based on the integration of certain features of the environment into an economic framework.

The growing interest in sustainability is largely attributed to the realization that the continuous sustenance of the current ecosystem is possible only if we carefully understand the implications of the policies that are being practiced and take corrective steps. In the absence of informed decisions, there is a greater possibility that the ecosystem may be irrevocably damaged even leading to the extinction of several species including the human race. Thus, it is imperative to study the sustainability of the ecosystem before implementing any major policy changes. To do so, it is beneficial to have a mathematical model corresponding to the ecosystem so that the sustainability of various species under different simulated scenarios can be evaluated. A model can be used in exploring sustainable environmental management strategies without the risk of experimenting with real ecosystems and with real people. Also, a model can be used to simulate over a long range of time which can be more than the lifetime of an average human being and help us in studying the long term implications of the current human actions. Moreover, many effects of our current actions are often not evident immediately and manifest themselves only over a period of time thereby necessitating a model with predicting capabilities.

Recently, Whitmore & co-workers (Whitmore et. al., 2006) proposed the integration of an economy under imperfect competition with a twelve compartment ecological foodweb model. The model was assumed to be closed to mass and open to energy. The model explicitly addresses resource limits as it is closed to mass. The distribution of mass among various compartments of the integrated system is governed by the economic decisions and biological interactions between various compartments and consequentially governs the scarcity of resources or extinction of any of the compartmental species. This model also accounted for a legal foundation as it identified the mass in terms of its property type. In addition, an explicit market system of decision making is also implemented in the form of a price setting model. This model has been used by various researchers for studying different aspects of sustainability. However, this model is based on the assumption of non-limiting supply of energy and hence limits its applicability to real-world scenarios where energy plays a crucial role. In this work, we present an enhanced model which overcomes the above mentioned limitations of the current model. In particular, we consider a fuel source (in addition to the accessible and inaccessible resource pool) and an energy producer supplying energy to the human compartment and the industrial sector. We also present preliminary results on two important scenarios: the scenario of population explosion and the scenario of an increase in the level of human consumption.

The article is organized as follows: The succeeding section briefly describes the proposed mathematical model and the simulation strategy. This is followed by two sections: each of these sections describes a potential scenario and its effect on the various aspects of the system. The article is finally concluded with a brief description of this work and also mentions the future work oriented in this direction.

2. MATHEMATICAL MODEL

The food web model enhanced in this work was initially presented in Cabezas & co-workers (Cabezas et. al., 2005) and Whitmore & co-workers (Whitmore et. al., 2006). The proposed model is shown in Figure 1 and represents a simple ecosystem. The model includes a human compartment, a simple industrial process, an energy producer and an agricultural system. The model accounts the flow of generic mass (biomass, nutrients, water, etc.) and energy within a closed system (i.e., the cumulative sum of masses and energy of all the system compartments is constant). The motivation for this model is to include crucial and representative elements of the real world ecosystem while keeping it simple enough for mathematical analysis.

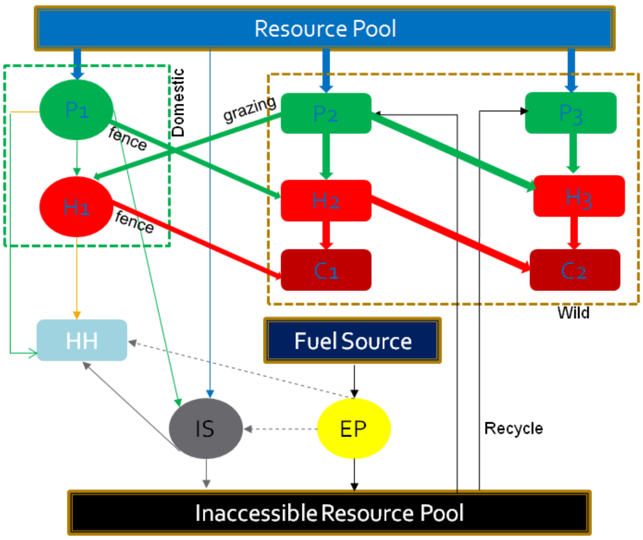

Fig 1. Integrated ecological-economic-social model

In particular, the proposed model includes four aggregated trophic levels (plants, herbivores, carnivores, and humans as a top omnivore), two resource pools along with a fuel source. There are 14 compartments, namely a resource pool (RP), three plants (P1, P2, and P3), three herbivores (H1, H2, and H3), two carnivores (C1 and C2), a human population (HH), an industrial sector (IS), a fuel source (FS), an energy producer (EP) and an inaccessible resource pool (IRP). The RP compartment is included to represent all biological resources (such as water, nutrients, etc.) whereas IRP is included to represent resources that are biologically unavailable as a result of human activity. The EP consumes fuel from the fuel source and supplies energy (FE) to HH and IS. The model can be conceptually divided into two characteristic branches as shown in the figure: domesticated (representing agricultural and livestock activities) comprising compartments P1, and H1 on the left, and non domesticated (representing species hunted, gathered, and species not consumed by humans) consisting of compartments P2, P3, H2, H3, C1, and C2 on the right. Primary producers make available resources from accessible resource pool (RP) to the rest of the food web. Mass from the IRP is recycled very slowly back to P2 and P3 through the action of bacteria and thus is "inaccessible" to the other compartments of the system. All biological compartments recycle mass back to the RP through death. These flows are not shown in the figure to aid in the clarity of the figure. The flow of mass from the biological compartments to RP is proportional to the death rate of the species represented by the compartment.

From an economic perspective the model contains five compartments: HH, IS, EP, P1 and H1. Households must decide either utilizing the time to work in one of the four industries (IS, EP, P1 and H1) or to leisure. The human birth rate at any instant of time is assumed to be a negative function of the wage. This assumption is based on the fact that the real wage represents the opportunity cost of opting to remain outside the labor force (at least part-time) for the purpose of rearing children. The P1 firm uses resources from the RP and labor from the HH to produce plant inventory P1 whereas the H1 firm uses resources from P1 and P2 along with labor from HH to produce an inventory of H1. H2 is a wild herbivore that consumes P1 and P2. The P1 firm devotes labor to build and maintain fences to keep H2 from consuming P1. The H1 firm pays a fee to have grazing access to P2. It is assumed that this access is limited by the government to a fixed quantity, and that the H1 firm will consume the maximum that is allocated by the government. The P1 and H1 inventory in terms of mass is directly transferred to their respective consumers. A cyclic variation in the ecological compartments of the model is also incorporated as discussed in literature (Cabezas et. al., 2002 and Shastri et. al., 2008b). This feature is to primarily depict the scenarios of natural low growth and high growth seasons which occurs in the real world.

The carnivore C1 is a protected species and preys on H1 and H2. The H1 industry invests labor in fences to stop C1 from consuming the H1 inventory. The carnivore C2 consumes H2 and H3 both of which are wild compartments. The industrial sector combines resources (RP) with plants (P1) and labor to produce goods that are consumed directly by the households. Unlike the P1 and H1 inventory, the mass associated with the consumption of IS inventory is directly transferred to IRP and does not increase the mass of the human compartment. The industrial sector is charged a waste discharge fee for contributing mass to the IRP compartment. The EP consumes fuel from the FS compartment to produce FE which is supplied to the HH and IS compartments. The mass of fuel used to produce energy is directly transferred to the IRP and does not increase the mass of any other compartment. The firms and the households have their own optimization goals. Firms attempt to maximize the difference between the sale of their products less the costs (of materials and labor), while households maximize their utility (incoming flow of goods balanced against leisure). A price setting mechanism has been used as against a general equilibrium setting as it allows trades to occur even if markets fail to clear. Any excess inventory is carried to the next time step whereas any shortfall is made up with current inventory.

Unless mentioned otherwise, the necessary equations and parameters used in this study are the same as those used in literature (Shastri et. al., 2008b and Cabezas et al.,2005). The simulation strategy employed at each time step is given as follows

Step 1: Determination of wage rate as governed by the industrial sector (IS).
Step 2: Determination of prices and production targets by the four industries P1, H1, IS and EP. This is based on the utility functions and internal models of demand of their products.
Step 3: Determination of demands for P1, H1, IS and FE by humans. The following equations represent the demands of various products by human households.

$$\begin{aligned} P1^{demand} &= d_1 - k_1 p_t^{P1} + \frac{1}{3} m_1 p_t^{H1} + \frac{1}{3} n_1 p_t^{IS} + \frac{1}{3} o_1 p_t^{FE} \\ &\quad + z_1 \left(P1^{demand} + H1^{demand} + IS^{demand} + FE^{demand} \right) \\ H1^{demand} &= d_2 + \frac{1}{3} k_2 p_t^{P1} - m_2 p_t^{H1} + \frac{1}{3} n_2 p_t^{IS} + \frac{1}{3} o_2 p_t^{FE} \\ &\quad + z_2 \left(P1^{demand} + H1^{demand} + IS^{demand} + FE^{demand} \right) \\ IS^{demand} &= d_3 + \frac{1}{3} k_3 p_t^{P1} + \frac{1}{3} m_3 p_t^{H1} - n_3 p_t^{IS} + \frac{1}{3} o_3 p_t^{FE} \\ &\quad + z_3 \left(P1^{demand} + H1^{demand} + IS^{demand} + FE^{demand} \right) \\ FE^{demand} &= d_4 + \frac{1}{3} k_4 p_t^{P1} + \frac{1}{3} m_4 p_t^{H1} + \frac{1}{3} n_4 p_t^{IS} - o_4 p_t^{FE} \\ &\quad + z_4 \left(P1^{demand} + H1^{demand} + IS^{demand} + FE^{demand} \right) \end{aligned}$$

where p_t^x indicates the price of the product x and all other terms denote constant parameters. These equations are based on the fact that the demand of a particular product decreases with an increase in its prices whereas the demand increases with an increase in the prices of other products. The above equations are simultaneous equations and explicit equations can be obtained using standard mathematical software (eg. MATLAB).
Step 4: Determination of demands for goods and labor for various industries like IS and EP.
Step 5: Checks are done for internal consistencies of flows (to be sure they meet positivity constraints on flows and compartment masses).
Step 6: The next step is implemented (flows are transferred) for both the economic and ecological parts of the model.

Some of the typical features of this combined ecological-economic-social systems are (1) it is an organization based on trophic levels, (2) the number of species decreases with higher tropic levels, (3) species specific preferences for food source (e.g., C2 consumes H2 but not H1), (4) the presence of humans with industrial production, agricultural production, an economy, and law including private property (5) the presence of mass that is biologically unavailable as result of industrial activity (6) the presence of an energy producer producing energy from a non replenishable source. The proposed model has 20 ecological model parameters such as growth and mortality rate of various compartments that govern the dynamics of the natural compartments and 72 economical parameters such as the coefficients of the economic function that compute the economic variables such as wage rate, production rate, product demand, and product price. In addition, the model has 20 state variables such as the initial amount of mass in various compartments and the initial population level. There are a total of 41 additional model outputs which indicate the flow of various species from one compartment to the other.

In the next section, we will study the effect of various scenarios on the proposed model. Scenarios are plausible, challenging, and relevant stories about how the future might unfold and can be described both in quantitatively as well as qualitatively (Millennium Ecosystem Assessment, 2005). These scenarios address real-world questions of systems dynamics, policy choices, technological evolution, and consumption & production patterns thereby helping in envisioning future pathways and accounting for critical uncertainties. It may be noteworthy to indicate that scenarios are not forecasts, projections, predictions, or recommendations for actual future. The actual future development can be a combination of multiple scenarios, and various scenarios might be realized for different ecosystems in the world. In this work, we have studied two important scenarios namely the population explosion and an increase in the consumption pattern of the humans. The following results are generated by simulating the model in MATLAB. In the following discussion, base case will indicate the simulation results in the absence of population explosion or increase in the consumption levels.

3. SCENARIO ANALYSIS: POPULATION EXPLOSION

The scenario of human population explosion has received considerable attention particularly from the perspective of resource availability. Factors like better health care have caused a decrease in the mortality rate whereas factors such as better education for women and increased awareness of birth control measures have caused a decrease in birth rate. In 50-100 years, the human population is expected to peak and settle to about twice the current value (Cohen, 2003, Capistrano et., al., 2005 and Shastri et. al., 2008b). After this period, aging population and a further drop in human fertility rates will be responsible for a steady drop in human population (United Nations Report, 2004). There has been no universal consensus on the exact numbers but this has been accepted to be the most likely scenario. In the current model, the variations in the dynamics of the human population are implemented by adjusting the trends in the mortality and birth rates.

Figure 2 shows the profiles of human mortality and human birth rate used in this study. For the population explosion scenario, the mortality rate drops in a piecewise linear manner and settles at a value, while the coefficients in birth rate function are nonlinearly varied as shown in this figure. These simultaneous changes lead to the desired variation in the population. Apart from the birth and mortality rates, other parameters of the model are fixed at their base case values.

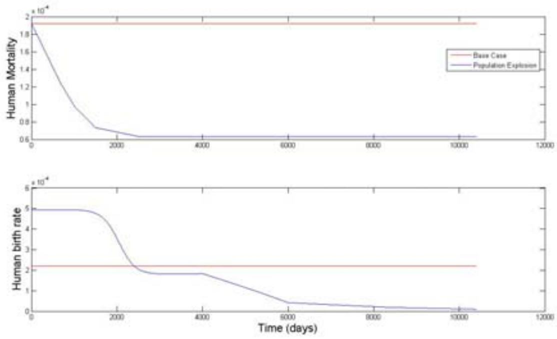

Fig 2: Profiles of human birth and mortality rate

Figures 3 to 8 show the profiles of various compartments and it can be seen that there are no catastrophic changes in these compartments. Figure 3 shows the profiles of the domestic compartments P1 and H1 along with IS and HH. It can be seen that the decrease in P1 for the case of population explosion is faster than that of the base case. This can be attributed to the fact that an increase in human population consumes a large amount of P1. Further, it can also be seen that the per capita mass of humans is growing throughout the simulation horizon despite a subsequent decrease in the population as shown in Figure 6.

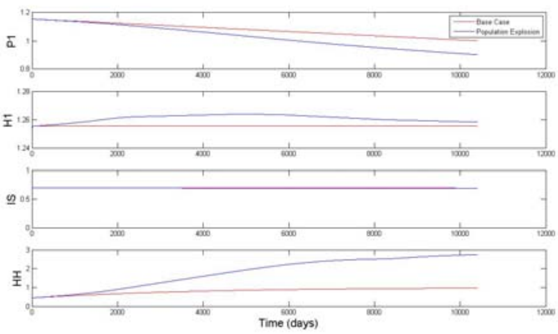

Fig 3: Profiles of compartments P1, H1, IS and HH

Figure 4 and Figure 5 show the compartmental profile of the non domesticated compartments of the ecosystem along with RP and IRP. An increase in the population causes a decrease in the growth of the plant P2 and P1 leading to a cascading effect on the subsequent compartments of H2 and C1. However, the mass of none of these species reaches zero thereby indicating that the population explosion scenario does not lead to extinction of the protected species C1. These figures indicate that the assumed population scenario does not affect the sustainability of any of the species in the ecosystem.

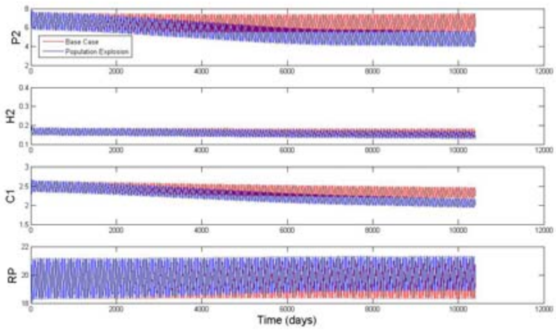

Fig 4: Profiles of compartments P2, H2, C1 and RP

Figure 6 shows the profiles of wage rates as decided by the IS industry and the growth of human population throughout the simulation period. It can be seen that the human population increases initially and subsequently starts to decrease. This nature is as desired (and as predicted in the United Nations Report, 2004) to account for the scenario of population explosion. It can be seen that the profile of the wage rates is inverse to that of the population i.e., the wage rate initially decreases and subsequently increases with a decrease in the level of population. This is attributed to the fact that an increase in the labor supply leads to a natural decrease in the labor cost and this trend is reversed when the supply of labor starts to decrease.

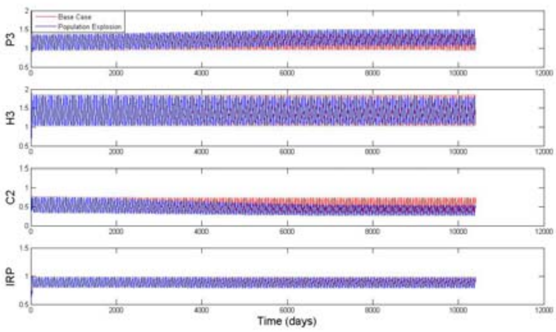

Fig 5: Profiles of compartments P3, H3, C2 and IRP

Figure 7 shows the profiles of various parameters related to the energy sector. It can be seen from this figure that the amount of fuel (FS) in the ecosystem continuously decreases as it is not being replenished. As expected, the decrease in the case of population explosion is faster than the base case due to the larger requirement of energy by the growing population. It can also be seen from Figure 6 and 7 that the demand for energy by the human compartment increases as the population increases. Additionally, the price of energy initially decreases despite an increasing scarcity of the fuel and hence the demand of energy also increases. This can be attributed to the fact that the increase in population decreases the wage rate thereby lowering the cost of production of energy. However, the price of energy starts increasing as the populations starts to decrease and the wage rates starts to increase.

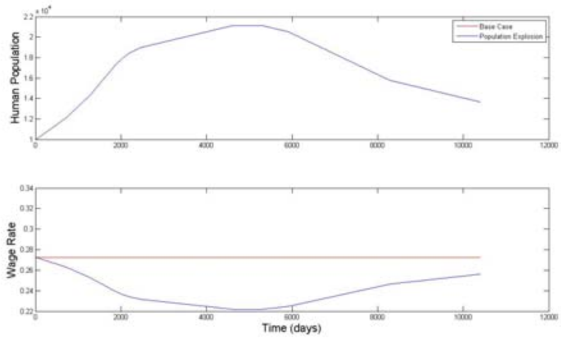

Fig 6: Profiles of wages and Population

From this scenario, it can be seen that the proposed model is able to effectively capture the various dynamics arising due to an increase in the human population. Additionally, it can also be seen that an increase in the human population does not lead to a drastic extinction of any of the species present in the ecosystem. In the next section, we present a similar analysis for the case of an increase in consumption levels by the human households.

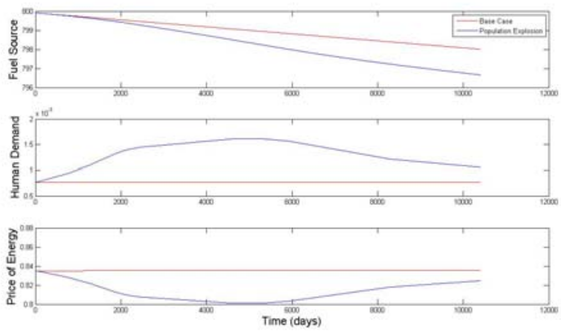

Fig 7: Profiles of FS, price of energy and energy demand by humans

4. SCENARIO ANALYSIS: CONSUMPTION INCREASE

The per capita consumption of both mass and energy is continuously increasing throughout the world primarily due to the increasing quality of life. This has even given rise to predictions that such an increase in consumption will ultimately lead to a breakdown in ecosystem (Arrow et. al., 2004, Shastri et. al., 2008b). A recent Global Environment Outlook study by the United Nations reports that the present level of human resource consumption is 40% more than the sustainable threshold (Rothman et. al., 2007). Some studies have been reported which predict that the average per capita consumption of many resources will increase on average by about 50% over the next 50 years (Meadows et. al., 1992). The increase in rate of resource consumption varies widely depending upon the type of resource and is hence more difficult to model than an increase in population.

In this work, the coefficients of per capita demand functions in the price setting model are scaled linearly to model the per capita consumption. Figure 8 shows the compartmental profiles of the domesticated compartments. It can be seen that an increase in consumption by the humans leads to the extinction of the species P1. This results in the extinction of the species H1 and also decreases the levels of the industrial product as these are primarily dependent on P1. It can also be seen that an increase in the consumption level increases the per capita mass of the human households. However, after the extinction of P1, H1 and IS, the average per capita mass of the human households also starts decreasing.

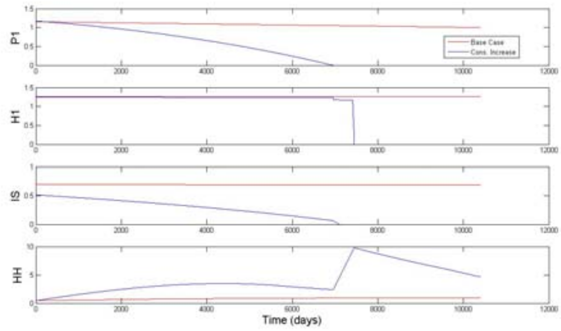

Fig 8: Profiles of compartments P1, H1,IS and HH

Figure 9 and Figure 10 show the profiles of the compartmental mass of the various non domesticated compartments and resource pools. From Figure 9, it can be seen that an increase in the consumption levels of humans causes the extinction of the species P2 which in turn leads to the extinction of the species H2 and C2 which are dependent on P2. From Figure 10, it can be seen that an increase in the consumption levels of humans increases the level of P3 and H3. This happens because the extinction of the species P1 and P2 leads to a larger RP and higher growth of P3 and H3.

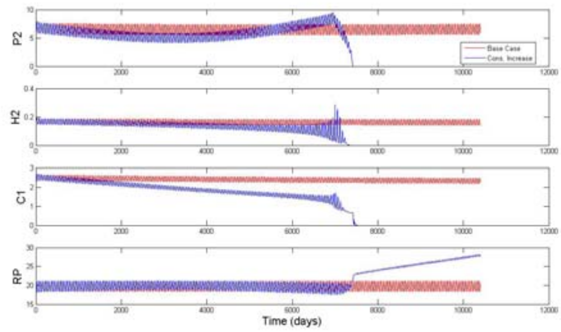

Fig 9: Profiles of compartments P2, H2, C1 and RP

Figure 11 shows the profiles of the human population and the wage rates. As expected, the initial level of human population is constant despite an increase in the human consumption levels as the ecosystem is able to support higher consumption levels. However, the population starts decreasing after the initial period due to the non availability of survival resources like P1 and H1. It can also be seen that the profile of wages is inverse of the population level. There is no significant variation in the initial wage rates due to the constant population. However, the subsequent decrease in population levels causes an increase in the wage rates due to the widening of the demand supply gap.

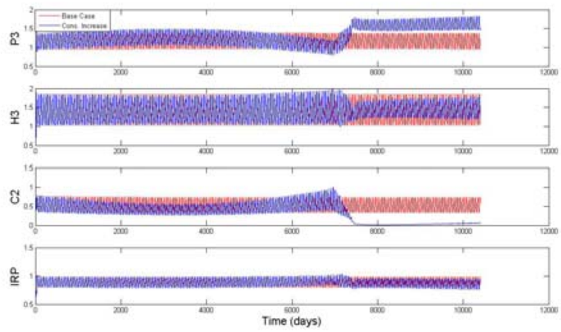

Fig 10: Profiles of compartments P3, H3 and C2

Figure 12 shows the profiles of the fuel source, the demand of energy by humans and also the price of energy. It can be seen from this figure that an increase in consumption leads to a continuous decrease in the fuel source. The price of energy keeps increasing due to the scarcity of the fuel source and an increase in the wage rates of the human households. Similarly, the energy demands by the humans reach a maximum and starts decreasing due to the high price of energy and also due to the decreasing population.

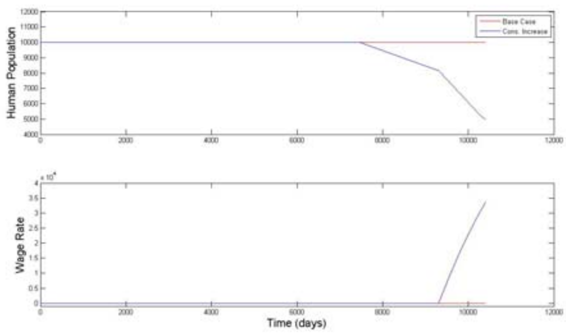

Fig 11: Profiles of wages and Population

The scenario of increased consumption levels by human households clearly shows that such increased consumption levels can be supported for a long period of time and ultimately leads to the extinction of critical components and a breakdown of the ecosystem. The extinction of many of the species can also ultimately result in the extinction of even the human race. Hence, it is necessary to note that the levels of consumption be maintained at current levels so as to avoid a catastrophic breakdown of the ecosystem.

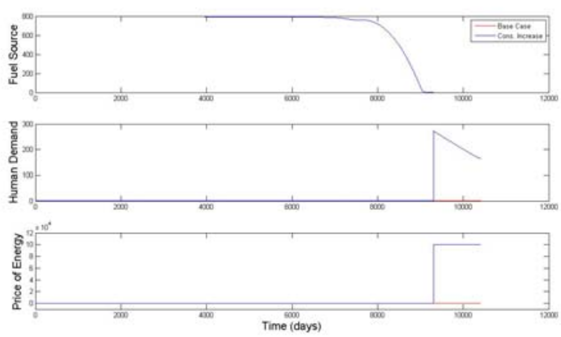

Fig 12: Profiles of FS, price of energy and energy demand by humans

5. CONCLUSIONS

In this work, we have presented a 14 compartmental food web model which is closed to both mass and energy and can be used to study various aspects of sustainability. In addition, various scenarios have been considered as part of this study to determine their effects on the sustainability of the ecological system. It can be seen that the proposed model is able to capture the various dynamics of an ecosystems. Future works in this direction will include implementation of control strategies under various kinds of uncertainty to maintain a sustainable system.

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