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Resource Scarcity and Sustainability—The Shapes Have Shifted but the Stakes Keep Rising

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Abstract: The objective is to provide an interpretive reading of the literature in resource scarcity and sustainability theory from the nineteenth century to the present time, focusing on shifts that have occurred in problem definition, conceptual framing, research tools applied, findings, and their implications. My reading shows, as one would expect, that the discourse has become more technical and the analysis more sophisticated; special cases have been incorporated into the mainstream of theory; and, where relevant, dynamic formulations have largely supplanted static analysis. However, that is barely scratching the surface. Here, I focus on more fundamental shifts. Exhaustible and renewable resource analyses were incorporated into the mainstream theory of financial and capital markets. Parallels between the resources and environmental spheres were discovered: market failure concepts, fundamental to environmental policy, found applications in the resources sector (e.g., fisheries), and renewable resource management concepts and approaches (e.g., waste assimilation capacity) were adopted in environmental policy. To motivate sustainability theory and assessment, there has been a foundational problem shift from restraining human greed to dealing with risk viewed as chance of harm, and a newfound willingness to look beyond stochastic risk to uncertainty, ambiguity, and gross ignorance. Newtonian dynamics, which seeks a stable equilibrium following a shock, gave way to a new dynamics of complexity that valued resilience in the face of shocks, warned of potential for regime shifts, and focused on the possibility of systemic collapse and recovery, perhaps incomplete. New concepts of sustainability (a safe minimum standard of conservation, the precautionary principle, and planetary boundaries) emerged, along with hybrid approaches such as WS-plus which treats weak sustainability (WS) as the default but may impose strong sustainability restrictions on a few essential but threatened resources. The strong sustainability objective has evolved from maintaining baseline flows of resource services to safety defined as minimizing the chance of irreversible collapse. New tools for management and policy (sustainability indicators and downscaled planetary boundaries) have proliferated, and still struggle to keep up with the emerging understanding of complex systems.

Keywords: resource scarcity; exhaustible resource; renewable resource; weak sustainability; strong sustainability; safety; planetary boundaries

1. Introduction

I offer a brief interpretive history of thought about resource scarcity and sustainability over the last two centuries, trying to discern the big picture which, not surprisingly, turns out to be a motion picture. The kinds of developments that might be expected have occurred: sketchy theories are elaborated to expand their scope, fill-in the details, and accommodate special cases; and where relevant, dynamic models have replaced static analyses of situations where feedbacks may influence the success of policy and management interventions.

A more interesting finding is a major problem shift that began in the mid-20th century with concern that variability in stocks of renewable resources may lead to depletion, perhaps irreversible, in bad years. The sustainability problem had been framed as restraining

human greed and impatience but, from this point on, it was more about dealing with risk. The venerable sigmoid growth curve provided a passably good account of growth for an individual specimen, but populations of species exhibited very different patterns that, by the 1970s, could be captured by dynamic models of complex systems. Soon, models of coupled human and natural systems were alerting us to the feedbacks that might undermine attempts to manage the risks that complex systems modeling had exposed. Not only was risk the big threat to sustainability, it took new forms: uncertainty, ambiguity, and unknown unknowns, in addition to its classical stochastic form. The old sustainability problems (depletion and scarcity, exploration and discovery, recycling, new technologies, substitution) still matter, but a new set of challenges (complexity, coupled human and natural systems, gross uncertainty, and resilience in the face of unanticipated shocks) have taken center stage.

This article (i) expands upon these developments; (ii) summarizes the contest between Ricardian formulations that see scarcity as relative and weak sustainability (WS) as the core of a coherent approach to sustainability, and Malthusian formulations that frame scarcity as absolute and gravitate toward strong sustainability solutions; (iii) observes that recent developments seem to have focused more attention on strong sustainability (SS) remedies while SS itself has been redefined to focus more on safety; (iv) briefly introduces newly emerging approaches to policy and management in the SS tradition, the precautionary principle and planetary boundaries, along with a WS-plus approach that would maintain inclusive wealth but insist that it include adequate stocks of particular resources deemed critical, i.e., essential and threatened. If the motion picture metaphor holds, this is one of those movies that does not resolve all of the ongoing mysteries in the last scene.

2. Methods and Materials

The goal is to develop an interpretive intellectual history of the discourse on resource scarcity and sustainability over the last two centuries, beginning in the early 19th century. In some ways, this literature exhibits the kinds of developments that must have been predictable. For example, the discourse has become more technical and the analysis more sophisticated; special cases have been incorporated into the mainstream of theory; and, where relevant, dynamic formulations have largely supplanted static analysis. However, that is barely scratching the surface. My focus is on more fundamental shifts.

What follows is not a conventional literature review and makes no claim to be comprehensive. It is an interpretive intellectual history, guided by what is now called economic theory, although important antecedents were attributable to a forester (Faustmann), an investor/politician (Ricardo), a preacher (Malthus), and a geographer (von Thunen). More recent developments have been even more interdisciplinary, with key contributions from philosophy, behavioral science, engineering, ecology, computer science, and many more disciplines and avocations.

Particular attention is paid to seminal publications and more recent exemplars of developments are highlighted, omitting many intermediate steps that would be addressed in a comprehensive literature review. The discussion of the foundations and early development of the theory of optimal extraction of exhaustible resources and harvest of renewables draws explicitly on theory, which is agreeably simple enough for a fairly broad audience. When the narrative gets to dynamic optimization, complexity theory, and modeling of coupled human and natural systems, the account focuses more on the big picture, but key references are provided.

An issue facing scholars of resource scarcity is whether to start with exhaustible or renewable resources. The problem framing and analyses for exhaustible resources are simpler than for renewables, and the industrial revolution in what are now identified as the high-income OECD countries, fueled by underground mining for coal and raw materials such as iron ore, was oriented toward exhaustible resources from the outset. During the strong economic recovery following World War II, a perceived threat of running out of exhaustibles was the earliest introduction to the resource scarcity discourse for the

senior scholars among us today. However, literature predating the industrial revolution was more concerned about scarcity of renewables and, for much of the world beyond the OECD countries, depletion of renewables has long been the primary focus. The earliest modern analysis relating natural resources to financial markets was addressed to forest management [1]. I have chosen to start with exhaustible resources, but that strategy requires a tip-of-the-cap to Faustmann the forester in Section 3.1. on exhaustible resources.

3. Results and Discussion

3.1. What Will We Do When the Coal Runs Out?

3.1.1. Exhaustible Resources

The Jevons report on Britain's coal supply [2] responded to worries about depleting exhaustible resources. This was a very industrial-revolution framing of the problem: industrialization was facilitated by mining—often but not always underground extraction of minerals in plentiful supply: coal, oil, and gas for fuel, and minerals for raw materials. Coal had become the fuel of choice not just for transportation and heating but also for refining of minerals to produce, e.g., iron and steel. Inevitably, concerns arose that the industrial economy would founder should coal become scarce and expensive. There was a precursor to this worry. Charcoal had become a preferred fuel for heating, and concerns that Britain would run out of trees for charcoal production arose as early as the 16th century [3]. Its increasing use in iron smelting exacerbated worries about impending scarcity of wood, but these were alleviated when coal mining at industrial scale became feasible. It is hard to imagine the industrial revolution without the development of underground coal mining methods in the late 18th century.

3.1.2. Cake Eating

Before addressing minerals, let us take a look at the simplest exhaustible-resource problem of all, cake eating. A cake of given size, S_0, has to last a prisoner a given number, T, of days. There are no complications: the cake is there for the eating, uneaten cake does not spoil, the initial quantity is more than enough for the prisoner's survival, and the terminal date is certain. What is the optimal time path of consumption? The flat path, consuming $\frac{S_0}{T}$ each day seems obvious, but the prisoner has a positive time preference, $r > 0$, i.e., prefers satisfaction sooner rather than later.

The stock of cake at the beginning of day τ,

$$S_\tau = S_0 - \sum_0^{\tau-1} C_t \tag{1}$$

where τ is a particular day in t and t in (0, T) is discrete time in days, and C_t is the amount consumed on day t, where C is non-negative. The initial value of the cake viewed as an asset,

$$V_0 = \sum_0^T C_t / (1 + r)^t \tag{2}$$

is implicit given the absence of markets in assets. If maximized, V_0 reflects the value the prisoner receives from the optimal time path of consumption.

The kernel of the user cost idea can be seen here: the value of the asset (the cake) at the beginning is positive even as the cost of extracting a meal from the cake is zero, and even as there is no market in which the asset value can be realized. The user cost of first-period consumption is equal to the value of later satisfaction that is thereby foregone. User cost is increasing as early consumption increases relative to the amount left for later. On the optimal consumption time path, where *MUC* is marginal user cost,

$$\frac{\mathrm{d}MUC_t / \mathrm{d}t}{MUC_t} = r \tag{3}$$

i.e., MUC_t grows at the rate of r. Note that r is individual time preference; the prisoner can save for future consumption, but has no opportunity to invest any savings at r.

3.1.3. Extraction of an Exhaustible Resource

In contrast to the prisoner's cake, extraction of a mineral resource is costly. The stock equation for a mine at time τ, where time, t, is now continuous and T may be far into the future, is

$$S_\tau = S_0 - \int_0^\tau H(t)\mathrm{d}t \tag{4}$$

where $H(t)$ is the quantity of raw material produced. The mine owner's net revenue at time t is $Rev(t) = p(t)H(t) - c(t)H(t)$, where $p(t)$ is the price and $c(t)$ the marginal extraction cost (defined broadly to include any refining prior to sale as raw material). Now, user cost (*UC*) is

$$UC(t) = (p(t)H(t) - c(t)H(t)) \tag{5}$$

i.e., the pure profit from $H(t)$ and the price of raw materials,

$$p(t) = MEC(t) + MUC(t) \tag{6}$$

where cost $MEC(t) = c(t)$ is the marginal extraction cost and $MUC(t)$ is the now familiar marginal user cost. *MUC* serves to optimize intertemporal consumption by bringing future demands to bear on current decisions. In a framework addressed to revenue rather than consumption, user cost is the difference between revenues and out-of-pocket (e.g., extraction) costs, which is defined as the economic rent, i.e., pure profit. The extraction time path that maximizes the present value of rents over a very long time is, under ideal conditions, the optimum intertemporal allocation. The value of the mine as an asset is

$$V_0 = \int_0^T (p(t)H(t) - c(t)H(t))e^{-rt}\mathrm{d}t, = \int_0^T (MUC(t))e^{-rt}\mathrm{d}t \tag{7}$$

To Faustmann, it was self-evident that it would take a return at least as great as could be obtained from bank deposits to induce an owner to hold property in natural resources [1]. More formally, the value of forest resources was equal to the present-valued sum of a very long stream of net revenues, i.e., economic profits, from forestry discounted at the bank rate of interest, r. The asset may be sold at any time τ prior to T, and its sale price would be

$$K_\tau = \int_\tau^T (p(t)H(t) - c(t)H(t))e^{-rt}\mathrm{d}t \tag{8}$$

This insight linked natural resource markets to financial markets and proved fruitful in inspiring subsequent theories of efficient extraction or harvest rates, raw materials prices, and the value of natural resource assets. At this point, two implications of the market context in which mining takes place are emphasized: user costs and economic rents, i.e., pure profit, are equivalent; and r, which was the prisoner's rate of time preference in the cake eating problem, is now the bank rate of interest.

Faustmann's insight seems to have influenced the work of Gray [4] and Hotelling [5] on the asset value of a mine. Neither cite Faustmann directly but both cite Alfred Marshall, who cited Faustmann liberally. Gray (1914) suggested that the value of a mine is "nothing more than the present value of the surplus income from the mine during a period of time, that is, the present value of the total rent which it will yield . . . .". Hotelling, applying the calculus of variations, developed theories of efficient extraction of exhaustible resources, focusing on resource rents, argued that markets for exhaustibles had stabilizing properties, and deduced the proposition that raw materials prices would rise sharply as reserves diminished, thus providing incentives for exploration, recycling, and substitution [5]. Nevertheless, there are limits to the relief that recycling, discoveries of new reserves, etc., can bring: they can ease the pain of increasing scarcity, but if demand is Malthusian, i.e., ever-growing, they can only postpone the inevitable.

Where R is the quantity of raw materials produced from recycled scrap,

$$S_\tau = S_0 - \int_0^\tau (H(t) - R(t)) \mathrm{d}t \tag{9}$$

$R(t)$ is limited by available scrap, so a user cost, $MUCS(t)$, emerges for scrap materials. Markets in newly mined and recycled materials are equilibrated when

$$MEC(t) + MUC(t) = MCR(t) + MUCS(t) \tag{10}$$

Where $D(t)$ is the quantity of mineral stock newly discovered via exploration,

$$S_\tau = S_0 - \int_0^\tau (H(t) - D(t)) \mathrm{d}t \tag{11}$$

Because the most fruitful locations for exploration tend to be near places where large discoveries have already been made, exploration yields potential discoveries and information useful in further exploration. With exploration in the mix,

$$MUC(t) = MHC(t) + IV(t) \tag{12}$$

where $MHC(t)$ is the marginal user cost of extraction, and $IV(t)$ is the information value of exploration.

To this point, the discussion of scarcity has had a decidedly Malthusian tone: we might run out of stuff. However, David Ricardo and JH von Thunen thought of scarcity in terms of heterogeneous quality. To Ricardo, scarcity of corn would lead to cultivation of less fertile land, which would raise the value of more fertile land; the least fertile land would be abandoned. To Thunen, increasing distance from the market made land less valuable because transportation was costly. So, more-perishable products would be grown nearer to the market, land values would fall with distance, and at the periphery land would be zero-valued and abandoned. Taken together, quality and distance are attributes of farmland and forests, and of mineral stocks, and differences in these attributes affect the location of production and the relative value of productive assets. If mineral stocks are non-homogeneous and the most profitable (higher quality, lower extraction and/or transportation costs) are taken first, there is a stock effect (*SE*) of extraction. Compare Equations (3) and (13)

$$\frac{\mathrm{d}MUC(t)/\mathrm{d}t + SE(t)}{MUC(t)} = r \tag{13}$$

Ricardian scarcity can be alleviated by bringing less attractive land and mineral deposits into production, but at the cost of higher product prices and higher premiums for better land and richer deposits.

3.1.4. Observable Indicators of Scarcity

With all of this as background, consider what markets might tell us about impending scarcity of exhaustible resources. Intuition suggests that raw materials prices would rise at any hint of future scarcity, and that would be to the good because it would encourage investment in exploration, recycling, and efforts to develop substitutes. Theory suggests that resource rents should rise at the rate r in order to leave owners willing to hold reserves [5]. Sharply rising rents should serve as indicators of increasing scarcity and incentives for substitution of less scarce resources and technological developments to reduce the costs of substitution. However, observed prices for raw materials and inferred rents for exhaustibles seem to bounce around without any sustained increase over long periods. Raw materials prices are observable, and conceivably may fall even while rents are rising if extraction and refining costs are falling (Equation (6)). Rents typically are unobservable and observable proxies are not quite satisfactory. Furthermore, recycling, exploration, and non-homogeneous deposits generate their own kinds of rents (Equations (10), (12) and (13))

that complicate inference about MUC(*t*). All of this makes it difficult to conclude much about the time path of scarcity from observation of raw materials prices and inference about the time path of rents [6].

Does Hotelling's rule (Equation (3)) suggest instability in markets in raw materials and assets in exhaustibles? For example, a downward price shock might encourage increased extraction if the resource owner expects prices to continue falling. The counter-argument is that asset markets adjust quickly to changes in price expectations: the asset value will quickly settle downward, adjusting to the level of rent, and from that point onward rents can grow at the rate *r*.

To answer the coal question, the coal has not run out. Substitutes—especially oil and natural gas, but more recently renewable energy has become a growing part of the mix—have reduced the demand for coal, as have environmental concerns. From the current vantage point, it seems feasible, perhaps even likely, that use of coal eventually will decline toward zero as will the asset value of the remaining coal reserves.

3.2. What Will We Do When the Whale Oil Runs Out?

Whale oil was a preferred fuel for lamps throughout the 19th century, and concern arose that excessive harvest would decimate the whale population and literally plunge the modernizing world into darkness [7–9].

In the 19th century, the industrial revolution, now well established, had shifted the focus toward exhaustible resources. However, concerns about potential scarcity of renewable resources did not disappear. Along with increasing understanding that renewables, too, could be depleted by excessive harvest, the heightened awareness of potential scarcity extended to renewables. Here I briefly examine the economics of renewable resources, with a focus on forests and fisheries.

3.2.1. The Contribution of Faustmann

Faustmann in 1849, seemingly far ahead of his time, offered a solution to the problem of valuing the economic loss attributable to the irreversible destruction of a forest by some event that rendered worthless the trees and the land on which they stood [1]. In the absence of the damaging event, the trees would eventually have been harvested. So, the net value of the damaged trees has been lost, but that is not all. Assuming that forestry is its highest use, the land would have been re-planted with trees. A very long sequence of forests could have been produced on that land in the absence of the damaging event. So, the total economic loss is the net value of the damaged trees plus the net value of the damaged land. The value of the land reflects its potential productivity, so its net value as an asset is the net value of a very long sequence of forests that would have been grown there in the absence of the damage. Faustmann's first contribution was the importance of including the lost value of the land in the claim for compensation. His second contribution was to observe that, at any time in this long sequence of potential forests, the owner would have the option of selling the land along with its forest cover and investing the proceeds at the going rate of bank interest. Thus, these net values need to be discounted at the rate *r*, in order to reduce the long sequence of losses to its net present value which he called the "land expectation value".

Faustmann had linked forests to financial markets by the simple observation that fungible assets such as forest land should yield enough economic rents to make their owners indifferent between keeping the land or liquidating it to invest in financial assets. His writings make it clear that he had some thoughts that he did not develop fully, about the value-maximizing age of trees at harvest and length of the forest rotation (length of time from one planting to the next).

There are murmurs in the literature to the effect that Faustmann was not the first to posit a formal link between land/resource markets and financial markets [10]. Furthermore, while Faustmann had an intuition re optimal time of harvest and length of rotation, it was left to subsequent authors to work-out the details. So, it seems that Faustmann's

reputation might have been inflated at both ends of his life: there were precursors who suggested how resource values might be linked to capital markets, and subsequent authors who established important details and tied together the propositions now labeled "the Faustmann formula".

The Faustmann formula generates the theorem: The optimal time to cut the forest is when the time rate of change of its value is equal to interest on the value of the forest plus the interest on the value of the land it occupies. The optimal time to harvest a stand of trees, ignoring any value that might be associated with the land itself (which, as has been observed, is usually not a good idea), is when the growth rate of stumpage value is equal to the rate of interest multiplied by the stumpage value. This is shorter than the time to maximum yield, because growth is still positive at the indicated optimal harvest time whereas it is zero at maximum yield. Consideration of the value of the land occupied by the trees further shortens the time to harvest. Length of rotation is influenced by the tree growth foregone by harvesting and the foregone value of having younger, faster-growing trees on the land it occupies. More fully elaborated models explicitly address optimal forest rotations. Economists recognized that maximizing resource rents required an optimal sustainable harvest less than the maximum, and hence a shorter optimal rotation [11–13].

3.2.2. Harvest of Renewable Resources

For renewables, the maximum sustainable harvest recognizes the role of regeneration and growth. The simplest models look a lot like minerals models with growth and recruitment substituted for recycling and discovery. However, biology plays a larger role in forest and fisheries models, and human interventions mediate the outcomes produced by living systems.

Trees grow in roughly sigmoid fashion, and the timing of harvest, controlled by humans, impacts the rate of growth. So, the stock of trees at time τ is

$$S_\tau = S_0 - \int_0^\tau (H(t) - G(t)) \mathrm{d}t \tag{14}$$

where *G*: growth. Trees should be harvested when

$$\mathrm{d}MUC(t)/\mathrm{d}t = rMUC(t) + MUCL(t) \tag{15}$$

where *MUCL*(*t*) is the *MUC* of the land on which they stand; that is, land value matters, too, as Faustmann insisted. The optimal time to harvest is less than the time to maximize yield and is yet even less when the opportunity cost of the land is considered. Generalized Faustmann formulae include adjustments for type and quality of trees, mixed-age stands, distance to markets, etc. Chang shows how the many conceivable wrinkles in forest management can be addressed with generalized Faustmann models [11,12].

Management of fisheries requires attention to regeneration and resource rents, along the lines of the forest rotation problem [14]. The principles for optimal rotation in a fish farm are essentially identical to those for a plantation forest. Not surprisingly, the optimal sustainable yield for a fishery, as for a forest, is less than the maximum.

Open access fisheries introduce nonexclusiveness of the fish stock, and open entry of fishers may lead to depletion of the resource [15]. Recruitment to fisheries depends on the rate of harvest, which itself depends on the stock of fishmass and the amount of fishing effort. Management of open access fisheries involves rationing of fishing effort, which may be done more efficiently, e.g., by limiting commercial fishing permits, or less efficiently, e.g., by shortening the commercial fishing season. Managing and regulating the harvest is complicated by fishing nets and trawling techniques that fail to distinguish target species and marketable sizes of fish, with the consequence that so-called bycatch is mostly wasted but nevertheless depletes the fishery ecosystem. Effort, *E*(*t*), itself is also a difficult concept

since it may involve the number of fishers, the number of vessels, the size of vessels, and the technologies in use. The stock of fishmass at time τ is

$$S_\tau = S_0 - \int_0^\tau (H(t) - G(t)) \mathrm{d}t \tag{16}$$

but $G(t) = f(S(t))$ and $H(t) = f(S(t), E(t))$, i.e., there is a stock effect on catch per unit effort. These relationships require adjustments to the marginal condition relating user cost and fishing productivity to r.

$$\mathrm{d}MUC(t)/\mathrm{d}t + MEC(t)\,\frac{\partial H(t)}{\partial S(t)} = (\mathrm{r} - \frac{\partial G(t)}{dS(t)})MUC(t) \tag{17}$$

Hardin [16] brought the "tragedy" of open access to the attention of a broader audience, and regulation of non-exclusive fisheries to ration access became the norm. Marketable permits for commercial fishing became a much-recommended way to limit fishing effort and compensate fishers exiting the industry [17]. Ostrom discerned that market solutions are not always compatible with community values and insisted that community-based resource management can achieve results approaching optimality in societies not so hospitable to privatization [18]. Her interests were more attuned to irrigation issues, but it is easy to see how her analysis might apply to fishing communities if not, perhaps, to the fishing sector characterized by deep-sea mega-vessels. Efficient management of fishing effort is especially difficult in ocean fisheries, where offshore jurisdiction may be contested and international authorities have relatively little power to regulate fishing effort in international waters, concerns that are exacerbated by the introduction of huge fishing vessels with on-board processing facilities that can stay out on the water for a long time.

All of the above problem formulations and conclusions are essentially static: long-term considerations are addressed, e.g., by intertemporal efficiency criteria and net present value calculations, but the sorts of feedbacks considered in system dynamics are absent. Fisheries dynamics emerged as a research area by the 1960s [19,20] and still thrives today. Examples of recent applications include a model that shows what happens when effort responds to open access incentives and when regulators respond to increasing effort by mitigating its potential harmful effects on biomass safety [21]; modification of the Beverton–Holt formulation [19] to allow study of populations experiencing a seasonally fluctuating environment, compared to a carrying capacity assumed constant year-round [22]; and a model that shows how investments in substitutability by augmenting the stock of knowledge affect the value of natural capital [23].

To answer the whale oil question, in the late 19th century petroleum-based distillates and, a little later, electricity provided superior fuels for lighting. The value of whale oil for lighting diminished [7–9]. These days, preservation of whales is motivated mostly by concerns about biodiversity and ecosystem integrity, while the relatively small whale harvest that continues is justified mostly by claims of cultural significance.

3.2.3. The Diminishing Distinction between Resource Management and Environmental Policy

Pollution of air and water had long been analyzed as a market failure [24], a problem attributable to inadequate property rights [25] and to incomplete specification of liability under civil law [26], and various solutions were offered based on these diagnoses. These analyses are all static in nature. The notion of waste assimilation capacity as a renewable resource gained currency around 1970, in the sophisticated technical literature [27] and in books written for a broad audience [28]. The waste assimilation capacity of the environment could be modeled dynamically and managed much as one would a fishery, i.e., a dynamic system subject to market failures [27].

3.3. How Do We Manage a World with Exhaustible and Renewable Resources?

In response to concerns that exuberant economic growth in the early post-war era might trigger serious scarcity of resources, the Scarcity and Growth literature [29,30] framed

scarcity as Ricardian, i.e., relative, whereas the Limits to Growth literature beginning with Meadows et al. saw things in terms of Malthusian absolute scarcity [28].

3.3.1. Ricardian Scarcity and the "Folk Theorem"

From its beginnings, economics has predicted that increasing scarcity would lead to higher prices of whatever is becoming scarcer. In our context, impending scarcity would be signaled by increasing prices of raw materials. In the Faustmann–Gray–Hotelling tradition of linking resource markets to financial markets, the maintained Ricardian hypothesis was that increasing resource rents would provide warning of impending scarcity. However, raw materials prices have fluctuated but the trend has not been increasing. Empirical calculations to infer rents, which were not directly observable, led to findings that seemed counterintuitive at the time: there was little evidence of increasing scarcity of exhaustible resources, but the evidence re renewables was mixed [28,29].

All of the above assumes individual owners operating at a modest scale in much larger financial markets such that, from the owners' perspective, interest rates for saving and investment can be taken as given. In contrast, weak sustainability (WS) was conceived for whole societies, implicitly the world, and encounters various difficulties when applied at national, regional, and local levels [31]. WS is essentially an economists' formulation with roots in Ricardian scarcity [31–36]. It was motivated by the claim that reasonable expectations about the evolution of technology and the substitutability of different kinds of capital suggest a goal of sustaining human welfare rather than particular resources. The WS narrative relies on discovery, but it is a different kind of discovery: not so much of new deposits of scarce resources, but of new technologies that use plentiful resources to satisfy human demands so that society could enjoy non-diminishing welfare, $w(t)$, even as familiar resources become scarce. Roots of the WS reliance on endogenous price adjustments and incentives lie in the works of the three seminal authors [1,4,5]

There is a "folk theorem"—it is labeled that way because it makes sense to many people even though the search for a rigorous proof has been frustrating—that suggests that depleting exhaustibles is acceptable as long as renewables can be substituted and sustained [37]. The prescription that emerges is, in metaphorical terms: extract exhaustible resources, plant trees; cut a tree, plant a tree.

3.3.2. Weak and Strong Sustainability

At the macro (e.g., global) level, r is endogenous and determined by the global supply of savings and demand for investment. However, WS insists on intergenerational equity, i.e., time preference = 0, which permits positive discount rates but only to the extent that the present generation is compensated for the expected growth that would make future generations better off [38]. Among other things, WS is a conscious appeal at the level of society for human restraint re time preference. It follows that WS seems inconsistent with financial markets to the extent that they reveal positive time preference. I am not entirely convinced of the inconsistency: a person seeking to maintain a certain level of wellbeing throughout her life, i.e., does not prefer consumption this year rather than next, will nevertheless require an incentive to deviate at the margin from the desired consumption path. That is, markets may reflect marginal time preference whereas the WS insistence on zero time preference operates at generational and intergenerational levels.

Weak sustainability summarizes multiple kinds of capital—natural, financial, built, human, social, and organizational/governance—in the concept of inclusive wealth (IW) which, if sustained, is sufficient for sustaining human welfare. Arrow et al. [39] summarize the current wisdom re IW, its components, and the substitutability of various kinds of capital.

Perceived threats of over-exploitation and extinction led to strong sustainability (SS) formulations [34,35,40] that require preservation of sustainable stocks of particular resources. While SS can be derived as a corner solution to a utilitarian problem, there also are many non-utilitarian justifications for SS [41]. It is important to recognize the influence

of ecologists and environmental ethicists, especially the latter who, initially at least, were provoked more readily by extinction threats than by pollution, for example.

3.3.3. Ricardian vs. Malthusian Scarcity

The Ricardian relative scarcity view in the Scarcity and Growth literature and the Malthusian absolute scarcity view in the Limits to Growth literature differ in important ways [42]. The Malthusians worry about absolute scarcity, which they are inclined to think is preordained by the laws of thermodynamics. Their main complaint about the Ricardians is that they are asking society to bet the future on some rather implausibly optimistic assumptions. The Ricardians complain that Malthusians have failed to credit the human capacity for adaptations that may well continue to save us.

Regarding empirical evidence, the Limits to Growth literature concluded, mostly on the basis of projections from dynamic models, that the world is on an unsustainable path and will encounter increasingly serious disasters unless global self-restraint intervenes. The Scarcity and Growth literature was mostly reassuring about WS prospects—on the whole, resource substitution and technical innovation are still working, but the predictive power of WS formulations is limited [39]—but not complacent. Interestingly, both literatures have produced updates from time to time, and have concluded that their earlier conclusions are still looking rather good. Ricardian updates show that resource substitution and technical innovation seem to be working; and Malthusian updated projections suggest big trouble lies just over the horizon [43]. The message of Sections 3.1 and 3.2 is that the indicators of impending scarcity, raw materials prices, and resource rents, send signals that are muffled and distorted at best, making empirically informed judgments about future prospects difficult and inconclusive [6].

3.4. The Shape of the Problem Begins to Shift

In all of the above, the threat was perceived as human greed and impatience, i.e., positive time preference—the slow but inevitable grind of over-exploitation of resources. By the mid-20th century, the perception of risk as the threat began to take hold. However, of course, greed did not go away: even with the primary focus on risk, greed motivates the pursuit of private profits while socializing the risks. Risk and greed are complements in magnifying the threat.

Ciriacy-Wantrup identified the observed variability of the stock of renewable resources as a problem [44]. Due to variation in natural conditions and perhaps human activity, low-stock periods may occur, apparently at random, and exploitation levels that were sustainable in ordinary seasons might extinguish a resource. He conceptualized this threat in the ordinary risk management framework, i.e., based on the logic of games of chance [45], but he recommended an abrupt intervention to remedy the situation: set a trigger point—a lower bound on the resource stock (the safe minimum standard (SMS) of conservation)— and suspending all harvest until the resource had recovered. That is, invoking the SMS was, and was intended to be, a sharp break from ordinary risk management.

3.5. What Should We Do When the Risks Are Really Scary?
3.5.1. Emergence of the Concept of Extraordinary Risks

Around 1970, ecologists—perhaps emboldened by developments in mathematics such as chaos theory—began articulating serious concerns about the vulnerability of natural systems to unexpected regime shifts, tipping points, sudden collapse, flip-flops, etc. [46,47]. One way to think about all this is that the sigmoid growth curve remains plausible for individual members of a species, ecosystem, etc., but population dynamics require very different specifications. Ecosystem modeling and modeling of coupled human and natural systems enjoyed a burst of growth that still continues. Developing a better understanding of regime shifts in complex systems has been a priority for dynamic systems modelers [48]. An ongoing active search for observable indicators, often statistical in nature, of prospective regime change [49] is bolstered by the intuition that a system approaching regime change

is likely to be unstable in some, perhaps observable, dimensions. Applications to human societies and coupled human and natural systems are proliferating [50].

How does the complex systems literature fit into a contest of ideas between Ricardians and Malthusians? Ricardians—whose models suggest that even impending scarcity proceeds fairly smoothly and with plenty of warning in the form of rising prices and/or rents—get little support from models that permit sudden collapse and expensive but incomplete recovery.

The sudden regime change possibility in complex systems is not exactly Malthusian—Malthus envisioned a long hard grind of persistent and increasing poverty—but doom has a Malthusian ring even when it is uncertain doom.

3.5.2. Management of Extraordinary Risks

The threat now is framed around risk, viewed broadly as chance of harm. Human greed and foolishness are still with us, but uncertainty in all of its dimensions is prominent. Again, these are complements in amplifying the threat. The chance of harm formulation of risk pushes well beyond stochasticity into uncertainty, ambiguity, and unknown unknowns, and is open to (perhaps literally requires) new risk management approaches. The conversation now revolves around resilience of systems, risk of collapse, the chance of partial or complete recovery, and the virtues and shortcomings of prioritizing safety [31,51]. Resilience is the ability of a system to maintain or recover its form and functioning following a shock or disturbance, and increasing resilience may reduce the risk of collapse and/or enhance the prospects of recovery. The domain of strong sustainability [32,34,35,40] has grown as this new understanding of the threats has taken hold, and the meaning of SS has evolved in the direction of safety. Whereas the earlier concept of SS focused on maintaining the flow of resource services [34], the newer safety formulation of SS is more concerned with minimizing the risk of irreversible collapse of the resource. There is now more recognition that safety may be motivated by concern for the resource per se and/or human dependence on the harvest generated by the resource, in kind or as a revenue stream [31,51]. Frameworks for responding to these newly recognized threats include the following, each of which is defined and discussed briefly. New formulations in the spirit of SS have emerged.

The Precautionary Principle (**PP**) [45,52,53] can be stated as: If there is evidence stronger than **E** that an activity raises a threat more serious than **T**, a remedy more potent than **R** should be invoked [45]. That is, precautionary remedies should be invoked when there is credible evidence that an activity introduces a threat of disproportionate and asymmetric harm. The opportunity cost of precaution—which may deny society the benefits of current technologies and prospective innovations—is recognized but should be accepted in the face of a credible threat of extraordinary harm. Some of these threats may be posed by innovations adopted in the spirit of WS, but with inadequate pre-release testing.

Planetary Boundaries (**PBs**) **1**. The Rockstrom et al. [54] PBs can be understood as an attempt to generalize the domain of SS. The PBs agenda seeks to elevate the influence of science-based information and use it to set bright-line boundaries on the anthropogenic impacts that the planet can tolerate. In some cases, this asks more of science than it can deliver, leaving a lot of scope for human judgment. Debate about human and social values is sidelined by asserting that transgressing the boundaries threatens planetary doom, an unacceptable outcome under any plausible system of values. Inside the boundaries is safe operating space (SOS) for human activities. Interestingly, given the 19th and 20th century background of framing scarcity as mostly a consequence of depleting the stocks of exhaustible resources, the PBs fall mostly into the category of renewable resources, including traditional renewables (e.g., freshwater), more recently recognized renewables (e.g., ecosystem integrity), and waste assimilation capacity (e.g., for atmospheric carbon and greenhouse gases). The SOS within the PB is viewed as a resource to be managed for human benefit [55] according to market signals or perhaps WS criteria. Strong sustainability

is reflected in the safety constraint, SOS $\geq$ 0, rather than in requirements that resource services be maintained at baseline levels.

Planetary Boundaries 2. Steffen et al. [56] offered a more nuanced formulation of the PBs idea. The boundaries are now fuzzy, there is an amber zone of uncertainty between the safe (green) and catastrophic (red) zones, and the possibility of tipping points, regime shifts, etc., is located somewhere as the green zone shades into amber. This reformulation is more plausible than the original but can be viewed as a partial retreat toward what had become the standard mental model of environmental risk: a zone of ordinary risk to be managed with instruments modeled on well-specified games of chance, a zone of increasing uncertainty, ambiguity, and unknowns that induce increasing risk aversion, and a zone where precautionary approaches make sense.

A group of distinguished sustainability scholars [57] has endorsed a policy framework that respects the PBs while accommodating human endeavors within the SOS. A team of modelers has calculated that the world's people could in fact live, and live well, within the global SOS, but that would require very substantial restructuring of global society, economy, and governance [58].

The opportunity costs of safety criteria are such that it is hard to imagine a viable sustainability policy that requires some form of SS for all resources. Even as the discussion has turned toward the PP and PBs, the efforts at IW accounting on a global scale have continued [59]. While IW is all about sustaining $w(t)$, a parallel discussion aimed at defining and measuring wellbeing—an inherently broader concept that includes equity, physical and emotional health and, in some renditions, social cohesion—has gained steam [60,61]. These developments have more in common with WS and the Ricardian view of scarcity than with SS. Returning to the standard notion of WS, nagging concerns remain that, with even the most optimistic plausible assumptions about substitutability, certain resources truly are critical. Therefore, a sustainability criterion with pragmatic appeal to policy makers and practitioners would treat WS as the default but impose SS constraints on resources deemed critical. The list of critical resources would itself be subject to revision in light of emerging evidence so, as time passes, particular SS constraints may be introduced while others are relaxed.

WS-plus [31,32] is a hybrid sustainability strategy with justifications that perhaps are more pragmatic than principled. The intergenerational bequest should maintain non-diminishing IW, as always, while including adequate stocks of a few truly critical natural resources. This approach is broadly consistent with the preference-based foundations of WS, and the Brundtland Commission's observation: "At a minimum, sustainable development must not endanger the natural systems that support life on earth" [62], (p. 42).

3.6. The Sustainability Toolkit Has Expanded, a Good Thing in the Long Run, but Not All of the Candidates Will Be Survivors

Now, we see attempts at synthesis in theory and in emerging instruments for policy and management. The market failure approaches—regulatory targets, pollution taxes, and/or trading in pollution reduction credits—are alive and well but coexisting with and informed by the assimilative capacity formulation and its foundations in the resource scarcity literature. Two of the developments noted above, the move to dynamic models and the problem shift from greed to risk, and their convergence in the dynamics of complex systems [63] have served to complicate assessment of sustainability. Tracking the demand for raw materials and the reserves of exhaustible minerals might have seemed a demanding task, requiring attention to potential substitutes, emerging technologies, final demand, discovery, and recycling. However, assessing the sustainability of coupled human and natural systems seems more difficult by more than an order of magnitude.

Policy and management require monitoring of extraction or pollution as the case may be, ambient conditions, and impacts on human and natural systems, and setting of targets and trigger points for preventative and remedial interventions of various kinds. Practical policy to promote sustainability requires science-based information that maps changes in resource stocks to ambient conditions and the wellbeing of human and natural systems,

and information on the values and aspirations of the people served by policy. Sustainability indicators, especially, have proliferated to the point where we have perhaps too much data and too little notion of how best to use it in sustainability assessment [64]. Lists of indicators may include several hundred, especially if a broad sustainable development agenda is pursued [65,66]. The USEPA's list is narrower, focusing on sustainability per se, but still numbers more than 80 [67,68]. Already, there is a literature reviewing and assessing the indicators that have been proposed [69,70]. My suggestions for winnowing the indicators to identify the most useful include favoring (i) indicators addressed to sustainability per se rather than the broader-based concept of sustainable development, (ii) ratio-scaled indicators that measure extraction (or emissions), ambient conditions, and consequences for human and natural systems, and (iii) indicators useful in mapping the key science-based relationships [64].

There is now a modest growth industry in downscaled PBs, DPBs [71–73], which have been proposed as ways of distributing responsibility for the planet down to regional and local levels where citizens might more readily become engaged: "Think globally, act locally." As with sustainability indicators, a literature assessing DPBs is emerging [64,74]. The choice of denominator for downscaling provides opportunity to reflect a variety of human values—e.g., egalitarianism, efficiency, or responsibility—in the downscaling process. Recently, I have argued [64] that DPBs are most useful in addressing global public goods (greenhouse gases, atmospheric aerosols, and ocean acidification), and make relatively little sense for resources that often are best managed at the problem shed level (e.g., freshwater and urban greenspace).

4. Conclusions

The industrial revolution was unleashed by the development of underground mining and extraction methods for fuel (first coal and then oil and natural gas) and raw materials, e.g., iron ore. It is no surprise that concern about potential scarcity during this period was led by worries about exhaustible resources. However, fear that renewable resources might be depleted, perhaps irreversibly, predated the industrial revolution and is now, once again, at the forefront of concerns about sustainability. Along the way, there have been shifts in focus, problem definitions, theory, and methods, with new and amended implications for policy and analysis.

During the industrial era, concerns about potential resource scarcity were motivated mostly by fear of the consequences of human greed and impatience. Economic theories of exhaustible and renewable resources cross-fertilized in both directions and in both cases linkages to financial and capital markets were developed. Gray [4] and Hotelling [5], writing about exhaustibles, harked back to Faustmann by way of Alfred Marshall. Theories of extraction decisions incorporated the opportunity cost of investment in mineral stocks, trees, and land, i.e., the foregone earnings from holding wealth in the bank. Concepts of sustainability were addressed to depletion of exhaustible resources—weak sustainability posits that humans can maintain welfare while stocks of exhaustibles are dwindling, so long as they develop new technologies that substitute more plentiful resources [36]—and concerns that market failures may permit depletion of forests and fisheries.

More recently, there has been productive cross-fertilization of environmental economics and the economics of natural resources: market failure concepts applied initially to pollution have proven useful in fisheries research and policy, while the concept of waste assimilation capacity, a renewable resource, is now fundamental to environmental policy concerning, e.g., atmospheric carbon and greenhouse gases.

The big problem shift began in the mid-20th century, when Ciriacy-Wantrup [44] expressed concern that variability in stocks of renewable resources may lead to depletion, perhaps irreversible, in bad years. Focus on renewables brings dynamics to center stage and, by the 1970s, complex systems models of biological populations alerted us to the possibility of boom and bust, flip-flops, and sudden regime shifts not easily reversed [46,47]. Relatively quickly, models of coupled human and natural systems highlighted the feed-

backs that might undermine attempts to manage the risks that complex systems modeling had exposed. Risk was now the big threat to sustainability—greed remained a concern, and can exacerbate risk when market failures expose the public to risks undertaken for private gain—and risk took newly recognized forms, uncertainty, ambiguity, and unknown unknowns, in addition to its classical stochastic form. The old sustainability problems (depletion and scarcity, exploration and discovery, recycling, new technologies, substitution) still matter. However, a new set of problems (complexity, coupled human and natural systems, gross uncertainty, and resilience in the face of unanticipated shocks) have taken center stage, and have shone a brighter spotlight on newer SS formulations, such as the PP and PBs, that emphasize safety and reflect a Malthusian, or maybe post-Malthusian, ethos.

Nevertheless, familiar Ricardian constructs, e.g., WS and IW accounting, have remained on the agenda because the opportunity costs of SS are substantial enough to discourage its widespread application. Newer Ricardian concepts such as wellbeing and sustainable development have earned strong international followings, perhaps on their merits, but also because Malthusian constructs applied globally leave little scope for low- and middle-income countries to fulfill their own aspirations for improving their wellbeing [75].

The three questions I have posed can be answered as follows. Fears that scarcity of coal and whale oil would lead to impoverishment were resolved much as Ricardian scarcity and weak sustainability would predict: superior substitutes replaced these resources in many uses, and human society continued to prosper. The question about how we should deal with extraordinary risks is still a work in progress. The paradigm shift in thinking about sustainability has tended to raise the profile of strong sustainability, i.e., sustaining particular resources rather than, or in addition to, human welfare and inclusive wealth. New formulations in the SS tradition tend to emphasize safety and include the precautionary principle and the concept of planetary boundaries, briefly introduced above. Because safety has its opportunity costs [31], and these may be large, weak sustainability remains the most plausible default sustainability objective. However, adherents of WS are becoming willing to take WS-plus—maintain inclusive wealth but insist that it include adequate stocks of particular resources deemed critical—more seriously [31,32], and supporters of the SDGs are prominent, especially in the international discourse.

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