CHAPTER 3

The Economics of Sustainability

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Abstract: Human society currently faces a number of unprecedented challenges, ranging from global climate change and biodiversity loss to peak oil and natural resource depletion. Unfortunately, competitive market economies systematically favor the conversion of ecosystem structure into economic products over its conservation in order to provide vital ecosystem services. In order to design a sustainable economic system, we must assess the desirable ends of economic activity as well as the scarce resources required to attain them. The most critical desired ends require cooperation, not competitive markets. Fortunately, humans have evolved as cooperative, social animals, and proper economic institutions can elicit cooperative behavior in order to attain these ends. Building a sustainable economy requires a scientific approach in which institutions for allocation are determined by the ends we hope to attain and the physical characteristics of the resources at our disposal, not by ideological commitments to a market economy.

Keywords: Biodiversity loss, climate change, peak oil, human needs, sustainable, scale, just distribution, scarce resources, rivalry, excludability, stock-flow, fund-service, cooperative behavior, collective action, public goods, open access resources, price rationing.

INTRODUCTION

Economic systems, other institutions and resource availability co-evolve over time [1, 2]. The industrial revolution, the use of fossil fuels and large scale social reorganization interacted with profound economic changes in the late 18th and 19th centuries. Microeconomic theory was developed to explain and channel these forces. The theory's central focus was on the role of prices in balancing supply and demand while allocating the factors of production towards the highest value economic products, and those products towards the consumers who valued them

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the most. A serious crisis, the Great Depression, illuminated a major flaw in the theory, which failed to predict that a drop in demand could lead to reduced production, unemployment and further decreases in demand in a vicious circle. Macroeconomic theory was developed to explain this inherent flaw, and propose solutions in the form of government intervention through expansionary monetary and fiscal policies. Rather than simply balancing supply with demand, macroeconomic theory called for endless increases in both. The economy was like a bicycle that must move forward or fall down. Both microeconomics and macroeconomics were examples of true paradigm shifts, fundamental changes in our understanding of the nature of economic systems.

Society currently faces imminent changes as profound as the industrial/fossil-fuel revolution, and emerging threats far more serious than the great depression. The great depression was the result of a lack of demand, but the current ecological-economic crises we face are the result of resource constraints, a lack of supply. Natural resource depletion threatens not only to deprive the economy of the raw materials needed for production, but also complex ecosystems and the biodiversity they sustain. No economy can function without energy, and today's industrial economies depend on oil. Global oil discoveries peaked in the mid-sixties [3] and oil production reached a plateau in 2005; even 200% price increases in 2008 scarcely affected output [4]. Waste absorption capacity for carbon dioxide and other pollutants, sink constraints, may be even more limiting than source constraints [5, 6]. Overuse of both sources and sinks is threatening the planet's biodiversity and the ability of ecosystems to generate life sustaining ecosystem services [7].

Sustainability in a complex, evolving world requires adaptation. Addressing the new crises humanity now confronts demands a fundamental rethinking of our entire economic system. A major new paradigm shift is required to develop a biophysically sustainable earth economics [1].

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[1] David Batker, Executive Director of Earth Economics, coined this phrase. I have also borrowed from him the analogies with micro and macroeconomics. There is no difference between earth economics and ecological economics, except the former phrase accentuates the role of increasing scale and the progression from micro to macro to earth.

WHAT IS ECONOMICS?

In moving forward to develop a new theory of economics, it helps to first return to the basics. What does an economic system do? A standard definition of economics is the study of the allocation of scarce resources among alternative competing ends. An economic system strives to balance what we have with what want, biophysical possibility with social, psychological and moral desirability. It follows from this definition that we must understand the desirable ends and the nature of the scarce resources before we can decide how to allocate [8].

THE DESIRABLE ENDS

Conventional micro and macroeconomics both come from a utilitarian tradition, which defines the desirable ends of economic activity as the maximization of utility. Utility cannot be readily measured, but conventional economists assume that rational people will strive to maximize utility, and therefore their preferences for activities that increase utility are revealed by their actions, or specifically, by their purchasing habits [9]. Utility is considered equal to consumption of market goods, and more is always better. Work is assumed to generate disutility. The utility of society is typically taken as the weighted sum of individual utilities. While utility is inherently subjective, economists argue that revealed preferences are objective.

Economists recognize the concept of diminishing marginal utility, which means that each additional unit of something desirable confers less utility than the previous unit. One implication of this assumption is that the wealthy receive less utility from the marginal dollar than the poor, and a more equal distribution of wealth would increase total utility. However, conventional economists generally assume that we cannot compare utility across individuals. We should therefore strive for a system that achieves all exchanges that make at least one person better off without making anyone else worse off. A situation in which no further such exchanges exist is said to be Pareto efficient. Under a number of very strict assumptions, competitive free markets reach Pareto efficient outcomes, and thus maximize utility for society. All of this is covered in virtually any introductory text in economics.

Unfortunately, there are several serious problems with this supposedly objective approach to defining the desirable ends and establishing that free markets maximize utility. First, revealed preferences weights actual preferences by purchasing power. The preferences of the poor therefore receive negligible weight. Second, revealed preferences for market commodities tell us nothing about the role of non-market commodities in generating well-being. Third, the assumption that more is always better may not be justified. There is evidence that beyond a certain level well below that of the wealthier nations, increasing wealth does not correlate with an increase in happiness or satisfaction with life as a whole [10-12]. In fact, those who continually strive for higher income and more consumption may be less happy and more stressed than those who do not [13]. Once basic needs are met, we may derive satisfaction from our wealth relative to others, in which case increases in general wealth may have little effect on individual well-being [14, 15]. Fourth, if utility results from our ability to satisfy our wants and needs, and the economic system continually creates new wants for new products as rapidly as it increases our ability to satisfy them, growth does not increase utility. Finally, as explained in detail below, continuous increases in consumption are biophysically impossible on a finite planet.

A sustainable economic system does not need to abandon the utilitarian approach, but must recognize that any definition of desirable ends beyond simple survival is normative, not positive. Perhaps most people would agree that an appropriate intermediate end for economic activity is a high quality of life for this and future generations. However, quality of life consists of far more than consumption of market goods. At a minimum, a high quality of life must satisfy basic human needs. Max-Neef [16] identifies these needs as subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom. These needs are satiable, and only appear insatiable when we pursue the wrong means for satisfying them. Advertisements tell us that material consumption will satisfy these needs, and when it fails to do so, many believe that they simply are not consuming enough.

How we satisfy these needs differs across cultures, but there are three essential instrumental ends necessary to attain a high quality of life for this and future generations. The first is ecologically sustainable scale, where scale is defined as the size of the economy in relation to the ecosystems that sustain and contain it. We cannot exceed the carrying capacity of the earth. Given the complexities of the global ecological-economic system and the potential for surprises, we cannot pinpoint a single specific carrying capacity for human populations and artifacts, but increasing evidence suggests we have already exceeded acceptable safety margins [17]. We must focus on restoring and sustaining ecological resilience. The second is a just distribution of resources. Sustainability focuses on the just distribution of resources across generations, and the same ethical standard requires a just distribution within each generation. We cannot ask the poor to sacrifice consumption to meet the needs of the yet unborn. Furthermore, people inherently care about fairness [18, 19], and an unjust distribution of resources is incompatible with a high quality of life. Finally, given a finite planet with many degraded ecosystems and unmet human needs, a sustainable society requires an efficient allocation of resources, where efficiency is defined as the ratio of welfare gained from economic services to welfare lost in ecosystem services [20].

THE SCARCE RESOURCES

What resources do we have available to achieve a high quality of life? We know from the first law of thermodynamics that matter-energy cannot be created or destroyed. This means that all economic production requires the transformation of raw materials provided by nature. We know from the second law of thermodynamics that energy is required to do work, and that work increases entropy, or disorder. In economic terms, low entropy resources are useful, and high entropy resources are not. The economic system transforms low entropy resources from nature into economic products, increasing entropy in the process. The ultimate resource at our disposal is the planet's finite supply of low entropy matter-energy, and the finite flow of solar energy [21]. Ultimately, a sustainable economy cannot increase entropy faster than solar energy can replenish it. The laws of thermodynamics limit the physical size of our economy. Physical growth of the economy must eventually cease.

Fossil fuels are a particularly important source of low entropy energy. The market economy and the fossil fuel economy emerged hand in hand during the 18th century, spurred by the development of the steam engine, which was used to pump water from coalmines. One barrel of oil contains energy equivalent to 25, 000 of human labor [22]. Economic growth and increasing fossil fuel use have gone hand in hand. It is not at all clear in fact whether the explosion in economic production initiated by the industrial revolution is the result of the magic of the market or the magic of fossil fuels. Fossil fuels are a finite commodity. Oil discoveries peaked in the early 60s, and have declined steadily since. Consumption has exceeded new discoveries for decades [3]. Oil production may have reached a plateau in 2005, as a subsequent tripling of prices failed to increase output by more than 4% [4].

Raw materials from nature such as food, fibers, fuels, minerals and water are not only essential inputs into economic production, but also serve an alternative role as the structural building blocks of ecosystems. When we remove ecosystem structure and return waste to the environment, we lose or degrade ecosystem functions, including functions essential for the survival of humans and all other species. Ecosystem functions of value to humans are known as ecosystem services, and include regulation of water, atmospheric gasses, and climate, provision of food, fiber and fuel, habitat, and cultural benefits, among many others. These services are also essential inputs into economic production. For example, agriculture, our most important economic activity, may be catastrophically affected by the loss of climate stability. While economists refer to the unintended, uncompensated loss of ecosystem services resulting from economic activity as an externality, the laws of physics and ecology ensure that such losses are an inherent part of the economic process. We must reduce the rate at which we extract raw materials from nature and spew back waste.

Finally, even the most primitive hunting and gathering requires knowledge of what foods are edible and where they are located. All economic activity requires information and this is truer now than ever. We have truly entered the era of the information economy

CHARACTERISTICS OF THE SCARCE RESOURCES

Before we can address the problem of allocation, we must understand the basic characteristics of the scarce resources. One important distinction is between stock-flow and fund-service resources. Another is between rival and non-rival resources, and a third between excludable and non-excludable resources. Together, these characteristics interact to determine what types of institutions are appropriate for allocation.

STOCK-FLOW AND FUND SERVICE RESOURCES

The raw materials provided by nature and physically transformed into economic products are stock-flow resources. Such resources can be used at any rate we choose. We can clear cut a forest in a year or harvest slowly over decades, pump the world's oil reserves over decades or centuries, as we choose. Stock flow resources are physically transformed into what they produce, which means they are used up in the act of production. A tree is transformed into a house, and fossil energy is transformed into alternative forms of energy or waste. Stock flow resources can be stockpiled. Most stock-flows generated by ecosystems can be bought and sold in markets and rapidly converted into financial wealth.

Fund-service resources, including ecosystem services, have entirely different characteristics. Fund services result from a specific configuration of stock-flow resources. For example, a car is a specific configuration of metal, rubber, glass and plastic, and generates the service of transportation. A forest ecosystem is a particular configuration of plants, animals, soils, water, nutrients and so on, and generates a wide variety of ecosystem services. When the forest is clear-cut (but before the trees are removed) it consists of precisely the same structural components, but no longer generates the same services. Funds generate services at a given rate over time. A forest can regulate and purify a certain amount of water per day, or regenerate itself at a given rate over time. A car can transport a certain number of people a certain distance in a given day. Fund-services cannot be stockpiled. If one refrains from driving a car for six days, it is not capable of generating more transportation services on the seventh day. Fund services are not physically transformed into what they produce, though production can change them qualitatively. A car is worn out a bit more each time it is driven. Ecosystems undergo qualitative changes when they generate services, but they are continually maintained by solar energy flows. For practical purposes, solar energy and information act like fund-services [23, 24]. Most fund services provided by nature cannot be bought or sold in markets.

Because stock flow resources generated by ecosystems can be bought and sold in markets, and most fund-services cannot be, markets will favor the conversion of stock flow resources into market products over their conservation in specific configurations that generate critical ecosystem services. Furthermore, even if fund-services were valued and traded on the market, they provide flows of value over time, whereas stock-flows can be liquidated at the rate we choose. Markets are impatient, valuing money now over money in the future, and again favor conversion over conservation.

RIVALRY

Another critical resource characteristic is rivalry. A rival resource is one for which use by one person leaves less in quality or quantity for another person. Rival resources are therefore also known as subtractive resources. When rival resources are scarce, there is competition for their use. They must therefore be rationed to prevent depletion or degradation and to ensure they are allocated efficiently towards those uses that contribute most to a sustainable and high quality of life. The value of a rival resource is determined by the benefits received by the single user who consumes it. Market prices are one possible rationing mechanism, ensuring that the resource will go to whoever is willing to pay the most for it. Examples of rival resources include food, fiber, fossil fuels, land, minerals, drinking or irrigation water, waste absorption capacity and so on. All stock-flow resources and most market commodities are rival.

In contrast, use of a non-rival resource by one person does not leave less for others to use. Such resources are not scarce in the conventional sense, as there is no competition for use and no need for rationing. If we price non-rival resources, use is reduced, rationed to those able and willing to pay the price, even though additional use imposes no additional societal costs. Rationing needlessly lowers sustainable quality of life. Non-rival resources are most efficiently allocated when they are open access, free for all to use.

The value of a non-rival resource is determined by the sum of benefits received by all users. However, there is typically a real cost to providing or protecting non-rival resources. Since competitive markets will not bear these costs as long as consumption is open access, cooperative or public institutions should provide them[2].

All non-rival resources are fund-service in nature, though not all fund-services are non-rival. Examples of non-rival resources include climate stability, the ozone layer, disturbance protection, streetlights, lighthouses, and scenic beauty, among many others—no matter how much one person uses, there is just as much left for others.

Information is not only non-rival, but actually improves through use. Technology builds on older technologies in a steady process of improvement. Language, literature, music and art behave in a similar fashion. Some types of information, such as vaccines for contagious diseases or environmental friendly technologies become more valuable the more they are used. Rather than subtractive in nature, information is additive, and using the price mechanism to ration it may create a "tragedy of the non-commons"[25]. As an example, the ozone hole reached a record size in 2006 [26], largely because China and India continue to rapidly increase use of ozone depleting HCFCs [27]. Non-ozone depleting substitutes are available, but they are also patented and charge royalties, raising their price and decreasing their use.

As another example, countries conventionally provide new strains of viruses to the World Health Organization (WHO), which provides unlimited access for anyone seeking a cure. Typically those seeking cures are corporations, and for a potentially serious virus, thirty separate teams of scientists may be seeking a cure. As the teams are competing to be the first to develop and patent a vaccine, they are unlikely to collaborate, which is likely to slow research and make it more expensive. Publicly financed research with shared knowledge is likely to be much cheaper. When one team finally develops and patents a cure, it will be sold at the profit-maximizing price, rationing use to a limited number of potential victims, and increasing the likelihood of a pandemic. As a result, when a new strain of

[2] Private provision would be more cost effective only if it is so much cheaper than public sector provision that it compensates for the reduction in use caused by pricing, which may be possible for very dysfunctional public sectors. However, pricing is likely to systematically exclude the poor, and distribution issues may trump cost effectiveness as a desirable end.

avian flu virus was discovered in Indonesia, Indonesia initially refused to turn it over to the WHO, and planned instead to sell it to the highest bidder, with the reasoning that Indonesians would not otherwise be able to afford the patented vaccine [28]. Indonesia's market approach would have meant only one team of scientists seeking a cure, rather than thirty, with presumably lower chances of developing one.

It's critical to recognize that rivalry is a physical characteristic of a resource in a particular use, and not a policy variable. There are many references in the economics literature to supposedly non-rival but congestible resources, such as roads, golf courses, and beaches. At low levels of use, one person's use does not leave less for others, while at high levels of use, it does. This gives the impression that rivalry is at least somewhat a policy variable as it is affected by the number of users, and that access to non-rival resources should be rationed. However, the physical space a car, golfer or bather occupies is in fact rival. When there are few users, the resource is abundant, which means there is no competition among users. With more and more users, the resource becomes scarce. We must not confuse abundance with non-rivalry.

EXCLUDABILITY

For rationing of a resource to take place, it must be made excludable. A resource is excludable when one person or group can use a resource while preventing others from doing so; in simple terms, property rights (state, common or private)[3],

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[3] Daniel Bromley [29] offers the following definitions:
"State Property: The political community is the recognized owner of the asset. Individuals in the political community may benefit from the asset but must observe rules of the government agency responsible to the political community. Examples: national forests and parks, military bases, government office buildings.
Private Property: Individual members of the political community have a recognized right to benefit from the asset, subject to legislative mediation and judicial review. Non-owners have a duty to allow owners to behave as above. Examples: Fee-simple land and buildings, automobiles, personal objects.
Common property: A group of owners holds rights in common, including the right to exclude non-owners. Individual owners have specific rights and duties with respect to their ability to benefit from the asset subject to legislative mediation and judicial review within the larger political community. Non-owners have a legal duty to respect boundaries of the regime."

exist and are enforced. Excludability is a prerequisite for markets to exist for obvious reasons. Most stock flow resources can be made excludable, as can information [4]. Excludability is the result of institutions and a policy variable.

A resource is non-excludable when no property rights exist. Such resources are open access by definition. Some non-excludable resources such as waste absorption capacity or oceanic fisheries can be made excludable by appropriate institutions. Many resources however are inherently non-excludable, including many ecosystem services. As long as the service exists in a given location, there is no practical way that we can let some people use a stable climate, the ozone layer or disturbance protection while preventing others from doing so.

As pointed out above, competitive markets will not provide adequate levels of open access resources, so it falls on cooperative, public institutions to do so.

HOW DO WE ALLOCATE?

By assessing the desirable ends of economic activity and the scarce resources required to achieve them, we have laid the groundwork for determining what allocative mechanisms and institutions are appropriate. However, it is first worth returning briefly to the desired ends now that we have a more complete understanding of the scarce resources.

Our goal remains to achieve the highest possible quality of life, but we must first understand what are the most binding constraints on achieving this. Historically, both raw materials from nature and ecosystem services were abundant, while human made capital, labor and economic products, all rival and generally excludable, were relatively scarce. The challenge lay in how to allocate capital and labor towards the transformation of raw materials into the most desirable economic products. Over the past two centuries however, the situation has reversed. Human populations are now

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Hereafter, this chapter will refer to state and common property rights together as public property rights.

[4] Though entirely different concepts, many people confuse excludability and rivalry. The case of information helps to clarify the difference. Information is inherently non-rival, and nothing can be done to change this. However, patents can make information excludable, legally rationing use to those who pay royalties.

vast, and per capita consumption of human made products is at record levels. Natural resources and biodiversity have been grossly depleted, while waste emissions have soared, resulting in serious threats to ecosystem services. The scarcity of resources provided by nature, both raw materials and ecosystem services, likely present the greatest threats to our quality of life, and without these economic production is also impossible. Most ecosystem services are non-rival and non-excludable. Our challenge now is to protect and restore life sustaining ecosystem services, which requires limits on the quantity of ecosystem structure that can be converted into economic products and waste. Specifically, we must address the problems of climate change, natural resource depletion, biodiversity loss, and peak oil. We must ensure that global ecosystems are capable of sustaining the global economy and resilient enough to recover from unpredictable shocks.

Competitive free markets are currently the dominant mechanism for allocating resources and it's worth understanding briefly how they work. Market allocation is based on the price mechanism. Natural resources are allocated towards whichever firm can generate the most profit from its use, equivalent to adding the most monetary value, and hence pay the highest price. This is known as the allocative function of price. Economic products in turn will go to whichever consumer is willing to pay the highest price for them. This is known as the rationing function of price. In both production and consumption, the price mechanism maximizes monetary value, and does so based on individual choices made by producers and consumers with no centralized information required.

As mentioned earlier however, markets equate utility with monetary value, so markets are only an appropriate allocation mechanism to the extent that maximizing monetary value is an appropriate desirable end. In addition, monetary value is determined by preferences weighted by purchasing power. Market allocation is plutocratic, based on one dollar, one vote. The preferences of the poor and future generations, and hence just distribution and sustainability, are systematically ignored. A more democratic system for decisions concerning ecosystem services and the shared inheritance of natural resources might be far more just. Even if we do accept the maximization of monetary value as a desirable end, markets fail to achieve this for non-rival resources. As explained above, the value of non-rival resources is paradoxically maximized at a price of zero, at which price markets fail to supply them. If society makes non-rival resources excludable so that markets will provide them, markets will not only fail to maximize their monetary value, but governments also must bear the costs of enforcing excludability. In fact, markets always rely on governments or other cooperative institutions to enforce property rights, and the conclusion that markets maximize monetary value does not account for the costs of making resources excludable. Markets fail to supply non-excludable resources. Finally, all market production degrades non-marketed ecosystem services, and in the absence of government regulations, market forces ignore these costs [30].

In other words, though markets have impressive positive attributes, they also have serious shortcomings, particularly when allocating non-rival or non-excludable resources. Unfortunately, most of the major problems human society currently faces involve such resources. Climate stability, protection from UV radiation, and many of the benefits from biodiversity, including ecosystem resilience, are inherently non-rival and non-excludable, and markets fail to protect them. Cooperative international efforts have already banned many ozone-depleting compounds, though concrete evidence that the ozone layer is actually recovering remains elusive [31]. Utilizing the fact that carbon absorption capacity is rival, global society is currently striving to forge cooperative institutions to make it excludable and allow no more emissions than ecosystems can absorb. Society can then directly charge for use *via* carbon taxes (actually user fees for waste absorption capacity), in which cases prices will determine the level of emissions, or issue tradable permits that allows for market allocation of socially determined supply[5], in which case ecological limits determine price. Taxes or auctioned quotas are equivalent to public property rights, in which society owns waste absorption capacity, a critical means of production. Negotiations on limits unfortunately are hampered by short sighted notions of national self-interest.

However, limits on emissions alone are probably inadequate. Confronting both climate change and peak oil will undoubtedly require the rapid development and dissemination of new low carbon energy technologies. Unfortunately, economists

[5] Offsets in the form of increased sequestration capacity (*e.g.,* reforestation projects) can actually increase the supply of waste absorption capacity, but are currently negligible.

tend to focus on the failure of markets to produce open access resources, and seek to solve the problem by creating and protecting intellectual property rights. However, this simply creates a new ‘market failure’ in the form of price rationing a non-scarce resource. A cooperative global effort to develop these technologies would instead ensure that adequate resources are available to produce essential new technologies, which would remain open access. Shared information would likely speed up the discovery process. Privately produced and owned information would be price rationed, reducing use of new technologies in favor of coal and other carbon based fuels [32]. Protecting oceanic fisheries, endangered species and endangered habitats will also require cooperative institutions.

As should be obvious from these examples, the use of cooperative economic institutions is an important solution to the shortcomings of competitive market allocation in both theory and practice. Markets already rely on such institutions to defend property rights, and could not exist without them. Nobel Laureate Elinor Ostrom and her colleagues have studied real life experiences with the management of resources which are rival but difficult to make excludable, known as common pool resources. While in many cases such resources are over-exploited, in numerous other circumstances a variety of institutions emerge that lead to sustainable, just and efficient management. One key to making such institutions work is that community members own the resources in common, while non-community members are not allowed to use them—they are common goods when viewed from within the community, but private goods from the perspective of other communities. It also helps when community members have broad input into management strategies, can effectively monitor resource use, sanction those who fail to respect community rules, and have access to mechanisms for cheaply and easily mediating any conflicts [33, 34].

To reiterate a central point, whether competitive or cooperative institutions are more appropriate mechanisms for allocation depends on the physical characteristics of the resources involved, as well as the desirable ends. Table **1** provides a summary.

IS COOPERATION POSSIBLE?

For generations, mainstream economists have assumed that economic man (Homo economicus) is purely self-interested and rational. Institutions requiring altruism or cooperative behavior do not conform to human behavior. The best possible outcome was the invisible hand of market institutions that channeled our egoism into the greatest good for the greatest number. For many decades, evolutionary biologists supported these assumptions, arguing that altruistic tendencies would be selected out of a population by genetic forces [35, 36]. In recent years however, both behavioral economists and evolutionary biologists have come to accept that cooperative altruistic behavior is both possible and desirable.

THE EVOLUTION OF COOPERATIVE BEHAVIOR

The best way to illustrate the evolution of cooperative behavior is with a concrete example. Throw a bunch of *Pseudomonas flourescens* bacteria in a beaker with food, and they will rapidly reproduce until they become starved for oxygen. At this point, the survival advantage shifts to a mutant type known as the 'wrinkly spreader', which can create a film that binds them together into a floating colony with access to oxygen from above and nutrients from below. Cooperation allows the group to thrive. However, within this cooperative colony there may be some defectors—they produce none of the sustaining film, but instead free-ride on that produced by others. With the energy they save by not producing the film, they are able to have more offspring than the cooperative Pseudomonas. Competitive individuals (*i.e.,* defectors) within the group out-compete cooperative ones. However, if there are too many defectors, the colony can no longer stay afloat, and plunges to the depths of the beaker, losing its relative fitness. Those colonies with fewer defectors will continue to thrive and leave more descendants than others [37]. What we see in fact is two distinct types of evolutionary pressure; competitive pressure at the individual level, and cooperative pressure at the group level. The basic rule is that "Selfishness beats altruism within single groups. Altruistic groups beat selfish groups" [38].

Humans evolved as small bands competing with other bands (and of course with other species) for resources. Those bands that engaged in cooperative behavior outcompeted those that did not, which selected for increasingly pro-social behavior. Humans are social animals who almost certainly owe their evolutionary success to their ability to cooperate. Unlike simple bacteria however, human culture can evolve as well, leading to the development of institutions that promote (or hinder) pro-social behavior [39].

Examples of the evolution of cooperative behavior are widespread in biology, but one other example bears mentioning for the analogy it provides to human society. *Myxococcus xanthus* is a bacterial predator that hunts cooperatively under conditions of food scarcity, traveling as a swarm to capture and digest prey. In starvation conditions, the bacteria cooperates to an even greater degree, forming a spore mass in which the vast majority sacrifice themselves to allow a few to sporulate and await better conditions. However, when these bacteria are placed into conditions of abundance, cooperative behavior is no longer necessary. If left in such conditions for long enough, they lose the ability to hunt as packs or sporulate in conditions of scarcity. However, if placed with cooperative populations, they become ten times more likely to form a spore than cooperators [40]. It would appear that when placed in conditions of resource abundance, these bacteria evolve to approximate the rational, self-interested behavior of *H. economicus*. One must wonder whether the advent of the fossil fuel economy, an era of abundance, has favored the evolution of economic systems based on selfish, competitive behavior that could not thrive in conditions of scarcity. If so, we can only hope that humans do not also lose the ability to cooperate, or that those that do lose the ability prove unable to increase their fitness by free-riding on the cooperation of others.

COOPERATIVE BEHAVIOR IN SOCIETY, AND INSTITUTIONS FOR PROMOTING IT

Fortunately, humans are not entirely constrained by our genetics to be selfish or cooperative, and abundant evidence exists that we are still a highly cooperative species. One simple experiment is called the dictator game. One participant is offered a sum of money, and told to divide it with another anonymous participant in whatever proportion she likes. While a selfish person would obviously keep all the money, few participants actually do so. American college students on average give away 20% of the money [41].

Two experimental games closely approximate the cooperation problems posed by common pool (non-excludable but rival) and public good (non-excludable and non-rival) resources. In the common pool game, participants can withdraw any amount up to some fixed limit from a common pot. What remains in the pot then ‘grows’ by some pre-specified proportion, say 50%, and is redistributed equally to all, regardless of how much each person withdrew. In the public good game, participants start with a fixed sum, and are allowed to donate as much as they want to a fixed pool. This money is then doubled (or increased by some other pre-specified amount) and redistributed equally to all, regardless of how much each person contributed. If people act in their rational self interest, then they will withdraw as much as possible and contribute as little as possible in the two games, even though minimum withdrawal and maximum contribution generate the greatest wealth for the group as a whole.

Once again, experimental evidence fails to support conventional ~~economics ’~~ assumption that people act only out of pure self-interest. Most people in the voluntary contribution game contribute something to the common pool. University students tend to contribute 40-60% of the total amount they are given, on average, with one mode at zero contribution and a typically smaller one at full contribution. However, in repeated games either among the same group or with different group members (*i.e.,* each person plays the game multiple times, but with different people) contribution rates fall. It appears that those who initially cooperate engage in a tit for tat strategy[6]: the most generous individuals ratchet down their contributions to the mean contribution, which further drives down the mean. Is there a way to avoid this sub-optimal outcome? In one variation of the game, participants learn after each round who contributed and how much, and are allowed to punish those who did not contribute. Punishment is costly: for example the punisher may have to give up 1/3 unit of reward to punish defectors by 1 unit. Yet, when punishment is allowed, the rates of cooperation go up with repeated rounds, not down. This is an example of what is known as altruistic punishment: individuals sacrifice their own welfare to make defection a losing strategy, encouraging cooperation even from people who are purely selfish, and even when they make up a significant percentage of the group. In other words, altruistic punishment can make cooperation the dominant strategy in prisoner’s dilemma type situations even for selfish individuals [42-45].

[6] ‘Tit for tat’ simply means acting towards your partners as they acted towards you in the previous round. In a famous experiment, ‘tit for tat’ was found to the most successful overall strategy in repeated prisoner dilemma games [49].

Altruistic punishment is not the only way to achieve cooperation, however. If participants in experimental games are allowed to talk about their strategies ahead of time, they are much more likely to cooperate. This is true even for “cheap talk”, which means that the decisions participants ultimately make are not revealed to others, and there is no way to create binding contracts [46].

Studies from behavioral economics suggest that some people are purely selfish by nature, like *H. economicus*, most are conditional cooperators, and some are very pro-social [47, 48]. The choice of institutions helps determine what behavior predominates, and the nature of the scarce resources and our choice of desirable ends determines what behaviors are appropriate.

SUMMARY AND CONCLUSIONS

As human institutions and the nature of resource scarcity have evolved over time, so too have economic systems. Human society currently faces a number of serious challenges, ranging from climate change and biodiversity loss to natural resource depletion, including growing scarcity of fossil fuels, and the economic system must again adapt. In order to intelligently guide a successful adaptation process, we must clearly understand the goals of the economic system, the resources available to achieve these goals, and human nature.

Perhaps the least controversial economic goal is survival. An economic system must use available energy to transform the raw materials provided by nature into basic necessities such as food, potable water, shelter, and energy.

For the past two hundred years, we have relied on competitive markets and fossil fuels to meet all of these needs. Food, water, shelter and fossil fuels are rival (*e.g.,* if I eat a sandwich or burn a barrel of oil, there is less available for you) and scarce (there is not enough for every desired use), so competition for them is inevitable. Because they can also be made excludable, market competition is possible. Using free choice and decentralized knowledge, markets and fossil fuels have helped us transform increasing amounts of ecosystem structure into highly valuable human artifacts. This transformation of course left less ecosystem structure available to generate ecosystem services, but such services were relatively abundant and there was little need to worry over them.

Table 1: Suitable Institutions for Allocation, as Determined by the Physical Characteristics of the Resources Involved

	Excludable (property rights exist, state, common or private)	**Non-excludable** (open access)
Rival and scarce competition exists	**Market Goods** Provision: Potential private sector Consumption: Rationing required, price rationing may be appropriate Examples: Stock-flow: Oil, food, fiber, water (for drinking, irrigation, industrial uses) Fund-service: land, labor, human made capital	**Common pool resources, open access regimes** Provision: Direct provision by public sector, or else public sector regulation or creation of property rights, which either allow market allocation of socially determined supply, or can create incentives for private sector provision if offsets are permitted. Consumption: Rationing appropriate, price rationing suitable, but only possible if institutions make resource excludable. Examples: Stock-flow: Stocking of fisheries (direct provision); treaties that provide state property rights to fisheries such as the exclusive economic zone; individual fishing quotas that assign privileges to a share of state owned fisheries (creation and regulation of property rights). Fund-service: Public sector clean up of pollution (direct provision); cap and trade for carbon (allows market allocation of socially determined supply).
Rival, borderline scarce Congestible; potential for competition	**Club or toll goods** Provision: Potential private sector Consumption: Rationing required when scarce, price rationing suitable Examples: Fund Service: Recreational uses of land, roads, national parks, game reserves, *etc.*	Provision and consumption: same as above when scarce or threatened by scarcity, no institutions needed when abundant. Examples: Stock-flow: Oxygen (still abundant, inherently non-excludable) Fund-Service: toll roads; golf courses; fees at public parks
Non-rival no competition; all fund-service	**Inefficient market goods (“tragedy of the non-commons”)** Provision: Potential private sector with government enforced monopolies on intellectual property rights. Consumption: rationing inefficient, price rationing decreases economic surplus. Should be open access. Examples: Patents on technologies that protect and restore ecosystem services, Property rights to genetic information and chemical components of biodiversity; Intellectual property rights in general.	**Public Goods** Production: Public sector financing required and desirable. Consumption: open access exists and is desirable. Examples: Protection and restoration of ecosystems to provide many regulatory services (flood regulation, disturbance regulation, erosion control, climate regulation, *etc.)*., supporting services (habitat for biodiversity) and cultural services (scenic beauty, spiritual values, *etc.)*.; publicly funded, open access technologies, especially those that protect and restore ecosystem services.

However, the very success of the fossil fuel market economy has dramatically changed the nature of scarcity. The scarcest and most important resources are increasingly non-rival, in which case price rationing is inefficient; non-excludable, in which case market allocation is impossible; or both.

To reiterate points made previously, the issue of climate change effectively illustrates the problem. Fossil fuel emissions are the major source of greenhouse gases triggering climate change. Though fossil fuels are a rival, excludable market good, their combustion causes a negative externality, disrupting the ecosystem service of climate regulation. The disruption occurs because greenhouse gas emissions exceed planetary waste absorption capacity. This absorption capacity is rival, in that its use by one country leaves less available for other countries to use, but is also non-excludable at the global level: There are no laws in most countries that prevent people from spewing as much CO_2 into the atmosphere as they choose. To solve this problem, collective action institutions must limit waste emissions to no more than absorption capacity, then distribute (ideally in a just fashion) the right to use it. As explained above, tradable permits and taxes both use price rationing. Markets cannot determine sustainable limits or just distribution. The same argument holds true for all waste sinks.

A stable climate itself is a pure public good, both non-rival and non-excludable. Because my use of a stable climate to grow crops leaves no less for you, it would be inefficient to ration access. It is also impossible to do so. The only solution is collective provision. Given the high stakes, urgency and uncertainty involved, simply limiting GHG emissions is probably inadequate, we should undertake other cooperative activities to sequester carbon, such as reforestation. The same arguments hold true for all public goods, including the ecological resilience provided by biodiversity.

We must also develop new, low carbon energy technologies such as wind and solar. As pointed out above, the market will only produce these technologies if they can be patented (*i.e.,* made excludable) and sold at a price. On the production side, when the private sector competes to obtain patents, they do not share information, which can slow down the advance of science. On the consumption side, patents create a monopoly with monopoly pricing, rationing use to the wealthy, even though ubiquitous use would maximize human welfare. The optimal approach is publicly financed cooperative production with the results freely available to all. Open access to non-rival resources maximizes their value.

In short, cooperation is essential to solving the problems of ecological sustainability and just distribution, which are currently the most pressing problems facing human society. The market can only be trusted once these two problems have been solved.

It would of course be futile to design an economic system based on cooperation if people were inherently incapable of cooperative behavior. Fortunately, in spite of assertions by conventional economists that humans are inherently self-interested, evolutionary biologists have convincingly established that group selection favors cooperative behavior. Behavioral economics in turn has fortuitously identified mechanisms that promote cooperative behavior. One such type of institution is societal rules that allow the punishment of greedy, self-interested behavior.

Unfortunately, capitalism tends to glorify greed, and actually claims that it is in the public interest. While market economies may be very efficient for allocating certain types of resources, they are very ineffective at allocating others, and have played a central role in creating the most serious problems we now face. Many economists seek to solve these problems by placing monetary values on all non-marketed ecosystem services so that they can be included in the market mechanism. This is an ideological approach however that decides on the allocative mechanism before examining the desired ends or the nature of the scarce resources. Economics is too important to be left to ideology. Rather than trying to force all resources into the market model, we must adapt economic institutions to the physical characteristics of the resources in question.

A paradigm shift in economics is again necessary. Close examination of the desirable ends and physical characteristics of resources tells us that some resources can be effectively allocated through competitive markets, while others require institutions based on cooperation. Evolutionary biologists, behavioral economists and political economists have shown the mechanisms through which cooperative behavior can evolve and increase fitness.

Following the great depression, the world's leading economic powers met together in Bretton Woods, New Hampshire, to craft a new set of institutions, including the World Bank, the International Monetary Fund, and the predecessor of the World Trade Organization. We need a new set of cooperative global economic institutions to produce and protect non-rival and non-excludable resources [50]. Rival resources such as atmospheric waste absorption capacity and oceanic fisheries should be rationed, which first requires the creation of global common property rights [51, 52]. After ensuring adequate access to these resources to meet basic human needs, the privilege to use remaining ecological capacity can then be auctioned off. The revenue should then be invested in inherently non-excludable or non-rival global public goods, such as the technologies required to protect and provide other global public goods [53]. Wealthy nations that refuse to participate should be sanctioned.

In conclusion, a more scientific approach to economics must first assess desirable ends and next the nature of the resources required to attain them before deciding which allocative mechanisms are appropriate. Institutions can promote competitive or cooperative economic mechanisms as appropriate. Economics can no longer be left to ideologues who favor a single allocative mechanism for all economic problems.

CONFLICT OF INTEREST

The author(s) confirm that this article content has no conflicts of interest.

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