Carrying Capacity

Carrying capacity has been used to assess the limits of a wide variety of things, environments, and systems to convey or sustain other things, organisms, or populations. Four major types of carrying capacity can be distinguished; all but one have proved empirically and theoretically flawed because the embedded assumptions of carrying capacity limit its usefulness to bounded, relatively small-scale systems with high degrees of human control.

The concept of carrying capacity predates and in many ways prefigures the concept of sustainability. It has been used in a wide variety of disciplines and applications, although it is now most strongly associated with issues of global human population. The idea that Earth has a finite ability to support humans, and that exceeding that limit will result in famine or other cataclysms, is at least three hundred years old (Cohen 1996). British political philosopher William Godwin's estimate of 9 billion, published in 1820, may seem prescient today. The term *carrying capacity* was not coined until the middle of the nineteenth century, however, and it was not originally conceived in relation to population at all. Rather, it emerged in the context of international shipping and subsequently was applied in a series of other fields—including engineering, range and wildlife management, agriculture and anthropology, and finally biology—before neo-Malthusians took it up in the second half of the twentieth century. An understanding of this history sheds valuable light on the limits of carrying capacity as a tool for evaluating and managing humanity's impacts on Earth.

Intuitively, carrying capacity is a simple relation or ratio: the quantity of some *X* that a given (amount of) *Y* can "carry." The myriad uses of carrying capacity distilled into a single definition probably would be "the maximum or optimal amount of a substance or organism (*X*) that can or should be conveyed or supported by some encompassing thing or environment (*Y*)." But the extraordinary breadth of the concept so defined renders it extremely vague. As the repetitive use of the word *or* suggests, carrying capacity can be applied to almost any relationship, at almost any scale; it can be a maximum or an optimum, a normative or a positive concept, inductively or deductively derived. Better, then, to examine its historical origins and various uses, which can be organized into four principal types: (1) shipping and engineering, beginning in the 1840s; (2) livestock and game management, beginning in the 1870s; (3) population biology, beginning in the 1950s; and (4) debates about human population and "overpopulation," also beginning in the 1950s. Carrying capacity continues to be used in all these senses, but in all except the first, it has been forcefully criticized and largely discredited among scholars, often after a lengthy period of enthusiastic use in both research and policy making. Its widespread popular use and continuing traction in public debates stand in sharp contrast to these critiques.

Shipping and Engineering

The earliest use of carrying capacity is the most literal, and it has been partially supplanted by other terms such as *payload*. It referred first to the amount of cargo that a ship could carry, measured in volume. This measurement served a specific purpose in the context of international trade in the 1840s, when steam propulsion was overtaking the older, wind-powered technology of sailing vessels. Previously, tariffs and duties had been imposed on cargo ships in terms of their "tonnage," a measure of volume descended from casks of wine known as tuns. A ship's hull was measured to compute its overall volume, crews' quarters were deducted, and the resulting figure was used to assess levies on all of that ship's voyages, regardless of the amount of cargo it carried on any particular trip.

Although somewhat imprecise, this method was a reasonably accurate way of calculating the volume of cargo a sailing ship could transport, because the hull was wholly available for cargo. With the rise of steamships, however, the tonnage system appeared faulty, at least to those whose interests lay in the newer technology—notably the British, whose steam-powered merchant marine fleet led the world. Steamships had to devote much of their "tonnage" to coal and fresh water (to generate steam), and to the huge boilers and engines that propelled them and gave them decisive advantages over sailing ships (e.g., speed, power, and independence from the vagaries of the wind). It seemed unfair to pay levies on this portion of a ship's volume, as it could not be used to transport cargo. Carrying capacity was invented to capture this distinction and provide an alternative basis for tariffs and duties.

Around 1880, carrying capacity began to be used to measure other human constructions, including canals, railroads, pipelines, irrigation systems, hot air balloons, lightning rods, and electrical transmission lines (Sayre 2008). No longer limited to shipping, it served the practical need of engineers and public planners to know how much *X* a particular *Y* was designed to carry without exceeding its tolerances. As in the case of shipping, it was possible to determine such limits with reasonable precision and accuracy; they were static, fixed by the design and materials used; and they were ideal—that is, they referred not to the amount of *X* actually carried by *Y* at a given point in time, but the amount that could or should be carried. These features—numerical expression, stasis, and idealism—gave carrying capacity its analytical power and have persisted in subsequent uses of the term (Sayre 2008).

Livestock and Game Management

Carrying capacity was transferred to the measurement of living organisms and natural systems beginning in the 1870s: how much *X* a human or a pack animal could carry; the amount of pollen carried on the legs of bees; the moisture carried by prevailing winds; the floodwaters that a river channel could carry. These were not engineering questions, but they shared the literal sense of something "carrying" another thing from one place to another.

The second type of carrying capacity emerged from a more figurative notion that transposed the earlier subject and object. Livestock, previously a *Y* that carried an *X*, became instead an *X* "carried" in the sense of "supported or sustained by" a new *Y*: pastures or land. Scientists in Australia and New Zealand appear to have been the first to use carrying capacity in this way, as they struggled to determine how many sheep and cattle these British possessions could reliably produce on their recently settled frontiers. Carrying capacity helped administrators allocate rangelands to as many settlers as possible while simultaneously avoiding overstocking. The idea quickly caught on in the United States, which experienced calamitous episodes of rangeland degradation in the 1890s, especially on the unclaimed public domain and in areas prone to drought. Between 1905 and 1946, the government implemented a system of leases for the vast areas of land the Forest Service and the Bureau of Land Management held, in which carrying capacity served the key role of measuring the number of stock and the amount of time they could be grazed each year in fenced areas known as allotments. These measurements were averages calculated over periods of years, often extrapolated from study sites to much larger areas of similar climate, soils, and vegetation.

The US conservationist Aldo Leopold, who worked for the Forest Service's Office of Grazing in 1914–1915, extended this use of carrying capacity from livestock to game animals. He formalized the concept in his famous 1933 textbook, *Game Management*, the founding work of the discipline now known as wildlife management. Leopold understood carrying capacity as an attribute of a piece of land (rather than a particular animal species) and as a function of multiple variables—including vegetation, weather, predation, competition, and disease—that together determined the size of a local wildlife population by affecting reproduction and survival. By identifying the limiting or deficient variable and manipulating it to improve the carrying capacity, the game manager could achieve conservation and optimize game populations for human uses such as hunting and fishing. Leopold's ideas influenced wildlife management in the United States and abroad for most of the twentieth century, resulting in many notable successes in sustaining popular species of game and fish, but also many outcomes that are now regretted by conservation biologists, such as the introduction of non-native species and the loss of biodiversity (Botkin 1990).

In both range and wildlife management, scholars in the second half of the twentieth century began to critique carrying capacity, due primarily to practical shortcomings and on-the-ground failures. International development projects aimed at replicating the US model of range leases, fences, and carrying capacities in Africa and other developing world areas routinely failed, in part because fixed carrying capacities, based on averages of rainfall or forage production, overlooked the large year-to-year variability of many rangelands (Behnke, Scoones, and Kerven 1993). The same problem occurred in wildlife management: if actual habitat conditions varied from place to place and year to year, and wildlife populations both responded and contributed to these changes, then carrying capacity was merely an ephemeral or local descriptor rather than a predictive or prescriptive tool for management. In shifting from engineered to natural systems, carrying capacity lost its static and ideal qualities and therefore much of its coherence and usefulness.

Population Biology

The third type of carrying capacity emerged from laboratory experiments in which scientists observed population growth in carefully controlled environments. Provided with optimal conditions of temperature, food, and so forth, populations of flour beetles and fruit flies grew slowly at first, then accelerated, and then slowed in asymptotic fashion toward a stable upper limit at which births and deaths balanced each other. When graphed, the line had a sigmoid shape, like a stretched-out *S*. These experiments took place in the 1920s, and the US biologist Raymond Pearl, who helped pioneer the research, also rediscovered the forgotten work of the nineteenth-century Belgian mathematician Pierre-François Verhulst, who had found a similar pattern in human population statistics and had quantified it as "the logistic curve" (Hutchinson 1978).

As population biology grew into a new scientific field, the logistic curve provided scientists with a way to redefine carrying capacity as a core concept that linked research, theory, and application. In his famous textbook, *Fundamentals of Ecology,* the US ecologist Eugene Odum (1953) called Pearl's and Verhulst's asymptote "carrying capacity" or, in mathematical language, *K*. Because scientists observed *K* under ideal environmental conditions, they took it as the maximum possible population of an organism, independent of the environment. Odum thus reversed Leopold's view that carrying capacity was an attribute of particular places or habitats, defining it instead as a fixed attribute of species themselves. In a fixed, ideal environment, one could observe fixed, ideal carrying capacities.

This new carrying capacity enabled major advances in applied and theoretical population biology for two reasons. First, it provided a benchmark or baseline against which to evaluate population dynamics in field settings. Odum noticed that the logistic curve also approximated patterns observed when a new species arrived (or was introduced) in previously unoccupied habitats: sheep in Tasmania, pheasants on Protection Island, Washington, and starlings in the United States. The pattern similarity helped validate the logistic curve empirically, while the difference between values of *K* in the lab and the field suggested that actual environments imposed restrictions on population growth, which Odum termed "environmental resistance." Second, by expressing population growth as an equation, the logistic curve allowed scientists to develop mathematical models of organism-environment interactions for single or multiple species. They could test the models in lab experiments or compare them to field data, informing both management and research.

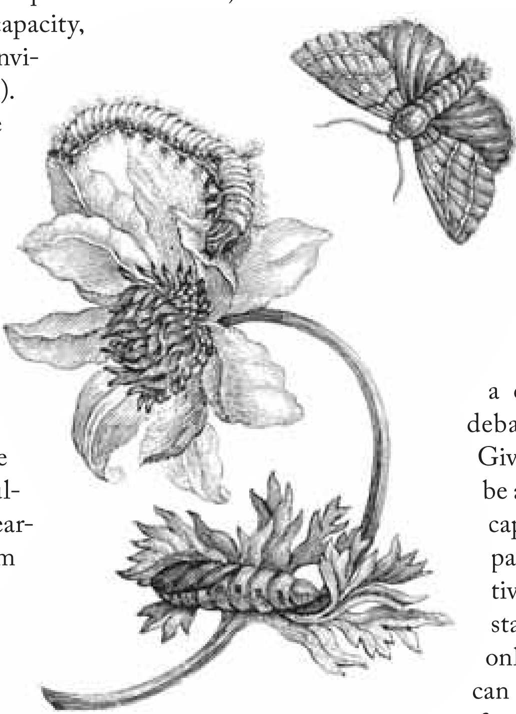
As in range and wildlife management, carrying capacity in population biology eventually proved faulty. Although the sigmoid curve could indeed be found in field settings, the actual value of *K* varied over time and space. Odum had conceded that "one should not use the sigmoid curve to predict the maximum 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" (1953, 125). This condition is rarely if ever met outside of the lab, however, except over very short time periods and in small or clearly bounded settings such as ponds or islands. It follows that models built on the logistic curve are unlikely to yield robust predictions of actual population dynamics. As the US ecologist Daniel Botkin noted, "[L]ogistic growth has never been observed in nature" (1990, 40), and fifty years of research has found little or no empirical support for the concept of carrying capacity (see also Hutchinson 1978).

Neo-Malthusianism

The fourth type of carrying capacity emerged concurrently with the third, and it drew on many of the same scientific developments. It applied the concept to human populations, however, and at much larger scales—countries, continents, and the world as a whole—with a view to influencing not scholars but policy makers and the public at large. Buttressed by the scientific authority of ecology, this final kind of carrying capacity helped to revive the arguments made famous in T. Robert Malthus's *Essay on the Principle of Population* (1798).

Carrying capacity had been applied to human populations before. In addition to his scientific work, Raymond Pearl had been active in debates in the 1920s and 1930s about eugenics, birth control, and the specter of overpopulation—although he had not employed the term *carrying capacity*. And in the 1940s, the British colonial administration of Northern Rhodesia (now Zambia) used soils maps, agricultural data, and population statistics to calculate the carrying capacities of different portions of the colony for various forms of native farming. It relocated some fifty thousand native Africans on the basis of the results (Allan 1949). The work went on to inform research by anthropologists studying native agricultural practices elsewhere in Africa and beyond.

Ecologists enlarged and popularized carrying capacity as a tool for promoting population control beginning with the US ecologist William Vogt's popular 1948 book, *Road to Survival*. Vogt was an ornithologist who spent World War II doing rural reconnaissance for the US government in South and Central America. His book sounded a plea for conservation and development to improve the lives of poor people throughout the world, both for their own sake and as a means to support the United States in the global struggle against communism. He built his arguments around what he called a "bio-equation": $C = B : E$, in which C stood for carrying capacity, B for biotic potential, and E for environmental resistance (Sayre 2008). He applied the equation to the world's continents and concluded that all but North America and Antarctica had already exceeded their carrying capacities, as evidenced by poverty, malnutrition, soil erosion, and other forms of environmental degradation. Humanity faced a stark choice: raise the carrying capacity by reducing environmental resistance through conservation and agricultural modernization or risk "the searing downpour of war's death from the skies" (Vogt 1948, 16).



Vogt's concept of carrying capacity contained the same flaws as its predecessors' ideas had. As in Odum's case, the idea of environmental resistance was tautological, because it purported to explain something that arose necessarily from an ideal, fixed concept of carrying capacity: namely, the disparity between that ideal and actual empirical cases. The very fact that humans could change their environment, and thereby raise (or lower) the carrying capacity, meant that Vogt's bio-equation could really produce only ephemeral and local inductive conclusions, just as with wildlife. As the US geographer Nathan Sayre (2008, 131) concludes, "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." These weaknesses did not prevent Vogt's arguments from recurring, in remarkable detail, in the works of subsequent neo-Malthusians such as Garrett Hardin (1968, 1986) and Paul and Anne Ehrlich (1990).

The concept of carrying capacity originated in contexts in which human control can be effectively wielded over discrete objects and bounded systems at small to medium scales such as a ship, a city, or a transportation system. In such settings, a quantified, static, and ideal measurement of limits was both desirable and achievable. As carrying capacity spread to other applications, however, these conditions were difficult or impossible to meet, except in laboratory experiments. Scholars in a wide range of social and environmental sciences concluded long ago that it is fundamentally flawed. The US anthropologist Stephen Brush (1975, 806) summarized the problem: "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." Similarly, the famous Anglo-American zoologist G. Evelyn Hutchinson (1978, 21) offered this judgment in 1978: "When the possible value of K is constantly increasing, Verhulst's equation loses its value."

The limits of carrying capacity as a concept have direct relevance to debates about sustainability today. Given its flaws, the question that must be asked is why the concept of carrying capacity has persisted. This is due in part, no doubt, to the concept's intuitive obviousness: everyone can understand the idea that a ship can carry only so much cargo, or that a pasture can support only so many livestock, and so forth. Also important is the authority various advocates gave carrying capacity along the way, before empirical evidence caught up with early enthusiasm. Finally, agencies of the state embraced and promoted most of the uses of carrying capacity as they sought to measure, regulate, tax, plan, allocate, or otherwise control people, commerce, land, wildlife, and natural resources of various kinds. But such control is elusive when sought over large, complex, and unbounded systems that are poorly understood and difficult or impossible to control. The history of the concept of carrying capacity teaches us that ideal, static, quantitative limits are extremely unlikely to exist in such cases; the same is probably true for sustainability.

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See also Community Ecology; Complexity Theory; Ecosystem Services; Fisheries Management; Global Climate Change; Extreme Episodic Events; Human Ecology; Natural Capital; Population Dynamics

Further Reading

Allan, William. (1949). *Studies in African land usage in Northern Rhodesia.* Rhodes-Livingstone Papers no. 15. London: Oxford University Press.

Behnke, Roy; Scoones, Ian; & Kerven, Carol. (Eds.). (1993). *Range ecology at disequilibrium: New models of natural variability and pastoral adaptation in African savannas*. London: Overseas Development Institute.

Botkin, Daniel B. (1990). *Discordant harmonies: A new ecology for the twenty-first century.* New York: Oxford University Press.

Brush, Stephen B. (1975). The concept of carrying capacity for systems of shifting cultivation. *American Anthropologist* (new series), *77*, 799–811.

Cohen, Joel E. (1996). *How many people can the Earth support?* New York: W. W. Norton.

Ehrlich, Paul R., & Ehrlich, Anne H. (1990). *The population explosion.* New York: Simon and Schuster.

Hardin, Garrett. (1968). The tragedy of the commons. *Science*, *162*, 1243–1248.

Hardin, Garrett. (1986). Cultural carrying capacity. Retrieved July 16, 2007 from http://www.garretthardinsociety.org/articles/art_cultural_carrying_capacity.html.

Hutchinson, G. Evelyn. (1978). *An introduction to population ecology.* New Haven, CT: Yale University Press.

Leopold, Aldo. (1933). *Game management.* New York: Charles Scribner's Sons.

Odum, Eugene P. (1953). *Fundamentals of ecology* (1st ed.). New York: W. B. Saunders Co.

Sayre, Nathan F. (2008). The genesis, history, and limits of carrying capacity. *Annals of the Association of American Geographers*, *98*, 120–134.

Vogt, William. (1948). *Road to survival.* New York: William Sloane Associates.

