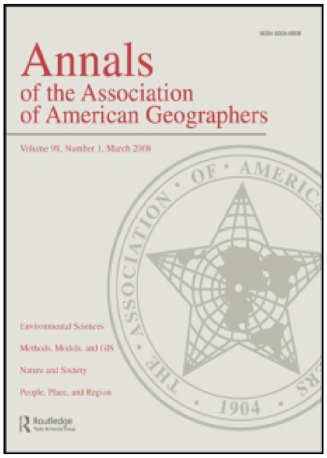

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The Genesis, History, and Limits of Carrying Capacity

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The Genesis, History, and Limits of Carrying Capacity

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The concept of carrying capacity is employed in a remarkably wide range of disciplines and debates, and it has been forcefully critiqued within numerous fields. Yet its historical origins remain obscure. I identify four major types of uses of carrying capacity: (1) as a mechanical or engineered attribute of manufactured objects or systems, beginning around 1840 in the context of international shipping; (2) as an attribute of living organisms and natural systems, beginning in the 1870s and most fully developed in range and game management early in the twentieth century; (3) as K, the intrinsic limit of population increase in organisms, used by population biologists since the mid-twentieth century; and (4) as the number of humans the earth can support, employed by neo-Malthusians, also since midcentury. All four uses persist to the present, although the first has been largely supplanted by other terms such as payload. In all cases, carrying capacity has been conceived as *ideal*, *static*, and *numerical*—characteristics that were appropriate in the first case but increasingly untenable as the concept was extended to systems of larger scale, greater variability, and lesser human control. *Key Words: carrying capacity, game management, neo-Malthusianism, population biology, range management.*

运载能力之概念虽已被非常广泛的学科与辩论所采用，并也受到多方领域的强烈批判，但其历史渊源仍模糊不清。我提供运载能力的四种主要用途：(1)1840年左右开始在国际航运中作为制品物体或系统的机械或工程属性；(2)从1870年间至二十世纪初期当牧场与狩猎管理得到最充分的发展时作为活的生物体以及自然系统的属性，(3)被人口生物学家自二十世纪用来作为k,也就是有机体数量增长内在的限制；以及(4)在二十世纪中叶被新兴马尔萨斯学派用来形容地球能负荷的人类数目。在所有情况下，运载能力被视为理想的，静态的以及数控的。这些特点在开始时虽然适合，但当这个概念被扩展到规模较大，变异性更大以及较少人类控制的系统上时就会越来越站不住脚。*关键词：运载能力，狩猎管理，新兴马尔萨斯主义，群体生物学，牧场管理*。

El concepto de capacidad de carga se emplea en una variedad notablemente amplia de disciplinas y debates, y ha sido fuertemente criticada dentro de numerosos campos. Sin embargo, sus orígenes históricos permanecen oscuros. Yo identifico cuatro tipos de uso principales de capacidad de carga: (1) como atributo mecánico o de ingeniería de objetos o sistemas fabricados, que comenzó aproximadamente en 1840 en el contexto de envíos internacionales; (2) como atributo de los organismos vivos y de los sistemas naturales, a partir de la década de los 80 del siglo XIX y desarrollado más completamente en la gestión de extensiones de tierra y caza a principios del siglo XX; (3) como K, un límite intrínseco de aumento de la población de organismos, usado por biólogos de la población desde mediados del siglo XX; y (4) como el número de seres humanos que la Tierra puede soportar, empleado por los neomaltusianos, también desde mediados del siglo. En la actualidad persisten los cuatro usos, aunque el primero ha sido suplantado significativamente por otros términos tales como carga útil. En todos los casos, el concepto capacidad de carga se concibió para describir las características *ideales*, *estáticas* y *numéricas*, que era apropiado en el primer caso, pero que fue cada vez más insostenible conforme el concepto se extendió a sistemas de mayor escala, mayor variabilidad y menos control humano. *Palabras clave: capacidad de carga, administración de caza, neomaltusianismo, biología de poblaciones, gestión de baldíos.*

Carrying capacity may be the most versatile and widely popularized concept in environmental politics today. Like sustainability—which it predates and in many ways anticipates—carrying capacity can be applied to almost any human–environment interaction, at any scale, and it has the additional advantage of conveying a sense of calculability and precision—something that sustainability thus far lacks. Indeed, scientists of many kinds have calculated carrying capacities: in range and wildlife management,

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chemistry, medicine, economics, anthropology, engineering, and population biology, for example. In political debates, carrying capacity sometimes serves to help justify hunting, but more often it informs neo-Malthusian arguments regarding the finitude of the world's resources relative to growing human numbers (as a Web search will quickly demonstrate). In both contexts, its authority is buttressed by association with the work of prominent ecologists such as Aldo Leopold, Eugene Odum, Garrett Hardin, and Paul Ehrlich—the last two having explicitly declared that the world's carrying capacity for humans is being exceeded.

However, the origins of carrying capacity are not found in Malthus—he never used the term—nor even in debates about population (human or otherwise). It is true that in 1820 William Godwin published a calculation of the number of humans the world could support, in *Of Population*, his polemical response to Malthus. Godwin took contemporary China as demonstrating the maxima of possible cultivation and population density, which he then extrapolated to the earth's habitable area, arriving at a figure of 9 billion people. Clarence Glacken (1967, 652) states that Godwin's was one of the earliest attempts to specify such a number, and the estimate might now appear prescient. In context, however, Godwin was mocking Malthus, and he nowhere referred to his estimate as a carrying capacity. In fact, the term was not applied to questions of global human population until the 1940s, after a century of serving various other purposes.[1] Similarly, several ecologists attribute carrying capacity to Pierre-François Verhulst, a nineteenth-century Belgian mathematician (Odum 1971; Botkin 1990). But Verhulst (1838) did not employ the term (or any French equivalent), and his logistic equation was utterly forgotten until the 1920s; it was not used to define carrying capacity until midcentury (Hutchinson 1978; Kingsland 1985).

Where did carrying capacity come from? How was it originally conceived, and to what extent have its origins shaped its subsequent history? No one has answered these questions. The concept is used in an unusually wide range of fields, and it has been criticized in many of them, yet its origins remain remarkably obscure. Biologists and historians have examined its development and questioned its utility within wildlife management (Edwards and Fowle 1955; McShea, Underwood, and Rappole 1997; Young 1998); rangeland ecologists have challenged its assumptions in relation to livestock grazing (see later); sociologists, anthropologists, and demographers have forcefully critiqued its relevance to human populations (Brush 1975; Ellen 1982; MacKellar 1996; Livi-Bacci 2007); and ecologists have concluded that after fifty years of research there is little or no empirical support for the concept (Hutchinson 1978; Botkin 1990). However, none of these scholars has recognized that the origins of carrying capacity lie elsewhere, outside of their respective fields. Despite its flaws, carrying capacity seems to have an intuitive conceptual obviousness.

This article examines the genesis and history of carrying capacity to destabilize this obviousness, to understand its extraordinary persistence and rhetorical potency and, in so doing, to reveal its conceptual limits. One can classify the uses of carrying capacity into four major types since the term was coined in the first half of the nineteenth century. At its origins, it referred to a *fixed quantity* of *X* that some encompassing *Y should* carry in abstraction from time or history. Since then, it has sometimes described a maximum limit and more often an optimal or normative one, but it has always aspired to idealism, stasis, and numerical expression. Only in the first of the four types of uses were these attributes justified, however, and even then only imperfectly; subsequently, only the most astute of its proponents have recognized the contradictions that arose in extending carrying capacity to realms where no such relation between *X* and *Y* actually existed. Rather, each new use appropriated the basic idea and, in some measure, the authority of its predecessors, overlooking—and ultimately forgetting—their contexts and limits. In each case, decades passed before the weight of evidence caught up with the enthusiasm of carrying capacity's various advocates. This might be merely a matter of intellectual history—of the shifting metaphors and models through which modern people have conceived of nature–society interactions—except that carrying capacity has almost always been deployed by institutions of the state, and it has often resulted in grievous errors of policy, administration, resource management, and ethics.

A note on methods: Until recently, this research would have required the kind of exhaustive review of texts that produced the *Oxford English Dictionary* (which, incidentally, contains no entry for carrying capacity). In this case, I instead relied on digital technology. Numerous search engines were asked to find the term "carrying capacity," and the results were sorted chronologically; additional research was then conducted "manually" as necessary. This, of course, ran the risk that earlier uses were not discovered due to incomplete digitization; the relative shortage of digitized newspapers from before 1900 is a particular problem in this regard. However, several of the relevant journals and archives have been digitized much further back in time than the first uses of the term found by the searches; moreover, when the search term was modified to read "carrying AND capacity," many much older sources turned up (e.g., Francis Bacon) without encountering the composite term. It remains possible, even likely, that earlier uses of carrying capacity can be found, and I have not attempted to trace possible non-English language antecedents, except in the case of Verhulst. Nonetheless, I am reasonably confident that the chronology presented here is basically sound.

We Call It Payload

Carrying capacity originally referred to mechanical or engineered attributes of manufactured objects or systems. It arose first in the context of shipping, triggered by the advent of steam power. Since the fifteenth century, "tonnage" had referred to duties imposed on cargo by volume (a "tun" being a cask of wine); it was often paired with "poundage," a duty calculated by weight. Tonnage was not determined by measuring cargo, however. Rather, each ship was measured from the outside and its tonnage was estimated by a series of calculations. This figure became an attribute of the ship itself. Duties were imposed on the ship according to its tonnage, regardless of how much cargo it carried on any particular voyage. Over time, "tonnage and poundage" appears to have coalesced into the single term, tonnage, and to have gravitated in meaning from the duty to the vessels themselves. The *OED* includes this phrase from 1751: "Of more Tonnage or Capacity than a Man of War of 40 Guns."

The earliest use of the alliterative "carrying capacity" that I have found is from 1845, in a report by the U.S. Secretary of State to the Senate on "changes and modifications in the commercial systems of foreign nations." It included the text of an act passed by the Republic of Texas in February 1844 imposing "a tonnage duty of one dollar per ton." The Secretary reported that the previous duty—sixty cents per ton on sailing vessels, thirty cents on steamboats—had been imposed "according to register tonnage," whereas the new law would be applied to steamboats "according to their carrying capacity only" (Secretary of State 1845, 170). The distinction is hard to discern—"register tonnage" already subtracted certain noncargo spaces (crew's quarters and engine rooms) from a ship's volume.[2] Some light is shed on the matter by another report, from the President to the House of Representatives nine years later. Describing a dispute over duties imposed by Spanish authorities on English and U.S. cargo ships, the report stated:

> Being side-wheel boats, and using sails only as auxiliaries, they [the steamers *Black Warrior* and *Cahawba*] are obliged to steam during the whole passage. Moreover, as a large portion of their holds is taken up by the boilers and other necessary machinery, their carrying capacity is very small in proportion to their tonnage. The "Tamaulipas" is a propeller, built in England, with a view to carrying merchandise principally. She is a sailing-vessel, and only uses her propeller as an auxiliary when the winds are unfavorable. She measures very small, but her carrying capacity is very large in proportion. (U.S. House of Representatives 1854, 310)

The advent of steam ships necessitated a new means of reckoning duties, one that compensated for the much greater volume of the new technology compared to sailing vessels. It was prompted, in particular, by the large quantities of fuel and fresh water needed for steam propulsion, as these burdens were not deducted in calculations of register tonnage. Fairness—from the point of view of steamboat proponents, at least—required levying each ship according to the amount of cargo it could convey, rather than a measure derived from the ship's overall size—a measure that had never been perfect but nonetheless sufficed when all cargo ships were wind-powered. Carrying capacity captured this distinction.

Disputes over trade remained the dominant context for the use of carrying capacity until the 1880s.[3] In 1863, an article in the *Journal of the Statistical Society of London* defended the rapid growth of the British merchant fleet—"the increased size of British ships, the increasing economy of labour in their navigation, the greater rapidity in their movements, their increased carrying capacity, and especially the great development of steam tonnage"—and decried "the foreign tonnage increase" as "exorbitant; not based on trade demand, but on political expectations" (Glover 1863, 17). An 1875 discussion, published in the same journal, remarked on "the decrease in the carrying capacity of the sailing vessel and the increase in carrying capacity of the steamer" in the preceding five years (Jeula 1875, 85). How to measure and assess wind- versus steam-powered commerce was a preoccupation of British statisticians for years to come, in which carrying capacity served as a categorical alternative to tonnage (e.g., Glover 1882).

If carrying capacity distinguished the amount conveyed by a ship from the ship itself, it was logical to extend it to other means of conveyance, especially as railroads and other systems of transport and communication were developed during the late nineteenth century. Thorstein Veblen (1892, 87) noted that "an increase of the carrying capacity of the Erie canal" had contributed to lower grain prices in the quarter-century up to 1892. Eventually, the term shed its connection to the levying of duties—which still attaches to tonnage—and became simply a measure of how much *X* an inanimate *Y* could carry. Lord Dunraven (1879, 367) praised the "strength, lightness, gracefulness, sea-going qualities and carrying capacity" of Native American birch-bark canoes. An 1894 paper in *The Geographical Journal* described cedar canoes in Canada that had "a carrying capacity of about 1800 pounds," suggesting that the term was coming to be associated with weight, rather than volume (Tyrrell 1894, 439). Other units of measurement were also possible, depending on the topic under consideration. An 1881 paper in *Science* used persons per hour to describe the carrying capacity of the electric railroad in Paris (*Science* 1881, 526). The capacity of irrigation ditches and pipelines to carry water, of hot air balloons to carry weight, and of lightning rods and transmission lines to carry electricity were all measured and reported as carrying capacities in the last decade of the nineteenth century (*Harvard Law Review* 1892; *Science* 1891, 1897; Gast 1898). Any human-made system lent itself to such measurement, particularly as the scale and rate of movement eclipsed earlier notions of what was physically possible and threatened to exceed what a person could directly observe and (therefore) believe.

In all these cases, carrying capacity was a quantitative measure of a human-made object or system; it could be calculated and predicted with reasonable (if not perfect) precision. Most of these uses of the term persist to the present, especially among engineers, although they are relatively unfamiliar to biologists and social scientists. In common parlance, this meaning of carrying capacity has migrated to the term payload (itself derived from the amount for which one is paid to haul something). Just as one can carry more weight in a truck than its official payload prescribes, carrying capacity in this use is a fixed ideal, abstracted from the variable amounts that any particular ship, railroad, canal, or power line might actually carry at a given moment in time. It refers to the amount of *X* that *Y* was *designed* to carry.

Range and Game Management: Carrying Capacities of Living Organisms and Natural Systems

When carrying capacity was first applied to living organisms and natural systems, in the 1870s, it retained its literal sense of conveying or transporting some *X*, and *Y* was expanded to include animals and humans; subsequently, it was applied to such things as rivers and the wind. In a monograph published in the *Transactions of the American Philosophical Society*, Gabb (1873, 127) described the hunting practices of the natives of Santo Domingo: "Their custom is to bring into the mountains a supply of salt, and then stay, killing wild pork and beef and drying the meat so long as the salt lasts, or until they reach the full carrying capacity of their animals." Here, carrying capacity was a measure of how much meat the natives' pack animals could carry back from the mountains at the end of the season. Ten years later, the same application was made to "the *genus homo*":

> His carrying capacity was limited to what his two hands would hold. Vessels and receptacles of every kind were for the future to devise. . . . While, without some such expedient, man was limited in his carrying capacity to a pebble in each hand, he found that, by securing a slender thong to each, he could carry (or drag) quite a number in each hand. (Seely 1883, 84)

In the *Botanical Gazette* of 1887, the legs of certain bees were said to have a carrying capacity for the pollen of specific flowers (Robertson 1887, 214). *The American Naturalist* of 1896 referred to "the carrying capacity of the walls of the vessels" through which water moved in cucumber plants (E. F. Smith 1896, 451). Such uses persisted well into the twentieth century, and they are still common in some fields.[4] In relation to animals and humans, however, they now seem anachronistic or crude.[5]

About a decade later, the realm of possible *Y*s was extended further to include inanimate natural phenomena. An 1888 article in *Science* referred to the carrying capacity for floodwaters of the main channel of the Atchafalaya bayou in Louisiana (*Science* 1888), and a 1901 article in the *Botanical Gazette* referred to "the moisture-carrying capacity of the winds" in western Texas (Bray 1901, 113).

These extensions appear, in hindsight, to have ushered in the second major type of carrying capacity by a subtle but significant transposition. It occurred first in discussions of livestock, as in this 1886 discussion of "acclimatization in New Zealand":

> The most important mammalian introduction into these islands has certainly been that of the rabbit. . . . Brought into a country where only a few sluggish hawks existed as natural enemies, the rabbits have increased almost without let or hinderance [*sic*], and now occur in millions. Ten years ago they were almost rare; now many districts of the South Island are quite alive with them. . . . The surface of the ground is honeycombed, the vegetation in places eaten nearly as bare as a macadamized road, while the animals towards evening are met with by thousands. Their effect on the stock-carrying capacity of the country has been ruinous, and their abundance has seriously retarded settlement. (Thomson 1886, 428)

The meaning of "carrying" changed from a literal to a much more figurative sense. What was previously a *Y*—the animals that carried things—became instead the *X* being "carried" by the land where they lived. By 1889, carrying capacity had become a measure of rangeland productivity:

> Australian records show that land favored with less than ten inches of rain a year is quite valueless without irrigation. In such regions only one sheep per square mile can be carried for each inch of rainfall. For from nine to thirteen inches, however, the increase is about twenty sheep per square mile, and from thirteen to twenty inches of rainfall the increased carrying capacity is about seventy sheep per square mile. (*Science* 1889, 458)

Australia and New Zealand became object lessons in the new use of carrying capacity during a period of widespread and severe overgrazing in the American West. Queen Victoria's government had instituted a system of grazing leases on Australia's vast rangelands, with lease fees and taxes based on the number of livestock they could support; this was reported to have spurred settlement by small, "yeoman" producers and increased investment in land improvements. Of a similar system in New Zealand it was said: "The stock carrying capacity of the land and the wealth of the country was therefore by this process made seven or eight times what it was before," much to the relief of English bondholders (Stout 1886, 574; Duckworth 1886; Gurner et al. 1899).[6] These examples helped inspire land legislation in Texas and later in the U.S. West as a whole (Public Lands Commission 1905). Soon, this new sense of carrying capacity was sufficiently well established that the earliest U.S. range scientists, writing in the late 1890s, felt little need to explicate it.

The adoption of carrying capacity as the core concept of range management has been treated elsewhere (Sayre and Fernandez-Gimenez 2003); here, only a summary of key points is warranted. That such a thing as a fixed carrying capacity existed for any piece of rangeland was taken as given, although researchers in more arid areas soon complained that determining such a number was problematic. A distinction was drawn between "original" carrying capacity (before the widespread overgrazing of 1873–1893) and "actual" capacity; the former was taken as fixed, whereas the latter reflected current conditions and could be increased by investments in revegetation, artificial water sources, or emergency forage supplies (Bentley 1898; J. G. Smith 1899). Definitions of carrying capacity from the time strongly resemble today's "sustainability"—use that does not result in long-term impairment—and the expectation was that grazing at "actual" capacity would allow natural recovery toward "original" capacity. Even "actual" capacity was deemed to be basically stable, however, and it was institutionalized in leases to graze *X* number of livestock on *Y* acres of land; fences fixed to the ground and credit secured against herds rendered allotments and stocking rates largely immune to adjustment (Sayre 2002). Clementsian successional theory is said to have inspired this system (National Research Council 1994; Society for Range Management 1995), but historical support for the claim is weak. Clements (1920) explicitly rejected fixed carrying capacities, and his theory appears to have provided a post hoc scientific rationale for decisions shaped principally by economic and political considerations: Static, ideal, quantitative carrying capacities assigned to fenced and leased allotments facilitated bureaucratic administration for government agencies and gave bankers and ranchers a way to capitalize public lands.

Less well known is how this use of carrying capacity was transferred from livestock and grazing management to game management. A 1913 announcement in *Science* described the U.S. Forest Service's newly organized research program this way: "Under grazing, work is being done to collect basic information on the forage, to find methods of reseeding the more valuable kinds, both artificially and naturally, and ways of handling stock so as to increase the carrying capacity of the range, better the condition of the stock, and insure complete utilization of the forage" (Moore 1913, 802). The quixotic relation to natural productivity—carrying capacity was at once fixed by nature, yet capable of being increased by management—aptly reflects the Forest Service's dual mandate to protect and to utilize the nation's resources. During the 1920s and 1930s, early game managers applied this concept of carrying capacity to wildlife in hopes of understanding and increasing the number of deer, quail, and other game various places could produce.

The link is direct and specific: Aldo Leopold encountered carrying capacity in 1914–1915, when he worked in the Forest Service's Office of Grazing. "The discovery would reverberate through his work for the rest of his life," beginning with the infamous collapse of the deer population on the Kaibab plateau in the mid-1920s (Meine 1988, 136). The episode, which recurred later in Pennsylvania, Wisconsin, and elsewhere, helped provoked Leopold to take up—and in large measure establish—the field of game management.

After hunting and grazing were banned in the newly created Grand Canyon Game Preserve in 1905, and large predators such as wolves were systematically exterminated, the Kaibab deer population increased, then dropped abruptly. The extent and causes were disputed and difficult to explain, however.[7] In a vast, rugged, and nearly unpopulated area, the exact number of deaths was virtually impossible to determine. Accurate census techniques did not yet exist, and federal land managers ignored warnings about the problem for a decade—after all, this was a protected reserve, managed in large part for the deer.

Leopold's diagnosis of the Kaibab incident both relied on and challenged the concept of carrying capacity. Alongside Stoddard's pioneering research on the bobwhite quail, deer irruptions stood as one of Leopold's chief empirical examples in his landmark textbook, *Game Management* (Leopold 1933).The core question was the locus of the mechanism determining game populations: Was it inherent in the animals themselves, or was it a function of external factors such as climate, vegetation, or competition? Carrying capacity, for Leopold, denoted the latter explanation:

> When the maximum wild density of grown individuals attained by a species, even in the most favorable local environments, tends to be uniform over a wide area, that maximum may be called the saturation point of that species.
>
> This is a different thing from the maximum density which a particular but less perfect range is capable of supporting. While this latter is literally saturation for that particular range, it is obviously a variable limit as between several ranges, and to avoid confusion, may better be called carrying capacity. A true saturation point occurs when a large number of widely separated optimum ranges exhibit the same carrying capacity.
>
> It should be observed that while saturation point appears to be a property of a species, carrying capacity is a property of a unit of range.
>
> Every range has, of course, a limit of carrying capacity. Not all species, however, exhibit a saturation point. The existence of a saturation point is not yet definitely proved in any species, although I am personally satisfied that it exists in bobwhite. (Leopold 1933, 50–51)

Leopold documented different population dynamics in different species—some more stable, others highly variable—that suggested potentially different management strategies. "In hoofed animals there is so far no visible evidence of any density limit except the carrying capacity of the food" (Leopold 1933, 54). A saturation point—if such a thing existed—could serve as a goal, beyond which no further manipulations were worthwhile, rather like the "original capacity" of the range scientists. If saturation points did not exist, however, then understanding the factors determining carrying capacity was the key to effective management. These factors not only varied in space and time; they were themselves affected by game populations. It is here that carrying capacity became a concept useful to hunting advocates: "The obvious lesson is not to let a good herd irrupt. To prevent an irruption this herd must be kept trimmed down to a safe margin, and the carrying capacity of the range built up so there is a safe margin of capacity above population" (Leopold 1936, quoted in Meine 1988, 370). Leopold's textbook helped launch game management on a new course, in which managers would treat wildlife as a crop that could be increased (or decreased) by careful observation and manipulation of environmental factors:

> Every range is more or less out of balance, in that some particular aspect of food or cover is deficient, and thus prevents the range from supporting the population which *the other aspects would be capable of supporting*. Management consists in detecting that deficiency and building it up. This once done, some *other* aspect will be found to be out of balance, and in need of building up. Thus, one move at a time, each skillfully chosen, does the manager attack the job of enhancing productivity. (Leopold 1933, 135, emphasis in original)

Leopold's idea of carrying capacity informed generations of wildlife managers who worked to produce harvestable surpluses of game species on refuges and reserves. Manipulating habitats and populations to suit one another—by flooding, burning, or cropping; controlling predators (both natural and human); relocating wild animals or releasing captive-bred ones—became the standard approach of state and federal wildlife agencies throughout the United States, and it remains prevalent to this day. Carrying capacity thus became complicit in both the successes and the mistakes of twentieth-century wildlife management: stabilization or increase in the abundance and distribution of many species of fish and game were achieved, for example, but often at the expense of predators, native competitors, genetic diversity, and ecosystem functioning. The unintended consequences of past management efforts based on carrying capacity constitute some of the major challenges facing today's conservation biologists (Botkin 1990).

Leopold nearly achieved a complete reworking of carrying capacity from an ideal and static norm to an inductive and dynamic guide, but the underlying tension was not so easily resolved. In both range and wildlife management, carrying capacity begged the question it was intended to address—that is, how many animals a given habitat could support at a particular point in time. This was the practical issue confronting managers, and simply using the term implied that such a number could be determined. But what if the number varied over time (Edwards and Fowle 1955)? Working with wildlife instead of livestock, Leopold had more latitude to accept swings in animal populations, and the most vocal constituency he faced—hunters—supported culling in the event of overstocking. This might explain how he could arrive at an idea of carrying capacity that would take range scientists three or four more decades to recognize. But conceived in this way, as a potentially unpredictable function of a habitat interacting with a population, carrying capacity might be contingently determined and of only local or ephemeral significance.

Range scientists did not embrace Leopold's carrying capacity, and when they later came to similar conclusions they instead rejected the concept outright. For example, Paulsen and Ares (1961, 83) concluded that "Sustained grazing capacity does not exist" on the semidesert ranges of the southwestern United States. More recently, the most thorough and effective critiques of this type of carrying capacity have come from places outside the United States—in particular, Australia and Africa—after pastoral development projects based on the U.S. model proved almost uniformly unsuccessful (Westoby 1980; Westoby, Walker, and Noy-Meir 1989; Behnke, Scoones, and Kerven 1993). Bartels, Norton, and Perrier (1993), for example, argue that carrying capacity cannot even be defined, let alone calculated and applied, in sub-Saharan pastoral settings.

The problem became still more acute around 1940, when carrying capacity was again applied to people, this time not as a *Y* carrying a burden but as an *X* being carried, like livestock or deer, by specific "habitats." Leopold did this himself, although only in a lecture not published until long after his death. In March 1941, with U.S. entry into World War II on the horizon, he pondered what ecology could teach about politics and war. "Every environment carries not only characteristic kinds of animals, but characteristic *numbers* of each. . . . Every animal in every land has its characteristic number. That number is the carrying capacity of that land for that species" (Leopold [1941] 1991, 282, emphasis in original). He went on to venture some thoughts about human population "by analogy with animals":

> One of the most emphatic lessons of ecology is that animal populations are usually self-limiting; that the mechanisms for limitation are diverse, even for a single species; and that they often shift inexplicably from one kind to another; that the usual sequence is for some limitation to act before the end of the current food supply is in sight. (Leopold [1941] 1991, 282)

Such mechanisms should be understood as "fixed attributes" of populations, he suggested, "probably as immutable as the color, form, and habits of the individual creature" (Leopold [1941] 1991, 283). War, he speculated, might be such a self-limiting mechanism in humans, and he asked: "If so . . . why not call a moratorium on human increase?" (Leopold [1941] 1991, 284) Yet Leopold ([1941] 1991) also explicitly acknowledged, in racialized terms, that carrying capacities for humans were not static: "[T]he characteristic number of Indians in virgin America was small. . . . When we arrived on the scene we raised the carrying capacity of the land for man by means of tools" (282).

At the very time Leopold delivered this lecture to his students at the University of Wisconsin, officials in the British colony of Northern Rhodesia—today's Zambia—were applying carrying capacity to people quite directly and coercively. Appropriation of farmland for white colonists, combined with labor migration to mines in the Copperbelt, had created an "extreme maldistribution of population": too many people in some places, whereas other areas remained only sparsely populated (Allan 1949, 18). To address the issue, William Allan, Assistant Director of Agriculture, developed "a method of estimating land carrying capacities for human populations under African conditions and systems of land usage." He drew on an "Ecological Survey" of the Eastern and Western Provinces of the colony, which had mapped eight types of soils and vegetation, in calculating "the land carrying capacity" for different agricultural systems in the region. The average acreage in staple crops, divided by the "number of people obtaining their food supply from a family land holding," yielded an "estimate of area of staple crops per head of population" (Allan 1949, 8). This was then multiplied by the "cultivable percentage of land" for a given region, derived from the maps. It was precisely the method employed by Godwin in 1820, but by much more elaborate quantitative and cartographic means.

At this scale, carrying capacity could be interpreted as the "critical population density" of an environment–population combination, above which one could expect "*land degradation*" to occur (Allan 1949, 17, emphasis in original). This, in turn, served to justify severe interventions to avoid "starvation" that would result from "land degradation and soil erosion" (Allan 1949, 22). "The adjustment of such anomalies should be a cardinal principle of land policy. . . . [W]here the critical point has already been greatly exceeded, immediate and possibly drastic action is called for" (Allan 1949, 18–19). Accordingly, in the years 1942 through 1945, the colonial administration effected the "transfer" of "about 52,000 people" in hopes of restoring "a complete population-land balance throughout the area." This was less than a third of the 160,800 people that the calculations determined "would have to be moved" to "re-establish a population-land balance on the basis of the traditional agricultural systems" (Allan 1949, 76). Allan's published report was at pains to represent these moves as voluntary, but it is patently clear that relocations took place under duress. People were also forced to modify their agricultural practices as a condition of receiving land, under an overall goal "to populate the new areas to the maximum of their carrying capacity" (Allan 1949, 83). That the overriding imperative was increased production and labor exploitation is evident in the closing words of the report: "The first difficulty is to induce the people to move, the second is to prevent them doing so to an excessive degree" (Allan 1949, 85).

In the following two decades, anthropologists refined Allan's method, employing carrying capacity to study "native populations practicing simple food producing methods such as shifting cultivation" (Brush 1975, 799). Meanwhile, pastoralists in Africa and elsewhere endured forced destocking, relocation, and sedentarization in the name of carrying capacities calculated by range scientists as part of international development projects (Turner 1998). In both cases, scholars would eventually conclude that carrying capacity was fundamentally flawed; in Stephen Brush's (1975) words, "the principal empirical weakness of the concept of carrying capacity lies in the fact that the theory of homeostasis inherent to the concept is neither testable nor refutable" (806). The practical failures of carrying capacity—whether applied to livestock, wildlife, or people—can be traced directly to the idealism, stasis, and numerical expression embedded in the concept itself. But if it was not stable, normative, calculable, and predictive, what did carrying capacity signify any longer?

K: Optimization and Dynamic Equilibrium

The two remaining uses of carrying capacity emerged concurrently after World War II, with overlapping points of origin but widely divergent audiences and applications. One retained flora and fauna as its object but transferred the epistemological basis of carrying capacity from inductive and applied to deductive and theoretical. The other took the object of the concept as humans and expanded the scale to continents and the entire globe, giving rise to the neo-Malthusian sense of carrying capacity that pervades general use of the term today.

As noted earlier, Leopold's notion of carrying capacity did not lend itself to theory building or experimental replication. In his landmark textbook, *Fundamentals of Ecology*, Odum (1953) extricated carrying capacity from these difficulties by collapsing the very distinction that Leopold had viewed as definitive:

> Populations characteristically increase in size in a sigmoid or S-shaped fashion. When a few individuals are introduced into, or enter, an unoccupied area population growth is slow at first . . . , then becomes very rapid, increasing in exponential or compound interest fashion . . . , and finally slows down as the environmental resistance increases . . . until a more or less equilibrium level is reached around which the population size fluctuates more or less irregularly according to the constancy or variability of the environment. The upper level beyond which no major increase can occur (assuming no major changes in environment) represents the upper *asymptote* of the S-shaped curve and has been aptly called the "*carrying capacity*" or the saturation level. (Odum 1953, 122, emphasis in original)

The curve and its upper asymptote were not new: Odum was drawing on the work of Raymond Pearl, Alfred Lotka, and Vico Volterra in the 1920s, all of whom recognized Verhulst as the original (if long forgotten) author of the logistic curve (Hutchinson 1978; Kingsland 1985). However, the asymptote had not previously been called a carrying capacity, aptly or otherwise: Odum's predecessors had termed it simply "an upper limit of growth."[8] Whereas Leopold had treated saturation points as a hypothetical possibility that awaited empirical verification, Odum asserted that such consistency had in fact "been observed again and again . . . regardless of whether one is dealing with fruit flies in a milk bottle or with fish in a new pond" (Odum 1953, 122–23). The universality of the sigmoid curve rested not on multiple observations of the same species but on a handful of observations of multiple species. Moreover, it was derived not from the kind of field measurements that Leopold cited—"data on population growth of field populations," Odum conceded, were "few, incomplete, and hard to come by" (Odum 1953, 123)—but instead from "laboratory studies of fruit flies, flour beetles, or other convenient organisms" (Odum 1953, 123). These were the studies that Pearl had helped pioneer, part of the larger turn toward a more mathematical and less historical systems ecology that was explicitly modeled on physics and chemistry (Kingsland 1985). "Convenient" thus referred to suitability for reproduction and observation under artificially optimized environmental conditions of temperature, food, and so forth. In such settings, "a rather sharp and definite asymptote is reached with very little fluctuation, natality and mortality being balanced so long as new media are added continually to maintain a constant environment" (Odum 1953, 123) Ideal and fixed environments revealed ideal, fixed carrying capacities.

By a curious logic, carrying capacity could then appear as a property of organisms abstracted from any environment whatsoever (rather as with ships before). Odum characterized growth under laboratory conditions as the "intrinsic rate of natural increase" of organisms: the rate that would obtain in the absence of "environmental resistance." He then likened the laboratory to situations that could be observed in the field, especially if one looked at short-lived organisms (such as those used in lab experiments): "The best opportunity to observe the fundamental growth form occurs when the population enters or is introduced into a new, unoccupied environment; this may occur every year or oftener in organisms with short life histories or only occasionally in other organisms" (Odum 1953, 125). Or, perhaps, never: most longer lived species only rarely enter into such an environment, except on very small spatial scales (e.g., after wildfire, soil disturbance, or disease outbreaks). Odum also found the same S-shaped curve, however, among introduced animal species: sheep on Tasmania, pheasants on Protection Island, Washington, and starlings in the United States. It was as though introductions and invasions were the standard of population growth in nature, against which actual observed cases should be evaluated.

The pattern similarity suggested a methodological turn of enormous significance: modeling population growth by expressing the sigmoid curve as a mathematical equation. "Such curves very closely approach the logistic curve," (Odum 1953, 123) a differential equation first proposed by Verhulst (1838) to model human population growth and independently derived by Raymond Pearl and Lowell Reed in 1920 (Kingsland 1985). In the equation, K denoted "the maximum population size possible, or 'upper asymptote,'" which Odum (1953, 123) chose to define as carrying capacity. Using such equations, he argued, one could infer "the environmental resistance created by the growing population itself, which brings about an increasing reduction in the potential reproduction rate as population size approaches the carrying capacity" (Odum 1953, 123). Even though K could never be observed in the field, its mathematical existence permitted the development of models that could be elaborated and tested for single or multiple species.

Environmental resistance was a concept necessitated by a static, ideal carrying capacity. It can be traced to an article by Chapman (1928), which both Leopold and Odum cited. In it, Chapman likened the behavior of populations in response to their environments to the transmission of heat and electricity through solid bodies. Just as Fourier and Ohm had used mathematics to deduce laws of energy and electromagnetism, Chapman proclaimed, ecologists were now on the threshold of quantifying the "environmental factors" that determine "animal abundance." "[I]t seems evident that we have in nature a system in which the potential rate of reproduction of the animal is pitted against the resistance of the environment, and that the quantity of organisms which may be found is a result of the balance between the biotic potential, or the potential rate of reproduction, and the environmental resistance" (Chapman 1928, 114). He went on to present results from laboratory experiments with flour beetles. Chapman did not, however, employ the term carrying capacity to characterize or conceptualize his arguments.

Odum's carrying capacity made it appear that the attributes of its predecessor concepts could be found in nature. The growth of a population in the wild could be indirectly calculated using models developed from findings produced in laboratories, where conditions resembled those of shipbuilding or engineering more generally: technical control of design, inputs, execution, and observation. The deer and wolves of the Kaibab, for example, could be modeled as interacting populations that rose and fell in lagged synchronicity, exhibiting a dynamic equilibrium—that is, a fixed point around which actual numbers fluctuated. The models could be modified to reflect circumstances affecting a given site and species of interest, and the results could help both to make decisions about management and to advance research in the new field of population biology. Carrying capacity was now an attribute of a dynamic system rather than a ship, and it was equilibrial rather than static. But it was nonetheless ideal, numerical, and theoretically stable.

Odum cautioned against mistaking his model for the reality it attempted to describe. Simply fitting Verhulst's differential equation was not sufficient grounds for treating the observed patterns as explained or predicted by mathematical means: "There are many mathematical equations which will produce a sigmoid curve. Mere curve-fitting is to be avoided. One needs to have evidence that the factors in the equation are actually operating to control the population before an attempt is made to compare actual data with a theoretical curve" (Odum 1953, 124–25).

Odum also recognized that his concept of carrying capacity could be applied to humans, and it was in relation to global human population that the epistemological difficulties of his carrying capacity concept became unmanageable. "Population growth forms and upper asymptotes are of extreme interest in human demography," he wrote, citing a 1936 study (by Raymond Pearl) that "fitted world population growth to a sigmoid curve." Based on the study, Odum predicted that:

> the population of the world, now about 2,200 million, is in negative acceleration phase and should reach an upper asymptote of 2,645 million in the year 2700, *provided* the carrying capacity of the world for human beings is not increased by that time. . . . To what extent the upper asymptote for man can be raised is a question being actively debated at present. Continued studies of the growth form of animal populations should help us to obtain an answer. In the meantime, one should not use the sigmoid curve to predict the maximum size of future populations of man or organisms unless one is sure that the carrying capacity of the environment will remain largely unchanged during the interval. (Odum 1953, 125, emphasis in original)

The problem of distinguishing between organisms and environment as factors determining population growth was rendered intractable by the variability of environment itself, especially where humans were concerned. People might intentionally alter their environment—much as scientists manipulated conditions in laboratories—in ways that raised (or lowered) the asymptote toward which their population moved. Like Leopold, Odum here chose to retreat from a static notion of carrying capacity, notwithstanding his own earlier arguments in deriving K. Discussing the curve for starlings, he conceded that "the asymptote . . . itself changes from year to year as environment changes, thus making it difficult to distinguish between changes caused by environment and changes due to population growth" (1953, 129). After reviewing the introduced populations mentioned previously, he concluded that "so far, ecologists have not been able to distinguish quantitatively" between environment and population as factors affecting growth (1953, 130).

Odum turned this difficulty into a virtue, however. Any observed downturn in the growth of a population in the wild could be interpreted as an instance of carrying capacity imposing its limits. Any decline followed by a rebound thus did not refute the universality of the sigmoid curve—rather, it signaled the initiation of a new period of growth that would again follow the sigmoid pattern. If the next downturn occurred at a different population size than before, then the carrying capacity could be inferred to have changed. Nonetheless, and by the same logic, internal checks on population could still be said to exist, even though they never expressed themselves independently from environment. The *shape* of the curve signified an organism's "intrinsic rate of increase," even if the gross value of the asymptote changed over time.

Taken together, these arguments suggested that carrying capacity is always fluctuating, including for reasons we do not understand and thus cannot model. Repeated testing and refining of models might lessen this gap in particular cases, but the overall theory was by this point self-validating. As Zimmerer (1994, 112) observes, the postulate of generalized carrying capacity assumed an idealized growth curve and spatial homogeneity, but neither assumption stands up to empirical scrutiny. According to Botkin (1990, 40ff), "logistic growth has never been observed in nature," and mere curve-fitting is all that research into carrying capacities for wildlife has ever achieved. He attributes the "balance of nature" assumptions contained in the concept of carrying capacity to physics envy, alloyed with "prescientific myths about nature." However, the case is stronger than this: carrying capacity was an engineer's concept from its origins, and it was tautological with or without appeal to myth. Environmental resistance and carrying capacity were the same concept viewed from opposite ends of an underlying—and entirely idealist—dualism of "nature" and organisms.

Global Human (Over) Population

Carrying capacity, as Odum formulated it, expressed with precision what could be expected if a population lived without relation to its environment. This could never occur empirically, of course, but knowledge of such a norm nonetheless allowed every observed deviation from it to appear as an actual shortage of some environmental resource. In this way Odum gave scientific expression to the so-called "principle of population" made famous by Malthus some 150 years earlier. Glacken (1967) sees its origins in the much older principle of plenitude: that life, by its (God-given) nature, is given to exuberant self-reproduction. The contradiction between this plenitude and the limitations of "environment" drove Malthus's argument, both substantively and rhetorically: life, in the absence of environmental constraints, would rapidly overpopulate the earth. The fact that it has not yet done so means that life must be "checked," and that the principle is therefore empirically true. Every empirical instance of misery and vice appears, conversely, as evidence of such checks, and the growing population emerges as the root of the problem, if only by bringing larger numbers of victims into the path of every check. As we have seen, however, Odum did not advocate such a notion of carrying capacity, and his arguments left open the possibility—at least in theory—that humans might increase their carrying capacity indefinitely. Rather, the final type of carrying capacity arose elsewhere, and it differs in scale, audience, and application from the type that Odum helped establish in population biology.

The neo-Malthusian use of carrying capacity appears to have its origins in the book *Road to Survival,* by ecologist and ornithologist William Vogt. Published in 1948 for a popular audience, *Road to Survival* captured a strain of fatalistic pessimism born of the horrors of World War II, even as it extended an American apocalyptic narrative form earlier voiced in terms of soil erosion and the collapse of ancient civilizations.[9] Vogt's first job out of college had been curator of a bird sanctuary; he had spent the war doing reconnaissance work throughout South and Central America and was deeply affected by the poverty he witnessed there. Later, he nearly enrolled at Wisconsin as one of Leopold's graduate students (C. Meine, e-mail communication, 25 January 2007). *Road to Survival* sought to persuade its readers that "we all live in one world in an ecological—and environmental—sense," and that the earth should be understood on the model of a sanctuary or preserve.

Vogt defined carrying capacity using a "bio-equation": C = B : E, in which C stood for carrying capacity, B for biotic potential, and E for environmental resistance. Biotic potential, Vogt wrote, had "an absolute or *theoretical* ceiling that is never reached, except under extraordinary conditions," and "a very large number of *practical* ceilings," which were "in most of the world dropping lower every year. . . . The practical ceiling is imposed by the *environmental resistance*, which is the sum of varying but always great numbers of limiting factors acting upon the biotic potential" (Vogt 1948, 22). The parallels with Odum's theory are striking, and it should be evident from the preceding section that Vogt's "equation" was a tautology: environmental resistance was conjured into existence by first positing a theoretical limit called carrying capacity, from which empirical reality necessarily deviated.

Vogt conceded that "the equation finds complicated expression in terms of civilized existence," but he insisted on its reality and its importance, and he applied it to vastly larger scales than had been attempted in range or wildlife management or in academic biology:

> Until an understanding of these relationships on a world scale enters into the thinking of free men everywhere, and into the thinking of rulers of men who are not free, there is no possibility of any considerable improvement of the lot of the human race. Indeed, if we continue to ignore these relationships, there is little probability that mankind can long escape the searing downpour of war's death from the skies.
>
> And when this comes, in the judgment of some of the best informed authorities, it is probable that at least three-quarters of the human race will be wiped out. (Vogt 1948, 16–17)

Like Malthus, Vogt reduced the environment to arable land and food production. He evaluated the carrying capacity of every continent in the world except North America and Antarctica—all but these two, he concluded, were already overpopulated. The result was a schizophrenic message: the ecological imperative that "man . . . must live within his means" meant, in practice, that carrying capacity must be increased by reducing environmental resistance through measures such as irrigation and insect control (Vogt 1948, 22). Protecting the environment and increasing productivity appeared as harmonious—even identical—goals, united by the concept of carrying capacity.

With ecology and wealth thus wedded together, Vogt could propound a political agenda that was at once environmentally deterministic and geo-politically timely. In his foreword, he asserted that America's prosperity rested solely on its "lush bountifulness," which was so great that it had more than compensated for sustained environmental abuse. Not only must we Americans learn to steward our natural resources more wisely, he wrote; we must also, "in human decency as well as in self-protection, use our resources to help less well-endowed peoples" (Vogt 1948, xiv). He chose for his frontispiece a bar graph of "living standards" in thirty-four countries, measured in weekly wages per worker; the graph was adapted from a book called *Global War, An Atlas of World Strategy*. It was a logical next step to see a direct trade-off between wealth and population size: "When the carrying capacity of the land rises, the possibility of higher living standards increases for limited numbers of people, or a lower living standard for excessive numbers" (Vogt 1948, 22–23).

Vogt's arguments can be traced with remarkable detail through the work of subsequent neo-Malthusian ecologists such as Garrett Hardin and Paul and Anne Ehrlich. Both Vogt and Hardin employ the range science sense of carrying capacity to illustrate their larger arguments, likening the world to a pasture that can only support a finite number of animals or humans; for both, the logical prescription is basically the same as the one Leopold reached regarding deer: Do not let the herd irrupt. The Ehrlichs, like Vogt and Hardin, use carrying capacity to conclude that the irruption has already occurred:

> The key to understanding overpopulation is not population density but the numbers of people in an area relative to its resources and the capacity of the environment to sustain human activities; that is, to the area's *carrying capacity*. When is an area overpopulated? When its population can't be maintained without rapidly depleting nonrenewable resources (or converting renewable resources into nonrenewable ones) and without degrading the capacity of the environment to support the population. In short, if the long-term carrying capacity of an area is clearly being degraded by its current human occupants, that area is overpopulated.
>
> *By this standard, the entire planet and virtually every nation is already vastly overpopulated.* (Ehrlich and Ehrlich 1990, 38–39, emphasis in original)

Hardin (1986) is apparently unaware of the flaws that range and wildlife managers have discerned in the concept of carrying capacity: "In the nonhuman world its application presents few problems . . . and its definition in particular circumstances presents no serious problem to the well-informed." He concedes that things are more complex when applied to humans, but he nonetheless insists that "for human populations as for others, the prime commandment must be Thou shalt not transgress the carrying capacity."

The two post–World War II uses of carrying capacity have blurred into one another, the more "scientific" lending academic credibility and the more popular providing political traction and hyperbole. Neo-Malthusian ecologists—along with prominent scientists from many other disciplines—have fallen into a conceptual trap first set more than 200 years ago: a theory that is self-validating and irrefutable by means of empirical evidence, even as it claims empirical support from a wide range of sources and fields. It seems that carrying capacity—a concept that did not exist when Malthus wrote his *Essay* and that acquired its scientific credibility between 1890 and 1950—was a major decoy in luring so many people into this trap.

Conclusion

Except in its earliest, literal sense, carrying capacity has been plagued with serious conceptual flaws due to the contrasting but frequently conflated characteristics of its various uses. Should carrying capacity be understood as a fixed quantity (like the tonnage of a ship) or as a dynamic one (like the amount of grass in a pasture)? Is it ideal, or real? Is it a function of human technology and adaptation, or of natural processes beyond human control? Finally, can something discerned at very small, bounded scales—in a Petri dish or a ship, a pasture or a pipeline—be expanded to much larger scales without a crippling distortion of meaning? The flaws of carrying capacity have been noted in several fields. Hutchinson (1978, 21) put the point succinctly nearly thirty years ago: "When the possible value of K is continuously increasing, Verhulst's equation loses its value." If carrying capacity is conceived as static, it is theoretically elegant but empirically vacuous; but if it is conceived as variable, it is theoretically incoherent or at best question-begging. The links between its different uses have eluded attention, however, allowing the origins of its flaws to be overlooked.

In each new use, proponents of carrying capacity have capitalized on the familiarity and authority of its earlier uses while somehow foreclosing scrutiny of whether the new application was appropriate or coherent. Its durability and power, despite all the criticisms, have undoubtedly been reinforced through serial application by agencies of the state. Determining an ideal, fixed, and quantitative measure of how much *X* a given *Y* should convey, support, or produce is, it appears, an abiding ambition of government in areas as varied as taxation, resource management, planning, transportation, communications, and conservation. That it has worked in certain applications—in bounded, usually small systems where control could be exerted—has ratified its use in other areas where control was desired and asserted. Even when carrying capacities proved illusory, they provided an appearance of objectivity, rationality, and precision to policies that might otherwise have been revealed as politically or economically motivated. It is as though the continuity of the term itself, aided by its intuitive sensibleness—who cannot understand the idea that one's capacity to carry something has a measurable and stable limit?—has enabled its potency and persistence as it moved from one field to another. Moreover, by appearing to refer to actual relations in the world, rather than ideal constructions, carrying capacity has benefited from a kind of linguistic Pandora's box: once one has used the term, one has tacitly affirmed that its referent exists, even if determining its values in a given case turns out to be impossible.

That the concept of carrying capacity has limits does not mean that the limits it purports to specify are nonexistent or meaningless—far from it. The point, rather, is that such limits are rarely static or quantifiable, let alone predictable and controllable. One can liken the world to a ship, but that does not make the world *like* a ship. To conceive of environmental limits in abstraction from time and history—as somehow intrinsic to an idealized nature—is to mistake the model of reality for reality itself. This mistake can have serious ramifications, as witnessed in colonial "relocations" and pastoralist sedentarization campaigns. "Whenever a theory of overpopulation seizes hold in a society dominated by an elite, then the non-elite invariably experience some form of political, economic, and social repression" (Harvey [1974] 2001, 63). It is unclear whether the concept of carrying capacity has any content at all without the idealism, stasis, and numerical expression that have clung to it throughout its history. What is clear is that it is a very dull tool for understanding the complex interrelations of humans with the face of the earth.

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Notes

1. Cohen (1995) reviews several earlier attempts to calculate the earth's maximum human population, the first from 1628, although he neglects Godwin. It appears that none of these efforts employed the term carrying capacity, however.
2. A ton equaled 100 cubic feet. Different countries used different methods to calculate a ship's tonnage, however, so the *OED* definition might not have applied in Texas.
3. Typically the disputes were international, but not always. In 1867, the U.S. Supreme Court settled a dispute between the federal government and the state of Iowa in which the carrying capacity of ships on navigable rivers was a central issue: Vessels over ten tons in carrying capacity—and by extension, the rivers they used—were judged to fall under federal jurisdiction (J. F. D. 1867, 595).
4. The oxygen-carrying capacity of blood, for example, can be found in recent medical journals.
5. As recently as 1961, a scholarly article presented a table of data described as showing "a great increase of carrying capacity between 1943 and 1946" in Costa Rica—measured in cubic meters of stone moved per worker and attributed to improvements in diet (Sukhatme 1961, 492).
6. I have not found evidence that "carrying capacity" was employed in the formulation of these systems at their origins, but the question warrants further research.
7. They continue to be disputed to this day. Caughley (1970, 56) famously dismantled the evidence that Leopold relied on, concluding that the data "are unreliable and inconsistent, and the factors that may have resulted in an upsurge of deer are hopelessly confounded." More recently, however, Binkley et al. (2006) found independent evidence to support Leopold's interpretation. For a comprehensive treatment of the Kaibab deer story, see Young (2002).
8. This is Pearl's (1924) formulation; Verhulst called it "*la limite supérieure de la population*" (1838, 116) or "*l'extrême limite de la population*" (1845, 9).

9. Several of Vogt's opening (fictionalized) anecdotes concern soil erosion. For an antecedent that does not employ carrying capacity, see Sears (1935).

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