Resource Scarcity and Conflict an Economic Analysis[*]

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Abstract

As time passes, renewable resource scarcities are becoming more common throughout the world. There is increasing evidence that these scarcities are a causal factor in civil unrest and violent conflict, especially in developing countries. We present a simple model of renewable resource dynamics, population dynamics and conflict. Conflict is triggered by per capita resource scarcity. We examine the role and nature of conflict on the bio-economic system. We find that conflict is Nature's way of protecting vital renewable resources from human exploitation. Conflict, as modeled, increases the death rate of the human population, damages the resource, and diverts resources away from harvesting the natural resource. These effects speed the return to a peaceful steady state, at the same time however if conflict results in resource destruction it may destabilize the system leading it towards collapse. On the policy front we find that increasing harvesting efficiency, fertility, and preference for the resource all increase system vulnerability to conflict. Policies directed at raising system carrying capacity, increasing resource growth rate increasing birth control all serve to stabilize the system and reduce its vulnerability to conflict.

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Contents

> Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetic ratio.
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> By the law of our nature which makes food necessary to the life of man, the effects of these two unequal powers must be kept equal.
>
> — Thomas Malthus (1798)
> emphasis added

1 Introduction

According to the World Resources Institute, by the year 2050 the world's human population is likely to exceed nine billion. At the same time, economic industrial output will probably quadruple.[1] These developments will no doubt put huge demands on renewable resources. Environmental decay in various forms such as air and water pollution, reduction in the quality and size of underground water reservoirs, dying lakes, shrinking forests, decline in the amount and quality of agricultural and grazing land, dwindling fishing grounds, depletion of the ozone layer, and global warming are already observed today. As pointed out by several analysts, as a result of the global trends of rising population and economic industrial output, environmental decay and depletion of renewable resources will probably become more widespread and severe in the future.[2]

What are the likely reactions of world societies to these scarcities? If societies are wealthy enough and identify scarcities early enough, the likely reaction will be to devote considerable funds to remedy the deficiency.. These may include the importation of the scarce resource, the implementation of a quota systems (where property rights are definable), and the allocation of funds to research and development directed towards innovations designed to remedy the scarcity. These innovations may enhance either the capacity to produce the scarce resource, or reduce the dependence on it. Scarcities are most severe in poor societies that lack well defined property rights and rely heavily on the natural eco-system. In these societies resource scarcity seems more likely to prompt competition over the remaining resource, and this competition may lead to conflict which could be violent. As an alternative to direct conflict, resource scarcities may trigger population movements in poorer societies. These movements themselves, however, have been identified as contributing to conflict.[3]

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[1] For a full projection see World Resources (1986, 1992).

[2] See, for instance, Westing (1986) and Homer-Dixon (1994).

[3] See Homer-Dixon (1994).

Our goal in this paper is to take an initial step in economic analysis of the study of the interplay of resource scarcity and conflict. This goal, of course, begs an immediate question. To what extent are environmental scarcity and conflict associated empirically? While our data on these links are generally limited, the empirical literature on these links is growing. Since the early 1990s, systematic evidence on the links between renewable resource depletion and conflict has been collected by the Peace and Science program at the University of Toronto, Canada and the American Academy of Art and Science in Cambridge, Massachusetts.[4] In general, environmental scarcities are found to be a systematic source of conflict. Thus far, the most violent consequences of these effects have taken place in the Third World where human dependence on the natural environment is higher than in industrialized nations. As time passes, however, developed countries may face similar problems as they are generally running "ecological deficits" with the rest of the world.[5]

Yet, the focus of the existing literature has been on investigating cases in which conflict is caused by environmental degradation. The destiny of the social-economic system once conflict erupts and the ensuing evolution of the system have not been studied. Important questions have not been addressed. How likely is it that conflict will erupt? If it does, how long will it last? What are the factors that determine the length of such violence? While human history teaches us that wars do not last forever, most past major wars were not directly caused by environmental degradation. Will conflict due to environmental scarcity come to an end at some point in time? If it does end, are additional environmental conflicts possible? What are the long term consequences of violence due to environmental degradation? These questions are at the center of our paper.

Our approach is deductive. Assuming that environmental degeneration leads to conflict, we develop a dynamic model in which the stock of renewable resources and the size of the human population are both endogenous. Assuming the existence of a certain exogenous threshold of small resource per capita beyond which violence erupts, we investigate the evolution of the resource stock and population size over time. Conflict is modeled to have three impacts. First, it diverts labor away from normal economic activities into war-making or domestic unrest related activities. Second, it may increase the death rate. Last, it may directly impact the resource, harming its growth rate.

Our results can be summarized as follows. First, conflict due to environmental scarcity

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[4] For an overview of this program see Homer-Dixon (1994) and Homer-Dixon and Percival (1996).
[5] On these deficits, see Rees (1997).

can not be a steady state of the system. Second, conflict that has a limited detrimental impact on resource growth can serve to bring the system back to a peaceful path. Ironically, then, conflict can serve as a harsh defense mechanism, ensuring the survival of at least some of the human species. Third, if conflict if conflict is sufficiently damaging to the resource growth rate of the resource it may destabilize the system. In this case the system could collapse to either of two equilibria, each with no human population. Fourth, peace could be a steady state, where by population and resource stock settle at certain "safe" equilibrium levels that assure no endogenous future conflict. Fifth, once the system is shocked away from equilibrium, we identify the conditions under which the dynamic path of the system involves conflict, as well as the time length of staying in the conflict zone. Finally we examine system variable which increase or decrease susceptibility to conflict. We find that technical progress in harvesting increases susceptibility to conflict while policies of birth control, reducing reliance on the harvested good, and raising system carrying capacity all serve to reduce conflict vulnerability.

The remainder of our paper is organized as follows. Section 2 discusses several theoretical links from environmental scarcity to conflict. Section 3 reviews the empirical literature on these links. Section 4 constructs a formal model to investigate the effect of conflict on the bio-economic system. Section 5 analyzes the steady state of the model. Section 6 deals with the model's transition path once the system is shocked. Finally, section 7 offers concluding remarks and highlights research extensions.

2 Conflict and the environment

Environmental degradation does not receive much attention by international conflict scholars. Recently, however, several studies identified theoretical channels through which environmental decay may cause conflict.[6] Next, we discuss theoretical channels from environmental degradation to conflict.

The links from environmental degradation to conflict could be classified in four types: (1) economic decline and dwindling of resources per capita; (2) population migration or displacement; (3) social problems aggravated by environmental scarcities; and, (4) disrupted institutions and the rule of law.[7]

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[6] To be sure, there are also studies which doubt the importance of these channels. See, e.g., Deudney (1990), and Molvaer (1991).

[7] This typology synthesizes arguments in Westing (1986, 1991), Volker (1990), Homer-Dixon (1991, 1994), and Gaan (1995).

The problems associated with economic decline per capita include factors such as a decrease in the quantity or quality of agricultural goods and livestock, insufficient supplies of crucial goods such as water and timber, and environmentally induced health problems due to air and water pollution or toxic waste. These effects may generate conflict by creating tensions over such questions as who will bear their cost, who will alleviate their effect, who contributed the most to their production, and who will get a bigger share of what is already a shrinking pie of resources per capita.[8]

The second link from environmental scarcity to conflict involves the migration or forced displacement of populations. As the resources in one region deplete or deteriorate, some of the region's population may migrate or may be displaced by other groups as the resource base of the land dwindles. If the destination land is already occupied, the newly arrived population may increase the pressures on the destination's resource base. As immigrants and natives meet, they may clash over many issues, including ethnic and cultural differences, upsetting of labor markets due to excess supply or competition over better jobs, and competition over the strained resources of the new land.[9]

The third channel which links environmental scarcity to conflict places the above channels in a context of an unstable domestic or international political foundation. For instance, if the land includes historically rival groups, the probability of conflict due to environmental scarcity increases as the relations of such groups may be already strained over past issues. In general, then, environmental degradation may exacerbate existing cleavages and/or conflicts.[10]

The fourth link from environmental degradation to conflict involves the weakening of institutions and the decrease in the efficacy of rule of law. This may happen in several ways. First, environmental degradation may erode the people's confidence in their government. In severe cases people may attempt to overthrow the current regime. Second, it may encourage people to strike or not pay taxes, acts which may further weaken the government. Third, it may reduce the willingness to undertake investments in economic and social infrastructure. Again, this may further elevate the sense of deprivation and weaken the rule of law. Last, environmental degeneration may embroil countries in conflicts over dwindling resources, possibly along lines dividing North and South, thus putting international order at risk.[11]

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[8] See Falkenmark (1986) and Wallensteen (1986) on conflict due to dwindling water resources and drops in food supply, respectively.

[9] See Jacobson (1988) and Ashok (1996a).

[10] On the consequences of scarcity for ethnic and class cleavages see Gurr (1985).

[11] The North-South argument is discussed in Ophuls (1977).

3 Empirical evidence and implications

Our main intention in this section is to demonstrate that environmental scarcities are already causing political conflicts. Given space limitations, our review is not intended to be exhaustive. For comprehensive reviews of empirical cases we refer readers to Westing (1986), Moss (1993), Homer-Dixon (1994), and Homer-Dixon and Percival (1996).

Most studies in the empirical literature on conflict and environmental scarcity employ a case study research design. One exception is the study of Choucri and North (1975). These authors estimate a simultaneous equation model from land size, population, military expenditures, trade, and industrial output. Their findings point out that in the late nineteenth and early twentieth centuries, population growth in Europe was associated with increased competition over colonial lands producing raw materials, agricultural foodstuff, and animal products. The competition increased the incentives to maintain large armies and heightened arms races, and thus could be considered as an indirect cause of World War I.

Next, we turn to several case studies. Mackey (1981) finds that food and crops scarcities played a role in instigating domestic violence in fifteenth century Spain. Ehrlich et. al. (1977) and Durham (1979) argue that agricultural land scarcities coupled with rising population caused migration from El Salvador to Honduras. As land was also relatively scarce in Honduras, the competition between the two populations led to the 1969 Soccer-War. Homer-Dixon (1991) supports these claims when he notes that in the 1950s and 1960s renewable resources per capita in El Salvador declined rapidly following large loses of virgin forest and land erosion. Analyzing the post World War II Philippines, Porter and Delfin (1988) and Hawes (1990) find that internal strife is linked to deforestation and land degradation. Coupled with a high population growth, these changes led to large domestic population displacements which triggered civil descent aimed at the central government. Along similar lines, Goldman (1991) argues that, in Eastern Europe and the former Soviet Republics, degradations in the quantity and quality of agricultural land, forests, and water, and excessive air pollution generated anti-Russian sentiments which contributed to the breakup of the Soviet Empire.

Homer-Dixon (1994) provides additional evidence on cases in which scarcities of renewable resources led to conflict. Since the mid-1970s, population growth and land exploitation in Bangladesh significantly cut the amount of cropland per capita and caused population migration to India. The migration is a source of ethnic conflict (the Bengali immigrants from

Bangladesh are Muslim while Indians are predominantly Hindu).[12] Other disputes over renewable resources include the 1972-1973 English-Icelandic Cod War, the clash between Mauritania and Senegal over the waters of the Senegal river, domestic violence in South Africa, water and agricultural land shortages in the Middle East, water conflicts between South Africa and Lesotho, and Egypt and Ethiopia, and the recent conflicts over fishery rights between Canada and the U.S., and Canada and Spain.[13] Evidence that environmental scarcities weaken institutions is presented in the cases of the Luminoso rebellion in Peru, and the fall of the "Baby Doc" Duvalier's regime in Haiti. Last, some researchers argue that demographic pressures accompanied by shortages of renewable resources are creating pressures in China that may lead to the country's fragmentation.[14]

In sum, several studies present evidence pointing out that environmental scarcity can lead to violent international or domestic conflict. Yet, these studies do not investigate the interplay between conflict and the economic-environmental system. Admitting that these processes are extremely non linear and complicated, studies focus on the mechanisms leading from environmental change to conflict. We start our analysis where those studies stop. Beginning from some steady state, we shock the system and investigate its dynamic path. If conflict erupts, we investigate what happens to the system over time. In particular, we investigate whether the system will return to a peaceful equilibrium, what determines the length of conflict, and how the answer to these questions varies with the parameters of the economy and the environment.

4 Renewable resources and conflict

Our model builds on the work of Prskawetz, Feichtinger and Wirl (1994), Milik and Prskawetz (1996) and Brander and Taylor (1998). Each of these papers focuses on the dynamic interaction between population growth, economic activity and a stock of renewable resources. The first two of these papers examines in detail specific attributes of the cycles which may arise from these interactions.. The final paper illustrates that cycles may arise and applies a similar cyclic analysis to develop an explanation of the apparent cyclical growth and the ultimate collapse of Easter Island civilization.

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[12] Most notably, in 1983 almost 2000 Bengalese were masquerade by natives who accused them of stealing the best land (Homer-Dixon, 1994:22). See also Ashok (1996b).

[13] The Middle water disputes were studied by many researchers. See, for instance, Lowi (1993).

[14] On Peru, see McClintock (1984). On Haiti, see Ehrlich et al. (1986). On China, see Smil (1992) and Goldstone (1992).

We also undertake an analysis of the interaction between population growth, economic activity and a stock of renewable resources. We add to the previous models the notion of violent conflict or political unrest. Following the empirical observations made by Homer-Dixon (1994), violent conflict and/or political unrest in these economies arise when per capita resources reach a minimum critical level. We use the model to examine the role and nature of such conflict on the stability of the bio-economic system, and the impact of various policies on the likelihood and duration of conflict. Conflict has several impacts in our model. First it distorts labor away from productive activities. In this way conflict may be violent (leading to death) or non violent (such as labor diverting strikes and political protests). Second violent conflict may in fact increase the rate of death in the population and account for this fact in our model. Finally we allow for the possibility that conflict may cause the direct destruction of the resource. This could result as a by product of war, but it may also result as part of a conflict strategy. For example fish may be harvested to extinction simply to prevent a rival from having access to the resource.

While our model is quite simple, we view it as a first step in the formal modeling of the impact of war on a system which capture the reality of the interaction between population and resource stocks. The underlying economic system, in terms of production and harvesting technologies, is simplistic. In addition, the model is one of harvesting an open access resource. As these considerations suggest, it is our intention that the model be used to gain insight into the role of conflict in developing rather than developed economies.

4.1 The model

The model features a population of $L(t)$ individuals at time t, which is assume to equal the labor force. Following Brander and Taylor (1998) we assume that each individual has preferences (u) over a harvested renewable resource good (h) and a composite good (c) given by

$$u = h^{\beta}c^{1-\beta}; 0 < \beta < 1 \tag{1}$$

The harvested good is assumed to be essential for procreation. We see this in equation (16) below which shows that the period t fertility rate is increase in the level of per capita resources. Thus the harvested good (h) may be thought of as food, or as the compilation of resources that are necessary for the production of food, such as water, air and land. The composite good (c) may be thought of as a composite of all other goods. Each individual in the population is assume to be endowed with one labor unit, which may be split between the harvesting activity and the production of the composite good. Individuals will allocate their labor unit between harvesting and production. Letting $L_H(t)$ denote the total amount of labor devoted to harvesting, and $L_C(t)$ denote the amount of labor devoted to production of the composite good, we obtain:

$$L(t) = L_H(t) + L_C(t), \tag{2}$$

during any period in which there is no conflict. One impact that conflict has is that it diverts resources away from production and harvesting; resources are spent on such activities as warring, or protesting during times of domestic unrest. To capture this idea, we assume that during any period featuring conflict, the total amount of labor devoted to production or harvesting is $\gamma L(t)$ where $\gamma \in (0, 1]$. The smaller γ is the greater is the intensity of conflict.[15]

$$\gamma L(t) = L_H(t) + L_C(t). \tag{3}$$

We treat the composite good as the numeraire good and assume that it is produced competitively according to a constant returns to scale technology, with labor as the only input. Given preferences (1), the composite good will always be in demand in equilibrium. Since its price is normalized to 1, this will be the equilibrium wage in the production sector. We assume that labor moves freely between the two sectors of the economy.

We denote the stock of the resource good in period t by $S(t)$. Following Prskawetz, Feichtinger and Wirl (1994) and Milik and Prskawetz (1996) we assume a Cobb-Douglas harvesting technology

$$H^S(t) = \alpha S(t)^{\alpha_1} L_H(t)^{\alpha_2}, \tag{4}$$

where $H^S(t)$ denoted the harvest supply, α represents the efficiency of harvesting, and $0 < \alpha_1, \alpha_2 < 1$are technology parameters. As is common, we assume competition in the harvesting and composite good sectors. Finally, for simplicity we assume a constant returns to scale

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[15] Depending on how one defines the boundaries of the bioeconomic system modelled here, this conflict may be thought of as purely domestic or as international. The latter would be the case if nations went to war over natural resources. We have outlined such cases in section 3.

technology for harvesting. That is $\alpha_1 + \alpha_2 = 1$. Perfect competition in the harvesting sector leads to the following zero profit condition

$$pH^S(t) - wL_H(t) = 0. \tag{5}$$

where p is the price of the harvested good and w is the wage in the harvesting sector. Thus, substituting (4) into (5), and using the fact that the competitive wage in both sectors must equal unity (which follows from profit maximization in the composite goods sector and labor mobility) we obtain the equilibrium price of the harvested good:

$$p\left(t\right) = \left(\frac{L_H\left(t\right)}{S_H\left(t\right)}\right)^{\alpha_1}. \tag{6}$$

Each individual is endowed with one labor unit; however, a portion of the unit $(1-\gamma)$ is diverted from productive uses due to conflict. Thus, the budget constraint facing each agent is[16]

$$p\left(t\right)h\left(t\right) + c = \gamma. \tag{7}$$

Maximizing (1) subject to the standard budget constraint (7) yields the optimal individual demands.

$$h\left(t\right) = \frac{\gamma\beta}{p\left(t\right)} \text{ and } c = \gamma\left(1-\beta\right)$$

Aggregating over the population yields the following demand functions for the harvested and manufactured goods.

$$H^D(t) = \frac{\beta\gamma L(t)}{p} \text{ and } C^D(t) = \gamma(1-\beta)L(t). \tag{8}$$

Substituting (6) into (8) we find that the equilibrium level of the harvested resource is given by

$$H(t) = \frac{\beta\gamma L(t)}{\frac{L_H(t)^{\alpha_1}}{\alpha S(t)^{\alpha_1}}} \tag{9}$$

From equation (4), $L_H = \left(H^S/\left(\alpha S(t)^{\alpha_1}\right)\right)^{\frac{1}{\alpha_2}}$. Using the equilibrium condition in the market for the harvested good $H^D = H^S = H$ we see that the number of workers in the harvesting sector is

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[16] Alternatively one could assume that $(1-\gamma)L$ individuals engage fully in conflict, while the remainder work full time and transfer some of their wealth to support those individuals engaged in conflict. The assumption embodied in (7) seems more realistic if one assumes political unrest rather than full scale war.

$$L_H(t) = \frac{L(t)\,\beta\gamma}{p\alpha S(t)} = \gamma\beta L(t) \tag{10}$$

Thus, using equation (4)

$$H(t) = \alpha\,(\beta\gamma)^{\alpha_2}\,S(t)^{\alpha_1}\,L(t)^{\alpha_2} \tag{11}$$

Substituting (10) into (3), and noting that the production technology of the composite good is $C(t) = L_C(t)$, and using the equilibrium in the harvesting sector we see that

$$\gamma L(t) = L(t)\beta\gamma + C(t) \tag{12}$$

so

$$C^S(t) = C^D(t) = C(t) = (1-\beta)\,\gamma L(t). \tag{13}$$

Equations (9) and (13) give the period t equilibrium quantities of the harvested resource and the composite good. The levels of these goods are dependent on the resource stock and the population level. We study the dynamic paths of the population and resource stocks in the following subsection. Before turning to this analysis however, it is worth noting that the period t utility for a representative individual in the economy will can be computed by substituting (13) and (9) back into one, which gives:

$$u = \left(\alpha\,(\gamma\beta)^{1-\alpha_1}\left(\frac{S(t)}{L(t)}\right)^{\alpha_1}\right)^{\beta}(\gamma\,(1-\beta))^{1-\beta}. \tag{14}$$

Thus we see that utility is increasing in the per capita level of the resource stock, an it is therefore reasonable to assume, as we do below, that conflict may be triggered when the per capita resource stock falls below a given level.[17]

4.2 Population and resource dynamic paths

Population is assumed to grow according to $\dot{L} = nL$ where n is the growth rate of population. In many models (i.e., Solow (1956), Stiglitz (1974) n is assumed to exogenously given. In other models (i.e., Sato and Davis (1971) Praskawetz et al. (1994), Milik and Praskawetz (1996)) n depends on income or consumption. Many models assume that n grows linearly

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[17] It is interesting to note that in Brander and Taylor (1998) per capita utility varies solely with the stock. This is so because somewhat ironically the per capita harvest in their model is independent of the population level. This can be traced back to the fact that their harvesting technology exhibits no diminishing returns to labor even for a fixed stock.

with consumption or per capita income. This basic assumption can be trace back to Malthus. Empirical data support this specification for under-developed countries. Following studies with endogenous fertility the assumed population dynamics are governed by the following differential equation

$$\frac{dL(t)}{dt} = L(t)\left[b - \eta d + F(t)\right] \tag{15}$$

where

$$F(t) = \phi H(t)/L(t) \tag{16}$$

represents the period t fertility rate. The parameter b represents the natural birth rate, and d the natural death rate.[18] The parameter $\eta \geq 1$ represents the direct impact of conflict on population. The more violent is conflict the greater will be the death rate during any period of conflict. In peaceful times $\eta = 1$, by assumption.[19] Using (11), the fertility rate may be rewritten as

$$F(t) = \phi\alpha\left(\beta\gamma\right)\left({}^{\alpha_2}S(t)^{\alpha_1}/L(t)^{\alpha_1}\right). \tag{17}$$

Note that as the as the resource stock falls, harvesting becomes more difficult and renewable resource per capita falls, negatively impacting fertility. Substituting (17) into (15) we obtain

$$\dot{L} = \frac{dL(t)}{dt} = L(t)(b - \eta d) + \phi\alpha\left(\beta\gamma\right)^{\alpha_2} S(t)^{\alpha_1} L(t)^{\alpha_2}. \tag{18}$$

The assumed dynamics of the resource stock are governed by the following differential equation

$$\frac{dS(t)}{dt} = (1 - \theta)\left[rS(t)\left(1 - \frac{S(t)}{K}\right)\right] - H(t), \tag{19}$$

where r denotes the intrinsic rate of growth of the resource, and K denotes the "carrying capacity" of the resource.[20] The term in square brackets on the right hand side of (19)

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[18] This specification is based on Brander and Taylor (1998). One criticism of this function is that the fertility rate is linear in the per capita harvest (wealth). While there is empirical data that demonstrates that the relationship between fertility and wealth would look more like an inverted U (increasing in come at lower levels of wealth and decreasing at higher levels), the approximation here is justifiable because our focus is on resource scarcity and conflict in developing countries.

[19] We assume that $d > b$, which ensures that the population will decline to zero for sufficiently low rates of fertility.

[20] This resource stock growth function is widely used in economics and biology (See Clark (1990)).

represents the period t natural growth rate of the resource, which is assumed to follow the familiar logistic form. Without harvesting, growth will be rapid, if the current stock is far from its carrying capacity; however, as this capacity is approached, growth will slow and eventually cease. The overall period t change in the resource stock is the difference between its growth rate and the harvest rate, $H(t)$.

The parameter θ in (19) captures the possible impact that conflict may have on the growth rate of the renewable resource. Specifically, we assume that conflict slows this growth rate. This may occur because of destruction of the resource itself or damage to inputs that allow the resource to grow. It is worth noting that, if $\theta = 1$, growth will be halted. Using (11) to substitute for the harvest rate in (19) we obtain

$$\dot{S} = \frac{dS(t)}{dt} = (1-\theta)\, rS(t)\left(1 - \frac{S(t)}{K}\right) - \alpha\,(\beta\gamma)^{\alpha_2}\, L(t)^{\alpha_2} S(t)^{\alpha_1}. \tag{20}$$

Conflict will alter the values of θ and γ in (20). The direct impact of θ (increasing from zero) on $\dot{S}$ is negative. The direct impact of the diversion of harvesting resources (a drop in γ from 1) on $\dot{S}$ is positive.

Equations (18) and (20) describe the model's dynamics. We have described the direct effects of conflict on the resource stock and population level. However, by observing (18), we see that population is affected by the stock of resources (via fertility), and from (20) we see in turn that population affects the resource stock (via harvesting). Thus there is a complex dynamic interaction between population and the resource stock. Consequently conflict will have indirect as well as direct effects on population and the stock of resources. To examine these effects we need to examine the nature of the system's dynamics.

4.3 A overview of the system's dynamics

As we show in section 5, the system has two steady states featuring positive levels of population and the resource stock, one characterized by peace and the other by conflict. The system also has two corner steady states in which $L = 0$ (one with $S = 0$ and the other with $S = K$). The dynamic behavior around these steady states can be cyclical. This means that ,if the system is stable, when the system is shocked, both population level and the resource stock will fluctuate around the steady state before returning to it, or return to it monotonically.

These cycles are illustrated in Panel 2a of Figure 2 (in section 5) for the ratio of the resource stock to the population level (i.e., S/L).

We assume that the initial steady state exhibits peace. As the system is shocked away from this steady state, the resulting fluctuations in population and the resource stock may bring the system into what we call a conflict zone.[21] This zone is characterized by low levels of per capita resources, i.e., $S(t)/L(t) < \bar{V}$, where $\bar{V}$ is an exogenous constant. In Panel 2a $\bar{V} = 1$, while the steady state is characterized by $S/L = 7/5$. In the peace zone $(S(t)/L(t) > \bar{V})$ system dynamics will be governed by peace time variables, that is where $\gamma = 1$, $\theta = 0$, and $\eta = 1$. When the system crosses into the conflict zone dynamics will change as $\gamma < 1$, $\theta > 0$, and $\eta > 1$. At the point of transition, the initial conditions of the system change, ensuring a smooth transition across the conflict threshold.

Assuming stable steady states and oscillatory behavior, after entry into the conflict zone the paths of the population and resource stock tend toward the steady state described by conflict. However, as we show in section 5 below, this "conflict steady state" is located further into the peace zone than is the "peace time steady state." That is, it is located above the upper line in Panel 2a. Thus we know that in approaching its war time steady state, the system will once again cross over the conflict threshold into the peace zone. At this time initial conditions and dynamics will change, once again being governed by peace time variables. Since time has passed however, we show that the new dynamics in the peace zone are more damped than before. The conflict zone could be crossed several times during this adjustment, but we show that the peace time interior steady state will eventually be reached.

If states are not stable, the system will wonder away from steady state, eventually hitting the paths that lead to the corner steady states with zero population and a zero, or positive stock of resources. In the subsequent sections we analyze the model's steady states and dynamics in detail. In doing so we are able to develop several policy implications, and answer questions such as what variables serve to increase or decrease conflict likelihood and length, and the degree of resource scarcity.

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[21] These shocks can be both "positive" or "negative". By positive we mean a shock that raises the per capita level of the resource stock. Thus examples of a positive shock include unusually good weather, or the introduction of a more hearty crop. A negative shock is one that decreases the per capita level of the resource stock. Examples of negative shocks are bad weather, or the influx of population from outside the bioeconomic region under study. Panel 2a illustrates the impact of a small negative shock.

5 General System Dynamics

The system described by the differential equations (18) and (20) has three types of steady state equilibria. Two of these types (corner equilibria) feature a population level of zero and exhibit saddle point stability. The first of these features a resource stock which is also zero, while the second features a resource stock equal to its carrying capacity K. These two equilibria types follow directly from observation of (18) and (20). The third type of steady state (the internal equilibrium) exhibits a positive level of population and resource stock. We describe this interior equilibrium solution in detail in the following proposition.

Proposition 1 *The interior steady state equilibrium solution to the bio-economic system described by equations (18) and (20) is described by* $\bar{S} = K\left[1 - \frac{\alpha(\beta\gamma)^{\alpha_2}}{(1-\theta)rE}\right]$; *and* $\bar{L} = \frac{K}{E}\left[1 - \frac{\alpha(\beta\gamma)^{\alpha_2}}{(1-\theta)rE}\right]$; *where* $E = \left[\frac{\eta d - b}{\phi\alpha(\beta\gamma)^{\alpha_2}}\right]^{\frac{1}{\alpha_1}}$.[22]

Proof. The solution is derived directly from solving (18) and (20), and will be an interior solution as long as $0 < \bar{S} < K$. That is, as long as $0 < \frac{\alpha(\beta\gamma)^{\alpha_2}}{(1-\theta)rE} < 1$. If this condition is violated the system will collapse to one of the corner steady states ($\bar{S} = K$, $\bar{L} = 0$, or $\bar{S} = 0$, $\bar{L} = 0$). ■

Differential equations (18) and (20) are highly non-linear and don't have analytical solutions. As is commonly done, we examine the dynamics of the system by means of a first order Taylor series approximation of (18) and (20) around the steady state equilibrium points ($\bar{L}$, $\bar{S}$).

$$\begin{bmatrix} \frac{dL(t)}{dt} \\ \\ \frac{dS(t)}{dt} \end{bmatrix} = \begin{bmatrix} \frac{\partial \dot{L}}{\partial L} & \frac{\partial \dot{L}}{\partial S} \\ \\ \frac{\partial \dot{S}}{\partial L} & \frac{\partial \dot{S}}{\partial S} \end{bmatrix} \Bigg|_{L=\bar{L}, S=\bar{S}} \begin{bmatrix} \left(L(t) - \bar{L}\right) \\ \\ \left(S(t) - \bar{S}\right) \end{bmatrix} \tag{21}$$

The general solution to this system is given by the equation

$$\begin{bmatrix} \frac{dL(t)}{dt} \\ \\ \frac{dS(t)}{dt} \end{bmatrix} = c_1\mathbf{E}_1 e^{\lambda_1 t} + c_2\mathbf{E}_2 e^{\lambda_2 t} \tag{22}$$

---

[22] *The reader will observe that these conditions describe two steady states of the interior type. The first under peace, where* $\gamma = 1$, $\theta = 0$, *and* $\eta = 1$. *The second under conflict where* $\gamma < 1$, $\theta > 0$, *and* $\eta > 1$.

where c_1 and c_2 are positive constants determined by initial conditions, λ_1 and λ_2 are the eigenvalues of coefficient matrix in (21), and $\mathbf{E}_1$ and $\mathbf{E}_2$ are the corresponding eigenvectors.[23]

Define

$$J = \left. \begin{bmatrix} \frac{\partial \dot{L}}{\partial L} & \frac{\partial \dot{L}}{\partial S} \\ \frac{\partial \dot{S}}{\partial L} & \frac{\partial \dot{S}}{\partial S} \end{bmatrix} \right|_{L=\bar{L}, S=\bar{S}} . \tag{23}$$

Then the two eigenvalues of the system J are given by

$$\lambda_{1,2} = \frac{1}{2}\left(\operatorname{tr} J \pm \sqrt{(\operatorname{tr} J)^2 - 4\det J}\right). \tag{24}$$

Using (18) and (20) we see that for our problem (23) is given by

$$J = \begin{bmatrix} b - \eta d + \alpha_2 \phi \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{\alpha_1} & \alpha_1 \phi \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{-\alpha_2} \\ -\alpha_2 \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{\alpha_1} & \left(1-\theta\right) r \left(1 - \frac{2\bar{S}}{K}\right) - \alpha_1 \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{-\alpha_2} \end{bmatrix}. \tag{25}$$

One can show that in addition to the solution (24) the eigen values of (25) are also the roots of the equation $\det\left(J - \mathbf{I}\lambda_i\right) = 0$; $i = \{1, 2\}$, that is:

$$\det \begin{pmatrix} b - \eta d + \alpha_2 \phi \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{\alpha_1} - \lambda_i & \alpha_1 \phi \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{-\alpha_2} \\ -\alpha_2 \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{\alpha_1} & \left(1-\theta\right) r \left(1 - \frac{2\bar{S}}{K}\right) - \alpha_1 \alpha \left(\gamma\beta\right)^{\alpha_2} \left(\frac{\bar{S}}{\bar{L}}\right)^{-\alpha_2} - \lambda_i \end{pmatrix} = 0; \quad i = \{1, 2\}. \tag{26}$$

This form will be useful in our investigation of the system dynamics below. The corresponding eigen vectors $\mathbf{E}_i$ satisfy

$$\begin{pmatrix} b - \eta d + \phi\alpha\beta\gamma\bar{S} - \lambda_i & \bar{L}\alpha\beta\phi \\ -\alpha\beta\gamma\bar{S} & \left(1-\theta\right) r \left(1 - \frac{2\bar{S}}{K}\right) - \alpha\beta\gamma\bar{L} - \lambda_i \end{pmatrix} \mathbf{E}_i = 0; \quad i = \{1, 2\}. \tag{27}$$

Solving (24) and (26) to obtain the eigenvalues and eigen vectors for each steady state type, we will be able to investigate dynamic changes around the steady state using (22). This may be seen by examining each type in turn.

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[23] Note, bold fonts denote vectors. For details on the solutions of the system of linear differential equations (see e.g., Boyce and DiPrema (1997)).

Type 1: $\left(\bar{L} = 0, \bar{S} = 0\right)$

Substituting the steady state value of population and the resource stock into (26) it is easy to see that the eigenvalues are $\lambda_1 = b - \eta d$ and $\lambda_2 = (1-\theta)r$. Since one root, λ_2, is positive and the other, λ_1, is negative this steady state exhibits saddle point stability.[24]

Type 2: $\left(\bar{L} = 0, \bar{S} = K\right)$

The eigenvalues corresponding to this steady state are $\lambda_1 = b - \eta d + \phi\alpha\beta\gamma K$ and $\lambda_2 = -(1-\theta)r$. Since $\frac{\eta d - b}{\phi\alpha\beta\gamma} < K$ we see that λ_1 is positive, and since λ_2 is negative we see that this steady state is also an unstable saddle point.

The fact that both steady states 1 and 2 exhibit saddle point stability means that there is only one dynamic path in the S, L plane which leads to the equilibria. This path is called the saddle path. The saddle path leading to steady state $L = 0, S = 0$ is along the $S = 0$ axis. The saddle path leading to $L = 0$, $S = K$ is along the $L = 0$ axis.

Type 3: ($\bar{S} = K\left[1 - \frac{\alpha(\beta\gamma)^{\alpha_2}}{(1-\theta)rE}\right]$; and $\bar{L} = \frac{K}{E}\left[1 - \frac{\alpha(\beta\gamma)^{\alpha_2}}{(1-\theta)rE}\right]$; where $E = \left[\frac{\eta d - b}{\phi\alpha(\beta\gamma)^{\alpha_2}}\right]^{\frac{1}{\alpha_1}}$)

At this interior equilibrium the matrix J (see equation (25) reduces to

$$\tilde{J} = \begin{bmatrix} (b - \eta d)\,\alpha_1 & \frac{\alpha(\gamma\beta)^{\alpha_2}\phi\alpha_1}{\left(\frac{\eta d - b}{\alpha(\gamma\beta)^{\alpha_2}\phi}\right)^{\frac{\alpha_2}{\alpha_1}}} \\ \frac{(b-\eta d)\alpha_2}{\phi} & -(1-\theta)\,r + \alpha^{\frac{1}{\alpha_1}}(2-\alpha_1)\left(\frac{\gamma\beta\phi}{\eta d - b}\right)^{\frac{\alpha_2}{\alpha_1}} \end{bmatrix} \tag{28}$$

and the eigen values are give by (24). That is

$$\lambda_1 = \frac{1}{2}\left(\operatorname{tr}\tilde{J} + \sqrt{\left(\operatorname{tr}\tilde{J}\right)^2 - 4\det\tilde{J}}\right)$$

and

$$\lambda_2 = \frac{1}{2}\left(\operatorname{tr}\tilde{J} - \sqrt{\left(\operatorname{tr}\tilde{J}\right)^2 - 4\det\tilde{J}}\right)$$

The dynamics around the interior steady states are quite complicated.. There are several possibilities. If the discriminant $\left(\operatorname{tr}\tilde{J}\right)^2 - 4\det\tilde{J} > 0$ then both roots will be negative, and steady state 3 will be approached monotonically. If $\operatorname{tr}\tilde{J}$ is positive and the discriminant is positive we could have one eigen value positive and the other negative. This gives rise to saddle point stability or 2 positive eigen values which results in an unstable (explosive) system.

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[24] To find behavior around $\bar{L} = 0$ we let $\bar{L} = \varepsilon > 0$, where ε can be arbitrarily small.

If the discriminant is negative then the eigenvalues occur in complex conjugate pairs, each containing a real and an imaginary part. That is, if $\lambda_1 = \omega + i\mu$, then $\lambda_2 = \omega - i\mu$. Furthermore the corresponding eigenvectors also occur as complex conjugates. That is, if $\mathbf{E}_1 = \mathbf{a} + i\mathbf{b}$, then $\mathbf{E}_2 = \mathbf{a} - i\mathbf{b}$. The real and imaginary parts of the eigenvalues are given by

$$\omega = \operatorname{tr} \tilde{J}, \tag{29}$$

and

$$\mu = \frac{1}{2}\sqrt{\left|\left(\operatorname{tr} \tilde{J}\right)^2 - 4 \det \tilde{J}\right|}. \tag{30}$$

This system will exhibit oscillations around the steady state. Note that using (28) we see that

$$\omega = \operatorname{tr} \tilde{J} = (b - \eta d)\,\alpha_1 - (1 - \theta)\,r + \alpha^{\frac{1}{\alpha_1}}\,(2 - \alpha_1)\left(\gamma\beta\frac{\phi}{\eta d - b}\right)^{\frac{\alpha_2}{\alpha_1}}. \tag{31}$$

The cyclical behavior of the system depends on ω. The first two terms in (31) are always negative while the third term is always positive, thus ω may be positive negative or zero. If $\omega > 0$ the interior equilibrium will be unstable. Since the oscillation will not be damped any shock to the system will cause labor and resource stocks to move away from the equilibrium. If $\omega = 0$ shock will cause the system to cycle endlessly about the interior equilibrium, this is known as Hopf bifurcation. If $\omega < 0$ the system is stable and a shock away from the equilibrium will result in labor and resource stock paths which return to the steady state with damped oscillations.

Summarizing, the stability of the system can be analyzed by examining $\operatorname{tr} \tilde{J}$. Factors which make $\operatorname{tr} \tilde{J}$ less negative will make the system less stable both when the system exhibits oscillations or monotonic behavior around the steady state.

6 The system under peace and conflict

6.1 The steady state and conflict.

Recalling our assumption that conflict arises whenever $S(t)/L(t) < \bar{V}$, we now investigate the impacts of conflict on qualities of the interior steady state.

Proposition 2 *The interior steady state under assumed conflict conditions (i.e.,* $\gamma < 1$*,* $\eta > 1, \theta > 0$*), will exhibit a higher per capita resource stock (S/L) than the non-conflict steady state.*

Proof. The proof follows directly from differentiation of the steady state per capita resources stock $\left(\bar{S}/\bar{L}\right)$. First recall that conflict diverts labor from harvesting (γ falls) and (if violent) raises the death rate (η rises), then note $\left(\bar{S}/\bar{L}\right) = E = \left[\frac{\eta d - b}{\phi\alpha(\beta\gamma)^{\alpha_2}}\right]^{\frac{1}{\alpha_1}}$. Finally observe that

$$\frac{\partial E}{\partial \gamma} = \frac{1}{\alpha_1}\left[\frac{\eta d - b}{\phi\alpha\left(\beta\gamma\right)^{\alpha_2}}\right]\left[-\alpha_2\beta\left(\frac{\eta d - b}{\phi\alpha\left(\beta\gamma\right)^{\alpha_2 - 1}}\right)\right] < 0, \text{and } \frac{\partial E}{\partial \eta} = \frac{1}{\alpha_1}\left[\frac{\eta d - b}{\phi\alpha\left(\beta\gamma\right)^{\alpha_2}}\right]\left[\frac{\eta}{\phi\alpha\left(\beta\gamma\right)^{\alpha_2 - 1}}\right] > 0.$$

Thus both parameters have the effect of raising $\left(\bar{S}/\bar{L}\right)$. A reduction in the rate of growth of the resource, (θ) has no impact on the interior steady state level of per capita resources.[25] This reduction of θ and K will slow the system's recovery to the steady state; however, as long as growth is not totally stalled the resource will recover. ■

Any peace time steady state equilibrium must satisfy $\bar{S}/\bar{L} > \bar{V}$. This observation, along with proposition 1. leads to the following important corollary.

Corollary 3 *Conflict induced by per capita resource scarcity cannot last forever.*

Proof. The proof follows directly from the observation that $\left[\frac{\eta d - b}{\phi\alpha(\beta\gamma)^{\alpha_2}}\right]^{\frac{1}{\alpha_1}} > \left[\frac{d - b}{\phi\alpha(\beta)^{\alpha_2}}\right]^{\frac{1}{\alpha_1}}$ $> \bar{V}$ for $\eta > 1$, $\gamma < 1$.[26] ■

Note that corollary 3 does not imply that conflict cannot arise in the model. It simply implies that conflict cannot last forever. Once the system is shocked from the peace time steady state, it may cross the threshold into the conflict zone.[27] At this point the system aims at returning to the steady state characterized by conflict, but in doing so we know that the conflict zone will be exited and peace time dynamics will take over. This is so because the conflict steady state per capita resource level is larger than its peace counterpart. Hence conflict cannot last forever. This result accords with casual real world observation. While conflicts arising from environmental scarcity vary in their severity and duration, and while tensions may seem to exist forever, conflict spells are finite. As hypothesized by Malthus (1798), conflict is a (cruel) way for the system to return itself to a stable sustainable equilibrium.

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[25] Note that if the destruction of resources is total ($\theta = 1$) the sytem will collapse to the steady state equilibrium characterized by $\bar{S} = 0$, $\bar{L} = 0$.

[26] Note that the left side of this inequality applies to conflict while the right side applies to peace.

[27] See section 6.2 below.

6.2 The likelihood and nature of conflict

We focus next on the vulnerability of the system to conflict. The system can enter the conflict zone either immediately (due to a large negative shock), or in a delayed manner (due to the resulting cyclical fluctuations about the steady state) or due to a monotonic move away from a non stable steady state. The likelihood of immediate entry is falling as the distance between the peace time steady state and the conflict zone increases. The likelihood of delayed entry is also affected by the size of the shock, and as such is also falling in the distance between the peace time steady state and the conflict zone. This observation leads to the following important proposition.

Proposition 4 *Increasing the system's carrying capacity K reduces the likelihood of both delayed and immediate conflict.*

Proof. Observe from proposition 1 that both $\bar{S}$ and $\bar{L}$ are rising in K. Observe also that the per capital steady state resource stock is independent of K. This implies that as K rises the peace time steady state level of per capita resource stock moves along a ray from the origin in the (S, L) plane. Furthermore, since $\bar{S}/\bar{L} > \bar{V}$ the ray along which $\bar{S}/\bar{L}$ is moving is steeper than the ray which defines $\bar{V}$. Thus as K rises, the steady state per capita stock moves away from the conflict threshold. ■

Observing $\left(\bar{S}/\bar{L}\right) = \left[\frac{d-b}{\phi\alpha(\beta)^{\alpha_2}}\right]^{\frac{1}{\alpha_1}}$ under peace, we see that various other parameters will affect the distance between the per capital resource stock and the conflict threshold. Those parameters which have a negative impact on the resource stock will increase system vulnerability to conflict while those have a positive impact will reduce such vulnerability. We deal with these issues specifically in the following proposition. Consider the case of immediate conflict. Imagine an exogenous population influx or an exogenous depletion of resources. The larger are these types of negative shocks the greater will be the likelihood of immediate conflict. However, as the following proposition points out, certain model parameters increase the vulnerability of the system to these negative shocks.

Proposition 5 *For a given positive shock to population, or negative shock to the stock of resources the likelihood that the shock will result in immediate conflict is rising in fertility (ϕ), harvesting efficiency (α), the preference for the resource good (β), and falling in the net death rate ($d - b$), ceteris paribus.*

Proof. The proof follows directly from the appropriate differentiation of the per capital resource stock in the peacetime steady state. ■

Proposition 5 has different policy implications for different types of innovation. One can view birth control (decreasing ϕ) and a reduction in reliance on the harvested good (decrease in β) as arising from technical innovation. These tend to reduce the system's susceptibility to conflict. The former tends to reduce the population and the latter tends to increase the resource stock. Technical innovation in harvesting, however, raises susceptibility to the conflict. This type of innovation makes workers more productive in harvesting. As a result the stock of the resource falls.

We now examine system vulnerability to delayed conflict. As the system is shocked away from its steady state, if the system is stable it will follow a path back to it.[28] As discussed in section 5.1 above, if the system oscillates, this path may lead the system into the conflict zone. That is, $S(t)/L(t)$ may fall below $\bar{V}$ even as $\bar{S}/\bar{L}$ exceeds it. To examine this type of delayed conflict we must study the system's dynamics.

We focus on the interior steady state, and assume that the conditions ensuring cyclic dynamic behavior about the steady state are met. That is, we assume the discriminant $\left(\operatorname{tr}\tilde{J}\right)^2 - 4\det\tilde{J}$ is negative. In this case system dynamics about the steady state are described by the following system of equations.

$$\begin{bmatrix} L(t) \\ S(t) \end{bmatrix} = \begin{bmatrix} \bar{L} \\ \bar{S} \end{bmatrix} + c_1 e^{\omega t}\left(\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}\cos\mu t - \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}\sin\mu t\right) + c_2 e^{\omega t}\left(\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}\cos\mu t + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}\sin\mu t\right) \tag{32}$$

where c_1 and c_2 are constants determined by initial conditions. Given (29) and (30) it follows that the convergence to steady state 3 will involve oscillations of population and the resource stock about their respective steady state levels. These oscillations are illustrated in Figure 1 below for the case in which the system is stable (i.e., $\operatorname{tr}\tilde{J} < 0$). In what follows we focus on a case in which the system exhibits stable dynamics around the interior steady state.

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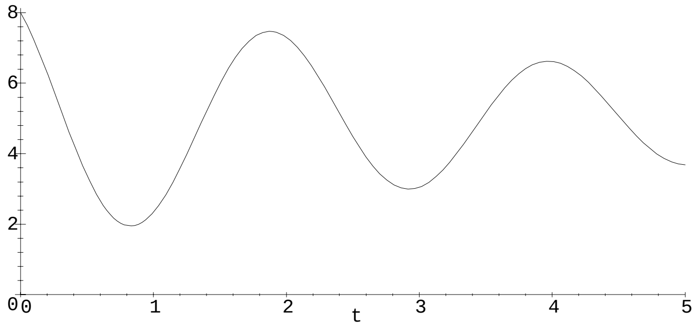
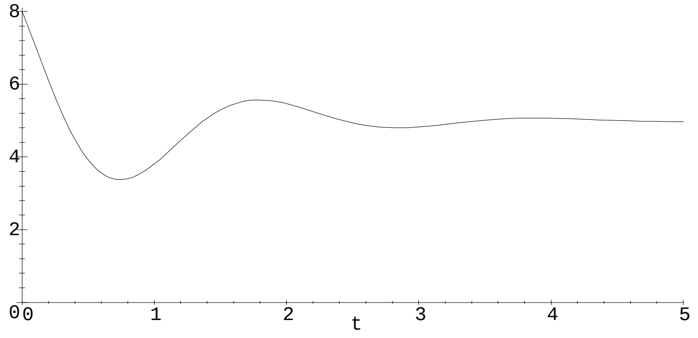
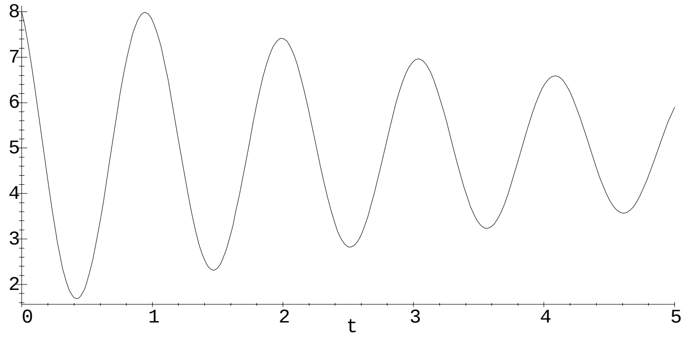
[28] We address system stability below.



Panel 1a. Benchmark Case



Panel 1b. High$|\omega|$



Panel 1c. High μ

Figure 1 (y-axis: $S(t)$ x-axis: time (t))

Now assume a positive shock to the peace time steady state. That is, the stock of resources is augmented, perhaps due to the introduction of a more hearty crop. As discussed, conflict will arise in the model whenever the line $\frac{S}{L} = \bar{V}$ is crossed. As we already discussed the likelihood and duration of conflict are affected by the following variables: the size of the shock,[29] the distance between the steady state and the conflict ray $\frac{S}{L} = \bar{V}$.[30] Yet it is also affected by the amplitude of the resource stock and population level dynamics, and finally, the frequency of those dynamics. These latter two parameters determine tightness of the dynamics around the steady state. The dampening of amplitude reduces the number of cycles it takes for the system to return to the peacetime steady state, while the frequency determines the duration of any cycle.

Using (32) we see that the amplitude oscillations about the steady state are determined by ω, while the frequency of these oscillations is determined by μ. The impact of changes in ω and μ on resource stock dynamics is illustrated in Figure 1. Each panel in Figure 1 illustrates the dynamic path of resource stock as it is shocked away from its steady state value. Panel 1a illustrates a benchmark case. Panel 1b illustrates that the impact of an increase in $|\omega|$ is a dampening of the fluctuations of the stock as it returns to its steady state.[31] Panel c illustrates the impact of an increase in μ, namely an increase in the frequency of the oscillations about the steady state.

We examine the relationship between system dynamics and the likelihood of conflict by examining the behavior of the ratio $\frac{S}{L}$ around the steady state. This ratio, along with the impact of changes in ω and μ are illustrated in the following Figure.

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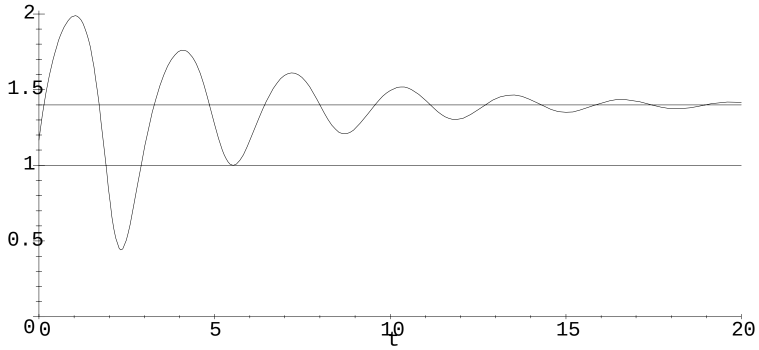
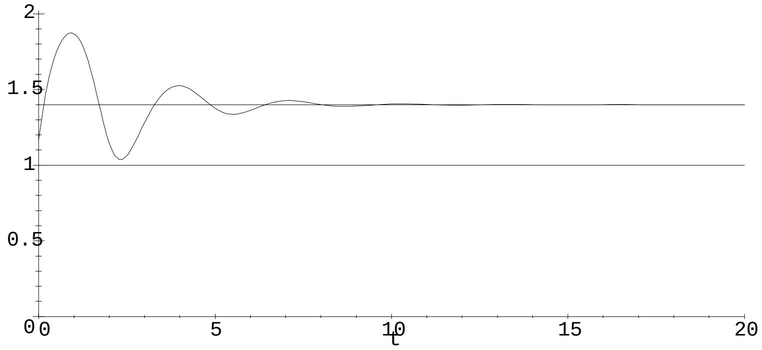
[29] The greater the shock to the system is, *ceteris paribus*, the greater both the likelihood of entering into conflict and the duration of conflict will be.

[30] This distance depends on the model's parameters, and has been examined (in terms of immediate conflict) in proposition 5.

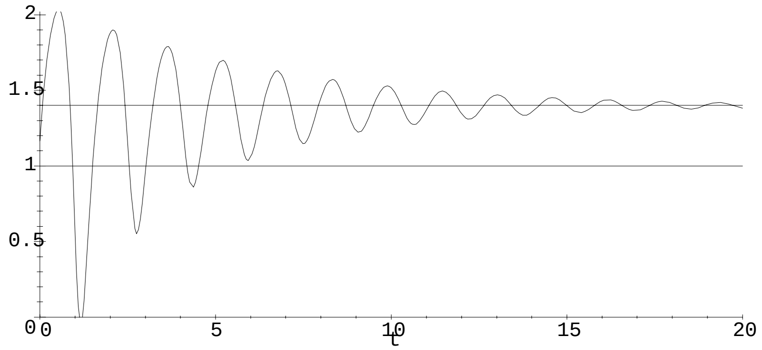
[31] Recall that ω is negative for the stable case.



Panel 2a: Benchmark Case



Panel 2b: Large ω



Panel 2c: Large μ

Figure 2 (y-axis: $S(t)/L(t)$ x-axis: time $\bar{V} = 1$ $\bar{S}/\bar{L} = 7/5$)

In Figure 2 the conflict threshold $\bar{V}$ is set to unity. Comparing panels 2b and 2c to the benchmark case in 2a we discern that the impacts of changes in ω and μ on the per capita resource stock are much the same as their impacts on resources and population individually. Since both $S(t)$ and $L(t)$ fluctuate with frequency $\frac{\mu}{2\pi}$, their ratio will fluctuate with the same frequency. As each series is damped, bringing both the peaks and the troughs of each series closer to their steady state values, so will be their ratio, $S(t)/L(t)$. Notice that the increase in the frequency of oscillations *reduces* the duration of each conflict phase (the time spent below the conflict line, $\bar{V} = 1$), but tends to *increase* the number times the system enters (and exits) the conflict zone.

Before mapping the impact of the model's parameters on ω and μ, and thus ultimately to the system's dynamics, it is important to note that the dynamics above and below the conflict line will differ. To simplify, these differences are *not* illustrated in Figure 2. The reason is that the parameters γ, η, and θ impact system dynamics. As the system crosses the conflict threshold, γ will fall (a diversion of harvesting resources to conflict activities), η may rise (a increase in the death rate), and θ may rise (limiting the growth of the resource). Whether the latter two effects change will depend on the severity of the resulting conflict. This change in frequency and amplitude will impact both the duration and severity of resource scarcity. Since system dynamics in the conflict zone are still governed by (32), and the conflict steady state is located further into the peace zone (see proposition 3) we know that the system *must* recross the conflict threshold.[32]

In order to study the impact of system dynamics on the likelihood of conflict we first note that entry into the conflict zone occurs from a peace zone.[33] System dynamics in the peace zone are affected by the following two parameters

$$\omega_p = (b-d)\,\alpha_1 - r + \alpha^{\frac{1}{\alpha_1}}\,(2-\alpha_1)\left(\beta\frac{\phi}{d-b}\right)^{\frac{\alpha_2}{\alpha_1}} \tag{33}$$

and

$$\mu_p = \frac{1}{2}\sqrt{\left|\left(\operatorname{tr}\tilde{J}_p\right)^2 - 4\det\tilde{J}_p\right|} \tag{34}$$

---

[32] Note that each time the system reaches the conflict threshold, the intial conditions governing the path of the system are reset to the corresponding point of entry or exit from the conflict zone. This ensures continuity of the systems dynamics as they crosses the threshold.

[33] The obvious exception being the case where the shock is large enough to throw the system immediately into the conflict phase.

Where $\tilde{J}_p = \tilde{J}\Big|_{\eta=1,\theta=0,\gamma=1}$. From Figure 2 we can see that the parameter which governs the likelihood of entry into the conflict phase is ω_p. The larger this parameter is, the *less* likely it is that conflict will arise since oscillations in both the resource stock and population level are lower. Linking this parameter to the model's underlying parameters brings about the following proposition.

Proposition 6 *The likelihood of delayed conflict is decreasing in r, $(d-b)$ and increasing in ϕ, α, and β, ceteris paribus, but does not depend on carrying capacity K .*

Proof. The proposition follows directly from differentiation of (33) with respect to each of the parameters of the proposition. ■

Proposition 6 gives rise to several policy implications. That is, policies of birth control $(\downarrow \phi)$, reduced reliance on the harvested good $(\downarrow \beta)$, and increased growth of the resource $(\uparrow r)$ all contribute to a reduced likelihood of delayed conflict, while an increase in the harvest rate $(\uparrow \alpha)$ increases the likelihood of conflict. These implications, except those concerning r, are similar to those from proposition 5.

It is worth recalling at this point that as ω_p ($\operatorname{tr}\tilde{J}_p$) rises first to zero and then to a positive number the system will move from being stable to being unstable. This observation gives rise to the following corollary, the proof of which is identical to the proof of proposition 6.

Proposition 7 *The factors which reduce the likelihood of delayed conflict also contribute to system stability.*

The conflict phase is described by per capita resource scarcity. Observation of Figure 2 illustrates that the resource scarcity is at its worst when the cycle reaches its trough. The depth of these troughs during the conflict phase are inversely proportional to the following parameter

$$\omega_c = (b-\eta d)\,\alpha_1 - (1-\theta)\,r + \alpha^{\frac{1}{\alpha_1}}\,(2-\alpha_1)\left(\gamma\beta\frac{\phi}{\eta d - b}\right)^{\frac{\alpha_2}{\alpha_1}}. \tag{35}$$

As this parameter rises, oscillations in the conflict zone of both S and L become more damped, limiting the extent of resource scarcity. One can observe this in panel 2b above. This leads to the following proposition.

Proposition 8 *The severity of per capita resource scarcity during any conflict phase is rising in the fertility rate (ϕ), harvesting efficiency (α), preference for the resource good (β), employment (γ), and falling in resource growth ($r\left(1-\theta\right)$), and the net death rate ($\eta d - b$), ceteris paribus, and does not depend on carrying capacity.*

Proof. The proof follows directly from differentiation of (35) with respect to the parameters of the proposition. ■

The policy implications for various parameters of proposition 8 are the same as those for proposition 6. It is interesting to examine the implications of our conflict parameters γ, η, and θ, on the extent of resource scarcity. We have seen that an increase the net death rate $(d-b)$ and the resource growth rate (r) serves to dampen oscillation. An increase in the death rate due to conflict (η) will reduce the severity of resource scarcity. The diversion of labor resources from harvesting to conflict activities (a decrease in γ) serves to decrease the severity of per capita resource scarcity. This diversion of labor resources not only works to raise the overall growth rate of the resource stock, but also lowers the fertility rate (both effects are due to the reduction of the level of the harvested good). Yet, a reduction in the growth rate (an increase in θ) of the resource due to conflict will heighten the extent of resource scarcity. Hence conflict may also be self perpetuating. Overall, conflict has competing effects on the severity of resource scarcity.

Panels 2a–2c illustrate the possibility cycling in and out of conflict phases.[34] Thus another natural question to ask regarding the peace time phase is how long intervals will be between periods of conflict. This question implicitly addresses the frequency of the cycles during the peacetime phase. We present a detailed discussion of the frequency of the system during the conflict phase below. Since this analysis includes all relevant parameters governing the frequency of peacetime cycles, we will return to this question after we study the frequency of cycles during the conflict phase.

The duration of the conflict phase is governed by the frequency of the cycle in the conflict phase, and is in fact inversely proportional to it. The frequency is determined by the following parameter

$$\mu_c = \frac{1}{2}\sqrt{\left|\left(\operatorname{tr}\tilde{J}_c\right)^2 - 4\det\tilde{J}_c\right|}. \tag{36}$$

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[34] Once again we caution the reader that Figure 2 illustrates equivalent dynamics above and below the conflict line. See our discussion above.

where $\tilde{J}_c = \tilde{J}\Big|_{\eta>1,\theta>0,\gamma<1}$. Define $\Gamma = \left|\left(\operatorname{tr}\tilde{J}_c\right)^2 - 4\det\tilde{J}_c\right|$, then $\frac{d\mu_c}{dz} \propto \frac{d\Gamma}{dz}$ where z denotes any of the model's parameters..

Since we are examining system dynamics where the discriminant is negative we rewrite it as

$$\Gamma = -\left[\left(\operatorname{tr}\tilde{J}_c\right)^2 - 4\det\tilde{J}_c\right]. \tag{37}$$

Thus for any parameter z in the model

$$\frac{d\Gamma}{dz} = -\left(2\operatorname{tr}\tilde{J}_c\left(\frac{d\operatorname{tr}\tilde{J}_c}{dz}\right) - 4\frac{d\det\tilde{J}_c}{dz}\right) \tag{38}$$

It is generally the case that the signs of $2\operatorname{tr}\tilde{J}_c\left(\frac{d\operatorname{tr}\tilde{J}_c}{dz}\right)$ and $-4\frac{d\det\tilde{J}_c}{dz}$ are opposite, and thus the sign of the overall derivative may be positive or negative depending on assumptions regarding various parameter restrictions. The over all sign of (38) is clear only in cases involving the growth rate of the resource. These are stated in the following proposition.

Proposition 9 *The duration of any conflict phase, under conditions of stability, is falling in the growth rate of the resource and therefore rising in θ, for sufficiently small α_1, ceteris paribus.*

Proof. The proof follows directly from the following derivatives of Γ

$$\begin{array}{l} \frac{d\Gamma}{dr} = 2(1-\theta)(\eta d - b)\alpha_1 - 2(1-\theta)^2 r - 2(1-\theta)\alpha^{\frac{1}{\alpha_1}}(2-\alpha_1)\left(\frac{\gamma\beta\phi}{\eta d - b}\right)^{\frac{\alpha_2}{\alpha_1}} < 0 \text{ as } \alpha_1 \to 0 \\ \frac{d\Gamma}{d\theta} = -2r(\eta d - b)\alpha_1 + 2(1-\theta)r - 2\alpha^{\frac{1}{\alpha_1}}(2-\alpha_1)\left(\frac{\gamma\beta\phi}{\eta d - b}\right)^{\frac{\alpha_2}{\alpha_1}} > 0 \text{ as } \alpha_1 \to 0 \end{array}. \tag{39}$$

Finally recall that the duration of the conflict phase is inversely proportional to the frequency, and that conflict raises θ. ■

Proposition 9 once again serves as a warning concerning the "positive" impact of conflict on the bio-economic system. We have seen that to the extent that conflict diverts labor resources from harvesting (both through direct diversion as part of the work force engages in conflict and indirect diversion due to the rise in the death rate) conflict is Nature's way of preserving the resource against the human predators. However if, as is sometimes the case, conflict is directed at resource destruction (which in our model harms resource growth), no positive benefit arises, system stability is put a jeopardy and even if the system remains stable, the likelihood of conflict rises and the time spend in conflict lengthens.[35]

7 Conclusions and extensions

As time passes it is becoming increasingly clear that in some regions of the world resource scarcity is a major causal and/or aggravating factor of domestic or international conflict and political unrest. Given the current trends, it appears unlikely that renewable resource scarcities will be alleviated in the near to medium term. In fact it is likely that such scarcities will worsen. A better understanding of the interactions between societies and resource scarcities and their consequences are therefore vital.

Resource scarcities and their consequences affect us all. While Third World countries clearly face the problem of resource scarcity head on, the increasing globalization of our economies means that more money and resources from developed countries are being invested in countries facing such scarcities. Consequently an understanding of the links between economics, resources scarcity and conflict are for country risk analyses which determine the desirability of foreign direct investment.

This paper represents a first step in the rigorous study of the links between renewable resource scarcities and conflict, and the characteristics of such conflict. The model, while admittedly simple, provides some interesting insights. The first insight we gain is that conflict is Nature's attempt to hasten an end to the scarcity. This is achieved by diverting resources away from a harvesting of the resource and by enhancing the death rate. Of course, if conflict manifests itself in a direct attack against the resource base these "efforts" on the part of Nature may be undermined. Since reliance on conflict to overcome resource scarcities is unpalatable, we have further investigated several policy prescriptions which might stabilize the bio-economic system and thereby avoid conflict. We found that technical progress in harvesting increases susceptibility to conflict while policies of birth control, reducing reliance on the harvested good, and raising system carrying capacity all serve to reduce conflict vulnerability.

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[35] Note that the qualification of $\alpha_1$being small is intuitive. As $\alpha_1$rises the economy can produce a larger amount of harvested good from an given resource stock, *ceteris paribus.* Note also, that under our assumption of constant returns to scale technology an increase in α_1 implies a decrease the marginal product of labor in harvesting. Each of these changes would tend to less the impact of a change in the resource growth rate on the dynamics of the system.

As stated, the model represents an initial step in the economic analysis of resource scarcity in conflict. As such it can be developed in many directions. Modeling directly competition between two population groups over a single renewable resource is one example. On the policy front, insight may be gained from modeling directly the possibility of storage of the resource to protect against the impact of negative shocks. Departing from a linear specification of fertility is another interesting extension. While these modifications are likely to aid in examining new policy insights they are unlikely to alter the main policy implications discussed in the previous paragraph.

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