

THE FEASIBILITY OF A TESTABLE GAIA HYPOTHESIS

A Project Presented to The Faculty of the
Undergraduate College of Mathematics and Sciences
James Madison University

In Partial Fulfillment of the Requirements for the Degree Bachelor of Sciences
by
Brent Franklin Bauman
1998

Introduction

In contrast to Darwinian theories of natural selection which hold that life evolves and adapts to existing geologic conditions, the Gaia hypothesis, first proposed by James Lovelock in 1969, states that Earth and the life inhabiting it coevolve as one globally integrated system. This system, Gaia, is homeostatically regulated through biological negative feedback reactions and creates conditions that are self-sustaining and comfortable for life itself. Lovelock compares the Earth's self-regulating abilities to those of a hypothetical planetary organism that is capable of maintaining the Earth's surface biogeochemistry as an organism maintains its own life-sustaining internal conditions.

Views regarding the relationships between life and the Earth have historically resulted in polar opposite positions of scientific thought. Within the natural sciences, two such positions currently prevail: reductionism and holism. Reductionism is the notion that systems can be understood by analysis of their component parts. It proposes, for example, that all biological phenomena can be understood and described by the laws of physics. Holism is the notion that the component parts of a system can only be understood in context of the whole system. For example, biological phenomena exhibit emergent properties that can be ultimately reduced to or explained by the laws of physics. Although numerous holistic theories have recently emerged, reductionism has remained the dominant paradigm in the sciences since the 1950's (Goldsmith 65). In view of the reductionist paradigm, it is unsurprising that Gaia, a holistic approach to science, has procured much division within the scientific community and has obtained many critics.

James W. Kirchner, a professor at the University of California, Berkeley, has become one of Gaia's staunchest critics in recent years. His criticisms focus on the testability of the Gaia hypothesis. Kirchner claims that the Gaia hypothesis has merits because of the interdisciplinary scientific research it has stimulated in fields that have historically remained isolated. He acknowledges also that it has reiterated the well-established fact that the Earth's biology influences the environment. As a scientific hypothesis, however, Kirchner finds Gaia untestable, ambiguous, and misleading.

Kirchner's criticisms of Gaia stem from the early works of Karl Popper, a notable philosopher of science who viewed theories as testable as long as remained open to falsification. Surfacially, Kirchner provides convincing arguments illustrating the untestable nature of Gaia. It is naïve, however, to brand Gaia as "untestable" without thoroughly exploring the philosophical foundations of scientific testability. A complex system like Gaia cannot simply be accepted or rejected based upon simple verification or falsification tests. The testability of Gaia can only be determined by careful examination of the philosophical foundations governing its testability.

This paper explores the feasibility of a testable Gaia hypothesis in a twofold endeavor. First, it is imperative to delineate the scientific foundations that govern scientific testability. Under the umbrella of this definition for testability, it then becomes possible to use mechanisms such as ecological modeling to prove the viability of inherently chaotic and complex systems such as Gaia.

James Lovelock and the Formulation of the Gaia Hypothesis

The Gaia hypothesis was first proposed by James Lovelock in 1969. Lovelock is a British scientist and inventor with a Ph.D. in Medicine from the London School of Hygiene and Tropical Medicine. Although Lovelock has been a visiting scientist at many institutions including Harvard, Yale, the Jet Propulsion Laboratories in Pasadena, California, and NASA, Lovelock is not formally associated with any major university or research facility. Lovelock, instead, practices science independently, using revenue earned from his inventions to fund his research. As an inventor, Lovelock is most well known for the development of the Electron Capture Detector (ECD), a device designed to detect trace amounts of chemical compounds in the atmosphere. Using this device, Lovelock was the first to confirm the accumulation of chlorofluorocarbons (CFCs) in the atmosphere. This research provided the first hard data leading to the ban of CFCs in order to protect the Earth's stratospheric ozone layer.

In spring of 1961, the National Aeronautics and Space Administration (NASA) invited Lovelock to work as a member of a team developing lunar soil analysis methods. Soon after he began with NASA, Lovelock was transferred to work with the Voyager mission, designing life detection instrumentation for other planets, namely Mars.

When faced with the task of detecting life on Mars, Lovelock was dissatisfied with the efforts of his fellow scientists who envisioned Martian life detection techniques which emulated those effective on Earth. Their ideas included automated microbiological laboratories to sample the Martian soil for its suitability to support fungi, bacteria, and other microorganisms, and devices to detect life's byproducts such as proteins and amino acids (Lovelock, A New Look 2). Lovelock questioned these methods, wondering "How can we be sure the Martian way of life, if any, will reveal itself to tests based on Earth's lifestyle...to say nothing of more difficult questions such as 'What is life, and how should it be recognized'" (A New Look 2).

When asked how he would detect life on Mars, Lovelock first considered the ideas that eventually led to his formulation of the Gaia hypothesis. He proposed to search for a decrease in entropy on Mars, since entropy reduction is a seemingly universal characteristic of life. Realizing the inherent difficulties in testing the properties of entropy reduction of possible life on distant planets, Lovelock reconsidered the problem.

After considering the notion of life and entropy reduction for some time, Lovelock envisioned a new method of life detection. Assuming that life requires the use of fluid media (the oceans and or the atmosphere) as 'conveyor belts' for raw materials and waste products, Lovelock deduced that some activities associated with the entropy reduction of living systems would affect and alter the composition of the 'conveyor-belt regions'. Thus, the atmosphere of a life-bearing planet would noticeably differ from the atmosphere of a dead planet. Since Mars currently has no oceans, the presence of life would require the utilization of the atmosphere to convey raw materials. Thus, Mars would be the ideal planet for life detection experiments based on its atmospheric composition (Lovelock, A New Look 6).

As Lovelock formulated his ideas, philosopher Dian Hitchcock was employed by NASA to evaluate the logical consistency of the Martian life detection experiments. Hitchcock fancied Lovelock's idea of life detection by means of atmospheric analysis. Lovelock and Hitchcock consequently explored the possibility of life detection experiments on distant planets from Earth using atmospheric analysis, and they co-authored two papers on the subject (Lovelock and Hitchcock 1967, Hitchcock and Lovelock, 1967).

Lovelock and Hitchcock noticed the atmospheric composition of the Earth differs greatly from the atmospheric composition of other planets. The Earth's atmospheric composition is in a constant state of disequilibrium, as it fosters the simultaneous existence of multiple incompatible gases. For example, the Earth's atmosphere simultaneously contains methane and oxygen, two gases that react chemically to produce carbon dioxide and water vapor.

The reaction rate between methane and oxygen mandates that to maintain the Earth's atmospheric composition of methane, over 1 billion tons of methane must be introduced into our atmosphere every year. Furthermore, there must be a constant source of oxygen to replace what was depleted during the oxidation of methane. This process requires the production of at least twice as much oxygen as methane. Lovelock speculates that the chances of randomly maintaining the correct proportions of these two incompatible gases at a constant level by abiological means is improbable by at least one hundred orders of magnitude (Lovelock, A New Look 7).

These initial observations and deductions first led Lovelock to formulate the Gaia hypothesis in the late 1960's. At this time the conventional wisdom regarded the Earth's atmospheric chemistry as the end result of volcanic outgassing and subsequent abiological chemical reactions. The Gaia hypothesis, in contrast, states that the Earth's atmospheric chemistry was homeostatically regulated by the biosphere, creating conditions that are self-sustaining and comfortable for life.

Today, nearly thirty years after its first proposal, the Gaia hypothesis, now the Gaia Theory, has been expanded and refined to explain not only the self-regulation of the Earth's atmospheric chemistry, but also the regulation of the biogeochemistry of the entire Earth. Since his first writings with Dian Hitchcock in 1967, James Lovelock, Lynn Margulis, an eminent microbiologist from the University of Massachusetts at Amherst, and numerous other proponents and critics of the Gaia hypothesis have authored dozens of books and journal articles concerning the scientific merits, faults, and implications of the Gaia hypothesis.

Evidence for Gaia

Lovelock maintains that during the Archean period (4.5 – 2.5 billion years ago), life acquired the capacity to regulate the Earth's surface biogeochemistry, thereby maintaining the Earth's surface conditions at levels favorable for life. To explore the feasibility of a testable Gaia hypothesis, it is necessary to examine the Gaian regulatory mechanisms supposedly responsible for creating these conditions. The following section briefly summarizes Lovelock's ideas concerning the origins of Gaia and outlines some Gaian regulatory mechanisms. Since the Gaia incorporates many regulatory systems, for simplicity sake, the following section simply examines Gaian atmospheric regulation.

Lovelock speculates that at the beginning of the Archean period, the atmospheric composition of the Earth was similar to that of Mars and Venus. This composition was primarily composed of

carbon dioxide, containing trace amounts of hydrogen and hydrogen sulfide, unknown quantities of nitrogen, and presumably no methane or oxygen. This early atmosphere maintained a state of thermodynamic equilibrium and was controlled by abiological chemical reactions. The Earth's surface presumably contained organic chemical components such as amino acids, the subunits of proteins, the subunits of polysaccharides, nucleosides, and other building blocks for life. The Earth contained liquid water and therefore ranged in temperature from 0 and 50 degrees Celsius. In addition, the Archean solar luminosity, or output of the sun, was 25% less than that of today (Lovelock *Ages of Gaia* 65-69).

Around 3.6 billion years ago, the first life on Earth evolved. This first Archean life consisted of two major types of bacterium: photosynthesizers and consumers. The photosynthesizers converted carbon dioxide into organic matter and oxygen. Small amounts of oxygen produced by these photosynthesizers quickly reduced by oxidizing chemicals such as iron and sulfur. The consumers, or decomposers, converted organic matter back into carbon dioxide and methane. As these simple bacteria colonized the Archean Earth and acquired the capacity to control their environment, Gaia first emerged.

According to Lovelock, in the anoxic Archean Earth, the simple balance between the photosynthesizers and consumers stabilized the planetary ecosystem. The growth of photosynthesizers cooled the Earth by consuming the 'greenhouse gas' carbon dioxide. The growth of the photosynthesizers, conversely, warmed the Earth by renewing carbon dioxide and methane into the atmosphere (Lovelock, *Ages of Gaia* 80). This balance required no foresight or planning and evolved naturally from simple evolutionary processes.

By the end of the Archean period, the atmospheric composition of oxygen greatly increased in an event known as the oxygen crises. This increase in oxygen resulted from both a decreasing supply of oxygen removers (iron and sulfur) from declining plate tectonic activity, and an increase in the amount of photosynthesizers producing oxygen (Lovelock, *Healing Gaia* 112).

Little is known about the atmospheric composition of the Proterozoic period (2.5 - .7 billion years ago) which immediately followed the Archean. Consequently, most Gaian arguments of atmospheric regulation describe the Phanerozoic period (570 – 0.7 million years ago). Lovelock cites numerous mechanisms of Gaian atmospheric regulation during the Phanerozoic period. His mechanisms describe the consistency of Phanerozoic atmospheric compositions of oxygen, carbon dioxide, methane, carbon, and nitrogen. In *Healing Gaia*, Lovelock cites the following Gaian mechanisms to support his claims of Gaian homeostatic regulation:

Regarding carbon dioxide regulation:

Ø Carbon dioxide cycles through the Earth from its source, volcanic outgassing, to its final sink, calcium carbonate (limestone). The atmospheric concentrations of carbon dioxide (currently 0.03 percent) depend on the balance between the rates at which it leaks in and is pumped out.

Ø As plants grow they break up surface rocks and draw carbon dioxide in the soil. There, carbon dioxide (dissolved in rainwater) reacts with basaltic rocks to form calcium bicarbonate, which washes to the oceans and is used by microscopic marine life to form shells. The ocean algae also pump down carbon dioxide from the air. When the algae die, their shells form chalk deposits on the ocean floor.

Regarding oxygen, methane, and carbon regulation:

Ø Plants photosynthesize and convert carbon dioxide and water into oxygen and organic matter of composition approximately CH_2O

Ø Animals and microorganisms consume most of this CH_2O , using up the oxygen made by the plants and returning carbon dioxide to the air.

Ø Approximately one percent of the organic matter is buried in the soil, where methanogenes convert it to carbon dioxide and methane.

Ø The methane escapes into the air and reacts with the remaining one per cent of oxygen to form carbon dioxide and water.

Ø A small proportion (about 0.1 per cent) of the buried organic matter escapes digestion by the methanogenes. The carbon is buried deep in the sedimentary rocks and the equivalent oxygen is left free.

Ø It is thus the small amount of buried carbon that accounts for the oxygen in the air. All remaining oxygen made by the plants is consumed by animals and microorganisms, by reaction with the methane and with the rocks and gases during volcanic activity and weathering.

Regarding nitrogen regulation:

Ø Lightning flashes combine nitrogen with oxygen; the oxides react with water and hydroxyl radicals to form nitric acid, which falls in rain and neutralizes to form nitrates.

Ø Without life, nitrates would lock up nitrogen as dissolved nitrate ions in the oceans. Life, however, reverses the flow as biofixation of nitrogen (the capture and conversion of nitrogen to biological compounds by nitrogen-fixing microorganisms) ensures a constant supply of useable "fixed" nitrogen for land and sea biota.

Ø Other microorganisms, the de-nitrifying bacteria, work on the detritus of life and return nitrogen to the atmosphere.

Regarding sulfur regulation:

Ø When marine algae are eaten, sulfur betadine (electrically neutral salts found in algae) decomposes to yield an acrylic acid ion and dimethyl sulfide.

Ø Onshore breezes carry the dimethyl sulfide inland where atmospheric gases decompose it into a non-sea salt sulfate aerosol comprised of sulfate and methane sulfonate.

Ø In this form sulfur is deposited on the ground, thereby enhancing the growth of land plants and increasing the rate of rock weathering (Lovelock Healing Gaia 108-119).

The Gaia hypothesis addresses a variety of biogeochemical regulatory mechanisms. Lovelock presents the preceding evidence to demonstrate Gaia's properties of atmospheric regulation. According to Lovelock, these atmospheric and biological relationships evolved as part of Gaia and are the mechanisms responsible for keeping the atmospheric composition at levels sustainable for life. These relationships arise automatically and require no foresight or planning.

Hypothesis to Theory: The Evolution of Gaia as a Concept

The Gaia hypothesis has undergone extensive revision since its first proposal in 1969 at a scientific conference in Princeton, New Jersey. Throughout its history, the information collectively grouped under "the Gaia hypothesis" has encompassed many different ideas and been explained by many forms of "evidence." Many Gaian critics cite the ambiguity of "the Gaia hypothesis;" Gaian criticisms, therefore, depend upon the reference with which the critics refer. In order to determine the feasibility of a testable Gaia hypothesis, it is necessary to chronicle and understand Gaia's developmental history through time. The following section explores the evolution and various definitions of the Gaia hypothesis as stated by Lovelock.

The concept that the Earth's atmosphere, biosphere, soils and oceans are homeostatically regulated by life on Earth was first published as the Gaia hypothesis in 1972 by James Lovelock (Atmospheric Dimethyl Sulphide 568-569). Lovelock initially termed this concept "Biocybernetic Universal System Tendency/Homeostasis" but changed the name to "the Gaia hypothesis" at the recommendation of author William Golding. The name "Gaia" comes from the name of the Greek Earth goddess also known as "Ge", from which the sciences of Geology and Geography derive their name (Lovelock, A New Look 10).

Lovelock's ideas concerning the relationship between the evolution of life and Earth were first published as "Gaia" in a 1972 article in *Atmospheric Environment*. In this article, Lovelock stated "The purpose of this letter is to suggest that life at an early stage of its evolution acquired the capacity to control the global environment to suit its needs and that this capacity has persisted and is still in active use" (579).

To justify this statement, Lovelock offered the following information as 'evidence' for Gaia's regulatory abilities.

Ø During the past 3+ billion years that life has existed on Earth, profound changes have altered the Earth's physical and chemical environment. The Earth's atmosphere has changed from reducing to oxidizing conditions, the output of the sun has increased dramatically, and the pH has changed substantially, yet the geologic record and persistent fossil record of life illustrates that the planet's surface conditions have not fluctuated substantially from present levels.

Ø The contemporary atmospheric compositions of the Earth differ greatly from those of Mars and Venus. The Martian and Venusian atmospheres are in a state of chemical equilibrium; the Earth's atmosphere, in contrast, is in a state of chemical disequilibrium. Lovelock cites the simultaneous presence of methane and oxygen (two gases that react violently with each other producing carbon dioxide and water) as well as the anomalous presence of atmospheric nitrogen in the Earth's atmosphere (the stable form of nitrogen in our oxidizing atmosphere is the nitrate ion found in the oceans) to illustrate the Earth's bizarre atmospheric chemistry.

Ø If life on Earth were to cease, the atmospheric quantities of oxygen and nitrogen would decrease in concentration until they were merely trace elements. This lifeless Earth would have an atmospheric composition of water vapor, carbon dioxide and noble gases. The atmospheric composition of the Earth would be a reasonable interpolation between those of Mars and Venus, depending upon its position in the solar system (Lovelock, (Atmospheric Dimethyl Sulphide 579). Since the Earth's atmospheric conditions are ideal for life and have remained constant for the past 300 million years, Lovelock regards the preceding facts as evidence for the regulatory properties of Gaia.

Lovelock also illustrates the following scenarios as evidence for Gaia. An increase in the Earth's atmospheric oxygen concentration to 25 per cent (from the present concentration of 21 per cent) would increase the probability of fires so that even the tropical rain forests would be at risk of combustion. A change in atmospheric pressure of 10 per cent, assuming that the composition remained constant, would cause a change of 4 degrees Celsius in the mean surface temperature; enough to provide unfavorable atmospheric conditions for life on Earth. Lovelock assumes that the probability of the biosphere interacting with the environment to regulate these delicate conditions is greater than the probability of these conditions arising randomly; therefore, Gaia regulates these conditions.

Although Lovelock cites all of the previously listed information as evidence for the existence of Gaia, he states that "As yet there exists no formal physical statement of life from which an exclusive test could be designed to prove the presence of 'Gaia' as a living entity" (579). Lovelock continues, saying:

At present most biologists can be convinced that a creature is alive by arguments drawn from phenomenological evidence. The persistent ability to maintain a constant temperature and a compatible chemical composition in an environment which is changing or is perturbed if shown by a biological system would usually be accepted as evidence that it was alive." (579).

Another of Lovelock's 1972 publications entitled "Atmospheric Dimethyl Sulfide and the Natural Sulfur Cycle" reports the first scientific findings discovered as a result of the Gaia hypothesis. This article addresses the well-known geochemical problem known as the sulfur gap. Essentially, the amount of sulfur that washes off the land into the oceans cannot be accounted for by all of the known sources of sulfur on land.

Conventional wisdom regarding this issue assumed that hydrogen sulfide was emitted from the oceans, incorporated into the atmosphere, and replaced to the land by precipitation, thus balancing the sulfur budget. Lovelock doubted this hypothesis based on the premise that (1) the atmospheric quantities of hydrogen sulfide were not substantial enough to balance the sulfur budget, (2) the oceanic surface waters are too oxidizing to permit the necessary accumulation of hydrogen sulfide, and (3) hydrogen sulfide smells like rotten eggs and the odor of the sea is reminiscent of dimethyl sulfide.

From the previous research of Frederick Challenger, Lovelock knew that marine organisms produced dimethyl sulfide to rid themselves of unwanted substances (Challenger 429). Since sulfur is the staple of existence for numerous land living organisms, Lovelock hypothesized that Earth's biota balanced the sulfur budget as a consequence of Gaian natural selection. With this Gaian mechanism in mind, he set out on a ship, the RSS Shackleton, to determine the atmospheric and oceanic quantities of dimethyl sulfide. In contrast to the conventional wisdom, he discovered that

dimethyl sulfide was ubiquitous in the atmosphere and available in sufficient quantities to potentially balance the sulfur budget. Since organisms were producing the dimethyl sulfide and therefore balancing the sulfur budget, Lovelock regards this process as possible evidence for Gaia (579).

In 1974, Lovelock and Margulis published two papers entitled "Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis", and "Homeostatic Tendencies of the Earth's Atmosphere". These two papers laid the theoretical framework for the Gaia hypothesis by addressing Gaia's philosophical foundations and offering thermodynamic and biogeochemical evidence for Gaia.

At this time, Lovelock and Margulis defined the Gaia hypothesis as:

The hypothesis that the total ensemble of living organisms which constitute the biosphere can act as a single entity to regulate chemical composition, surface pH and possibly also climate. The notion of the biosphere as an active adaptive control system able to maintain the Earth in homeostasis we are calling the 'Gaia' hypothesis...Hence forward the word Gaia will be used to describe the biosphere and all of those parts of the Earth with which it actively interacts to form the hypothetical new entity with properties that could not be predicted from the sum of its parts (Lovelock and Margulis "Atmospheric Homeostasis" 3).

In 1979, Lovelock published his first book on the Gaia Hypothesis entitled *Gaia: A New Look at Life on Earth*. This book, though relatively short in length (merely 150 pages), interested both scientists and laypersons. In this book Lovelock describes the Gaia in a bare bones scientific approach. "I tried to write this book so that a dictionary is the only aid needed" (vii). Because of Lovelock's simplistic writing style and the controversial nature of the topic, *A New Look at Life on Earth* received considerable critical review from the scientific establishment. Although the Gaia Hypothesis has undergone extensive revision since its first introduction, many critics look no farther than the arguments presented in *A New Look at Life on Earth* as the basis for their criticisms.

In *A New Look at Life on Earth*, Lovelock describes Gaia as:

A complex entity involving the earth's biosphere, atmosphere, oceans, and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life on this planet. The maintenance of relatively constant conditions by active control may be conveniently described by the term 'homeostasis' (11).

Of the atmosphere, Lovelock explains "The atmosphere is not merely a biological product, but more probably a biological construction: not living, but like the cat's fur, a bird's feathers, or the paper of a wasp's nest, an extension of a living system designed to maintain a chosen environment" (10).

Lovelock also stated:

I have frequently used the word Gaia as a shorthand for the hypothesis itself, namely that the biosphere is a self-regulating entity with the capacity to keep our planet healthy by controlling the chemical and physical environment. Occasionally it has been difficult, without extensive circumlocution, to avoid talking of Gaia as if she were known to be sentient. This is meant no more seriously than is the appellation 'she' when given to a ship by those who sail her, as a recognition that even pieces of wood and metal when specifically designed and assembled may achieve a composite identity with its own characteristic signature, as distinct from being the mere sum of its parts. (xii).

In *A New Look at Life on Earth*, Lovelock lists numerous examples of Gaian regulatory mechanisms. These mechanisms include the relationships between methane, oxygen, carbon dioxide, and nitrogen in the atmosphere, the chemistry and salinity of the oceans, numerous examples of positive and negative feedback, and the possible relationship between Gaia and plate

tectonics. This book also describes, in detail, the evolution and activities of Gaia throughout time, from the Archean to today.

It is important to note that in 1979 Lovelock viewed Gaia as an untestable hypothesis, stating: "Like a religious belief, it (Gaia) is scientifically untestable and therefore incapable in its own context of further rationalization"(ix). He also stated "If we discover sufficient evidence of planet-sized control systems using the active processes of plants and animals as component parts and with the capacity to regulate the climate, the chemical composition, and the topography of the Earth, we can substantiate our hypothesis and formulate a theory (ix)."

In 1983, Lovelock and Andrew Watson first published on the concept of Daisyworld. In "Biological homeostasis of the global environment: the parable of Daisyworld," Lovelock and Watson introduced Daisyworld models, derivative-equation based models created to dispel criticisms that the Gaia hypothesis was teleological.

Daisyworld models depict a hypothetical planet inhabited solely by one species of multicolored daisies. Daisyworld's temperature results from the relative reflection or absorption of light by the daisies. For example, white daisies reflect light and heat, thereby keeping themselves and their local environment cool. Dark daisies absorb light and heat, thereby keeping themselves and their local environment warm. Through simple natural selection processes, the multicolored daisies maintain a consistent planetary temperature despite the increased output of a growing sun. According to Lovelock and Watson, Daisyworld regulates its surface temperature automatically, requiring no foresight or planning.

In 1986 Lovelock introduced the concept of "geophysiology," the science of Gaia ("Geophysiology: A New Look"). Lovelock describes geophysiology as a "systems approach to the earth sciences...the essential theoretical basis for the putative profession of planetary medicine" (392). Lovelock states that geophysiological models are more powerful than biogeochemical models because they can adjust their operating points as a system evolves instead of having an operating point fixed by the chemical and physical constraints of the system (393). It is in this paper in 1986 that Lovelock first began referring to his ideas as the Gaia theory (as opposed to the Gaia hypothesis).

In 1988, Lovelock published his second book on the Gaia Hypothesis entitled *The Ages of Gaia*. In *The Ages of Gaia*, Lovelock re-examines many examples of Gaian evidence under the framework of Geophysiology. He describes Gaia as "...a new theory of evolution, one that does not deny Darwin's great vision but adds to it by observing that the evolution of the species of organisms is not independent of the evolution of their material environment. Indeed the species and their environment are tightly coupled and evolve as a single system...the largest living organism, Gaia" (xv).

Lovelock also states:

The name of the living planet, Gaia, is not a synonym for the biosphere. The biosphere is defined as that part of the earth where living things normally exist. Still less is Gaia the same as the biota, which is simply the collection of all individual living organisms. The biota and the biosphere taken together form part but not all of Gaia. Just as the shell is part of a snail, so the rocks, the air, and the oceans are part of Gaia. Gaia, as we shall see, has continuity with the past back to the origins of life, and extends into the future as long as life

persists. Gaia, as a total planetary being, has properties that are not necessarily discernable by just knowing individual species or populations of organisms living together (19).

In 1990 Lovelock first stated that the Gaia theory was testable. In his article "Hands up for the Gaia hypothesis", Lovelock describes numerous predictions, tests, and resulting conclusions spawned from the study of Gaia. In this article, Lovelock states:

In many ways Gaia, like an invention, is difficult to describe. The nearest I can reach is to call Gaia the theory of an evolving system – a system made from the living organisms of the Earth, and from their material environment, the two parts being tightly coupled and indivisible. This evolutionary theory views the self-regulation of climate and chemical composition as emergent properties of the system. The emergence is entirely automatic; no teleology is invoked (102).

He also questions Gaia's unpopularity among scientists, citing as the obvious reason "the natural inertia of science which means that large-scale theories are digested only slowly. It took forty years for another Earth theory, plate tectonics, to be accepted" (102).

Lovelock's most recent book, *Healing Gaia*, was published in 1991. This book presents Gaia in a strict geophysiological manner. In the preface to *Healing Gaia*, Lovelock writes that he explores Earth "through the eyes of an imaginary planetary physician" (6). In *Healing Gaia*, Lovelock clearly outlines the context under which he defines a living Earth. Lovelock states:

In this book I often describe the planetary ecosystem, Gaia, as alive because it behaves like a living organism to the extent that temperature and chemical composition are actively kept constant in the face of perturbations. When I do I am well aware that the term itself is metaphorical and that the Earth is not alive in the same way as you or me, or even as a bacterium. At the same time I insist that Gaia theory itself is proper science and no mere metaphor. My use of the term "alive" is like that of an engineer who calls a mechanical system alive to distinguish its behavior when switched on from that when switched off, or dead. Engines on whose proper function many lives depend have health monitors; devices that ensure signs of failure are detected early enough for a cure, not a tragedy (6).

In 1995, Lovelock published "New Statements on the Gaia Theory." In this article Lovelock defines Gaia as a "planet-sized ecosystem...something that emerged when organisms and their material environment evolved together" (296). He also states that "Gaia is...a straightforward scientific theory about the Earth and the organisms that inhabit it. A theory that views the Earth as if it were alive. As if it were able to regulate the climate and chemistry to keep it comfortable for life (298). Lovelock makes the remark in "New Statements on the Gaia Theory" that "Gaia theory is testable and has a proper mathematical basis in a set of closely coupled differential equations" (298).

In this article, Lovelock presents a list of predictions from Gaia Theory that has led to "significant planetary discoveries" (299). Table 1 paraphrases these predictions.

Table 1.

Some Predictions from Gaia theory that have led to significant planetary discoveries

Some Predictions from Gaia theory that have led to significant planetary discoveries		
Year	Prediction	Test, result, and year
1968	That Mars was lifeless (from	Viking Mission, 1977. Strong

	atmospheric evidence).	Confirmation.
1971	That organisms would make compounds that can transfer essential elements from the oceans to the land surfaces.	Dimethylsulfide and methyl iodide both found, 1973.
1973	That oxygen has stayed at 21 + or -5% of total atmospheric gases for the last 200 million years.	Still under test
1981	That climate may be regulated by the control of carbon dioxide concentration through biologically enhanced rock weathering.	Microorganisms greatly increase rock weathering, 1989.
1987	That climate regulation via cloud density control is linked to algal sulfur emissions.	Still under test. Evidence that oceanic cloud cover geographically matches algal distribution, 1990.
1988	That Archean atmospheric chemistry was dominated by methane	Still under test.

Criticisms of Gaia

There are 3 major criticisms of Gaia. In order to fully understand the implications of Gaia, it is necessary to examine these criticisms and Lovelock's subsequent responses to them. The first criticism states that Gaia is unnecessary to explain the history of the Earth. This criticism is an extension of the conventional wisdom that regards the Earth's atmospheric chemistry as the end result of volcanic outgassing and subsequent abiological chemical reactions. The second criticism states that Gaia is teleological, or would require foresight and planning to regulate the biogeochemistry of the Earth. The third criticism states that Gaia is untestable. The first major criticism, that Gaia is unnecessary to explain the history of the Earth, is predominately argued by Heinrich Holland, a geochemist at Harvard University. In Holland's 1984 book, *The Geochemical Evolution of the Atmosphere and the Oceans*, Holland states:

I find the hypothesis intriguing and charming, but ultimately unsatisfactory. The geologic record seems much more in accord with the view that organisms that are better able to compete have come to dominate, and that the Earth's near surface environment and processes have accommodated themselves to changes wrought by biological evolution. Many of these changes have been fatal or near fatal to parts of the contemporary biota. We live on an Earth that is the best of all worlds but only for those who have adapted to it (539).

Lovelock responded to Holland's criticism saying:

I do not think that able scientists, such as Holland, would have rejected Gaia with such feeble criticism were it not for their faith in conventional wisdom. Had they taken thought they would have noticed that the world is massively modified by living organisms. The air, the oceans, and the rocks are all either made by living organisms, or else changed by their presence. Organisms do not just

adapt to a dead world by physics and chemistry alone. They live with a world that is the breath and bones of their ancestors and that they are now sustaining (539).

The second major criticism, that Gaia is teleological, is predominantly argued by Richard Dawkins and Ford Doolittle. In his article, "Is Nature Really Motherly", Doolittle states (referring to Gaia: A New Look at Life on Earth):

The good thing about this engaging little book by Jim Lovelock is that reading it gives one a warm, comfortable feeling about Nature and man's place in it. The bad thing is that this feeling is based on a view of natural selection – that force which alone is responsible for the existence and characteristics of the biosphere – which is unquestionably false (60).

Dawns states "I admit that I find myself involuntarily impressed with some of the facts that Lovelock has unearthed, like the constancy of oxygen levels in the atmosphere and so forth. He doesn't have any real explanations, but I do thank him for bringing it all up" (Joseph 57).

Doolittle also states (referring to evidence of Gaia):

I do not doubt that some of the feedback loops which Lovelock claims exist do exist, but I do doubt that they were created by natural selection, or that they were anything but accidental. Methane production may now balance oxygen production nicely, but it is not written into the genetic codes of either oxygen producers or methane producers that this should be so, and either could easily get out of hand (61).

Concerning teleology, Doolittle writes "Gaia, as a cybernetic system, must have mechanisms for sensing when global physical and chemical parameters deviate from the optimum, and mechanisms for initiating compensatory processes which will return those parameters to acceptable values" (59).

After defining the above principles of a cybernetic system, Doolittle analyzes numerous Gaian regulatory mechanisms including: temperature regulation, atmospheric regulation, and oceanic salinity regulation, then questions how each mechanism could arise naturally. Illustrating Doolittle's viewpoint concerning the teleological nature of Gaia, he responds (with respect to Gaian salinity regulation) "I guess it is possible, but Lovelock is silent on the question of how Gaia knows her oceans are becoming too salty, how in response she instructs reef builders to construct...evaporation lagoons and why...these intrepid creatures obey her instruction" (60).

To these criticisms, Lovelock responded:

The critics who made this...criticism were not concerned with the practical evidence that the Earth has kept a climate favorable for life in spite of major perturbations, or that the atmosphere is now stable in its composition in spite of the chemical incompatibility of its component gases. They were criticizing from the certainty of their knowledge of biology. I think their criticism was dogmatic...it is easy to answer (45).

Lovelock's answer to the teleological criticisms of Gaia manifests itself in the derivative equation-based Daisyworld models. Lovelock and Andrew Watson created Daisyworld in 1983 to demonstrate that Gaian regulatory mechanisms require no foresight or planning. Through the use of a model depicting a world inhabited strictly by multi-colored daisies, Lovelock argues that Gaia is non-deterministic, and not teleological.

The third major criticism, that Gaia is untestable, is predominantly argued by James Kirchner, a theoretical ecologist from Berkeley. Kirchner first expressed his criticisms in 1988 at the American Geophysical Union's (AGU) Chapman Conference. The Chapman Conference is a biannual symposium dedicated to a specific topic or branch of earth science. In 1988, the entire week-long conference was devoted to the study of the Gaia Hypothesis.

Of all the critics present at the 1988 AGU Chapman Conference, James Kirchner stood out as the most noteworthy. Kirchner's criticisms challenged the validity of Gaia as a hypothesis and means for scientific inquiry. In his arguments, Kirchner divided Gaia into numerous hypotheses and analyzed each for its validity and scientific testability. By illustrating the vast ambiguities of Gaia, Kirchner has become one of Lovelock's most valued critics.

In his 1989 AGU publication "The Gaia hypothesis: Can it be Tested?," Kirchner pursues the testability of the Gaia hypothesis. He illustrates that much of the confusion resulting from Gaia stems from that fact that numerous distinct hypotheses have been proposed under the single name "the Gaia hypothesis." To clarify the resulting confusion, Kirchner divides Gaia into four distinct statements or hypotheses. These distinct hypotheses are: Coevolutionary Gaia, Homeostatic Gaia, Geophysiological Gaia, and Optimizing Gaia. Using these four hypotheses, Kirchner analyzes each for its testability and scientific validity.

Kirchner's "Coevolutionary Gaia" is the notion that life on Earth influences the environment and that, in turn, the environment influences the evolution of life on Earth by Darwinian processes of evolution (224). Kirchner uses a quote from Lovelock and Watson (Lovelock and Watson 284) to illustrate this "hypothesis:"

The biota has effected profound changes on the environment of the surface of the earth. At the same time, that environment has imposed constraints on the biota, so that life and the environment may be considered as two parts of a coupled system...perturbations of one will affect the other and this may in turn feed back on the original change. The feedback may tend to either enhance or diminish the initial perturbation, depending on whether its sign is positive or negative (224).

Kirchner's Homeostatic Gaia is the notion that life on earth influences the environment in a stabilizing manner; the major linkages between life and the environment being negative feedback loops (224). To illustrate this hypothesis, Kirchner quoted Lovelock and Margulis (Atmospheric Homeostasis 2-9):

From the fossil record it can be deduced that stable optimal conditions for the biosphere have prevailed for thousands of millions of years. We believe that these properties of the terrestrial atmosphere are best interpreted as evidence of homeostasis on a planetary scale maintained by life on the surface (224).

Kirchner's Geophysiological Gaia is the notion that the biosphere can be compared with a single immense organism. This organism may exhibit homeostatic and unstable behavior like any other organism (224). Kirchner quoted Lovelock to illustrate this idea "Gaia theory suggests that we inhabit and are part of a quasi-living entity that has the capacity for global homeostasis" (Geophysiology 11-23).

Kirchner's Optimizing Gaia is the notion that earth's biota manipulates its physical environment in ways that create favorable conditions for itself (225). To illustrate Optimizing Gaia, Kirchner quoted Lovelock and Margulis:

We argue that it is unlikely that chance alone accounts for the fact that temperature, pH and the presence of compounds of nutrient elements have been, for immense periods of time, just those optimal for surface life. Rather we present the "Gaia hypothesis" the idea that energy is expended by the biota to actively maintain these optima conditions (Homeostatic Tendencies 93) Kirchner also quoted Lovelock "The most important property of Gaia is the tendency to optimize conditions for all terrestrial life" (A New Look 157).

After presenting these four distinct Gaia hypotheses, Kirchner dismisses each as untestable and scientifically invaluable. In formulating his arguments, Kirchner defines the following criteria for testability:

Ø Ill-defined hypotheses are untestable because they can be endlessly reinterpreted to fit almost any data. For the same reason, they cannot contain specific empirical information for they exclude no possibilities.

Ø Tautological hypotheses are untestable because they are true by definition; their conclusions are entirely contained within their premises.

Ø Unfalsifiable hypotheses are untestable because they fail to make falsifying predictions. Confirmation of these hypotheses does not exclude data because unfalsifiable hypotheses contain no empirical content and no excluding data (data inconsistent with the hypothesis) (226).

Of Coevolutionary Gaia, Kirchner argues that Lovelock simply restates the obvious and well-documented fact that life influences the environment. Kirchner cites numerous examples, dating as far back as 1844 that illustrate the premise that biological processes alter the physical environment. Kirchner states "An observation that is so widely recognized lacks the tentative character of a true hypothesis" (227).

In criticizing Homeostatic Gaia, Kirchner divides the hypothesis into two separate forms: weak and strong. The weak form of Homeostatic Gaia states that "the dominant interactions between the biotic and abiotic worlds are stabilizing" (227). The strong form states that "these dominant interactions make the Earth's physical environment significantly more stable than it would have been without life" (227).

Kirchner states that climatic homeostasis alone is not evidence for Gaia because it is impossible to determine whether the climate is stable as a result of those biological processes or regardless of them. He criticizes the proposed feedback mechanisms of Gaia because it unclear whether these mechanisms are stabilizing or destabilizing. Without the ability to determine which mechanisms are destabilizing, or tend to weaken homeostasis, Kirchner argues it is impossible to understand an organism's homeostatic regulatory function.

Kirchner criticizes that Homeostatic Gaia is unfalsifiable. To support this claim, he points to Lovelock's explanation of the oxygen crisis, the switch from oxidizing to reducing conditions in the Precambrian atmosphere. Lovelock cites the fact that terrestrial life survived the oxygen crises as evidence for Gaia's ability to adapt to changing conditions. In response, Kirchner states: If the most destabilizing biotic event in Earth's history can be construed as evidence for Gaia, and the relative stability since then can also be cited as evidence for Gaia, one wonders what conceivable

events could not be interpreted as supporting the Gaia hypothesis. If there are none, Gaia cannot be tested against the geologic record...If Gaia stabilizes and Gaia destabilizes...is there any possible behavior which is not Gaian? (228).

Concerning Geophysiological Gaia, Kirchner states that the use of Gaia as an "Earth-as-organism" (231) metaphor and applying the same to terminology to both Gaia and recognized biological organisms is both unwise and potentially misleading. He states that although some may find it useful to view the Earth as if it were an organism, viewing the Earth as an organism itself "is neither scientifically meaningful nor scientifically answerable"(231). Kirchner argues that falsification of such a hypothesis is futile, and thus devoid of meaning.

Kirchner regards Optimizing Gaia as the most speculative version of Gaia, stating that it is both ill defined and unfalsifiable. He states that unless there exists a definition of what constitutes optimal conditions, any given function can be argued as optimal for at least some sets of conditions. Kirchner also asks the question "What could possibly be optimal for the whole biosphere?" (232).

With these criticisms, Kirchner dismisses Gaia (both as a whole and as four distinct hypotheses) as unscientific, untestable, and potentially misleading. In his conclusions, Kirchner remarks:

Ø "Attempts to test this metaphor (Gaia) as a scientific proposition will be, in my opinion, ultimately futile" (233).

Ø "Gaia is crippled by its great generality" (233).

Ø "Gaia may be a grand vision, but it is not the kind of vision that can be scientifically validated" (234).

Lovelock's Response to Kirchner

When Kirchner presented these arguments at the 1988 Chapman Conference, Lovelock's response was surprising to many. After a 45 minute attack on the Gaia hypothesis and its principles, Lovelock mounted the stage and muttered a few brief remarks concerning the discoveries that have been made as a result of Gaia and thanked Kirchner for his stimulating analysis.

It is important to note that although Kirchner's arguments were very scholarly and logically consistent, much of the information they attacked was from the 1970's and early 1980's. As illustrated earlier in this paper, the concepts proposed as "Gaia" have greatly evolved through time and many of Kirchner's criticisms of older material do not apply to Lovelock's later works. When asked about his response to Kirchner at the Chapman Conference, Lovelock stated:

Young Kirchner's attack was rather invigorating. I saw no point in making the obvious logical arguments about his attacking old material, because those who cared enough about the subject matter knew that already, or would come to realize it over the course of the meeting or thereafter. Or they might remember that they had known how extensively Gaia had been revised, and that they had forgotten it in the heat of the debate. To counterattack wouldn't have much point, would it? Much better to wave your hat and get out of the way (Joseph 89).

As suggested by Lawrence Joseph in his book *Gaia – The Growth of an Idea*, "Kirchner's attack on Gaia was ultimately less concerned with the theory's logical viability than with the intellectual integrity of its formulator, which is one reason why Lovelock's graciousness was so effective in response" (89). It is interesting to note that since the conference, Lovelock has been a contributing

editor for Kirchner's anti-Gaian articles, and that in the credits to his 1991 paper entitled "the Gaia Hypotheses: Are they testable? Are They Useful?" Kirchner states "I particularly want to acknowledge Jim Lovelock's gracious response to this paper at the conference. I wish that all scientific debates could be as free of acrimony" (46).

Lovelock, however, has not remained silent to Kirchner's criticisms. In his 1989 paper, Kirchner criticized the notion of Gaia as a living organism in more than one reference. This view of Gaia, although implied in some of Lovelock's earlier writings, no longer applied to his definition of Gaia by the late 1980's. To this, Lovelock responded "Our thoughts have evolved over the last 20 years. In the early stages one tended to speak poetically. I hope that we are now speaking more scientifically" (Kerr 393). Although by 1988, Lovelock was not claiming that the Earth was an immense organism, he called Kirchner's criticisms of Homeostatic (strong) Gaia "a clear-cut demolition of Gaia"(Kerr 393) and admitted that all remaining notions of Gaia as an actual living organism must be abandoned. In light of the preceding arguments, the question that still remains is: which of Kirchner's criticisms are still valid and should be taken into account when determining the feasibility of a testable Gaia?

Of Kirchner's four distinct hypotheses, only two hypotheses are relevant to this analysis. Kirchner's Coevolutionary Gaia, which states that Lovelock simply reiterates the conventional wisdom concerning life's influence on earth, will not be analyzed. This criticism was adequately answered by Lovelock when he made the statement (previously quoted), "Organisms do not just "adapt" to a dead world determined by chemistry and physics alone. They live with a world that is the breath and bones of their ancestors and that they are now sustaining" (The World 25). Independent of whether Lovelock is correct in making this statement, he refutes Kirchner's criticism, thus leaving it invalid. In addition, this criticism, even if valid, is independent of Gaia's testability and therefore irrelevant to the scope of this analysis.

Kirchner's Geophysiological Gaia, which states that the Earth can be compared to a single immense organism, will not be pursued. As previously mentioned, although in the past Lovelock may have implied that the Earth is a living organism, he clearly recanted this idea in 1988 (Kerr 393). Kirchner's criticisms of Geophysiological Gaia are thus outdated, irrelevant, and not important to the scope of this analysis.

Having refuted Coevolutionary Gaia and Geophysiological Gaia, it is thus Optimizing Gaia, and Homeostatic Gaia that must be analyzed in order to determine the feasibility of a testable Gaia hypothesis.

The Nature of Science and Scientific Testability

Kirchner's criticisms of Homeostatic and Optimizing Gaia primarily concern the untestable nature of these hypotheses. Surfactually, Kirchner provides logical, deductive arguments illustrating the untestable nature of Gaia. In the context of his criticisms, Kirchner's evidence is convincing that Gaia, both Homeostatic and Optimizing, is untestable. It is naïve, however, to brand Gaia as untestable without thoroughly exploring different types of scientific testability and their philosophical foundations. A complex system such as Gaia cannot simply be accepted or rejected based upon simple verification or falsification tests. The testability of Gaia can only be determined

by careful analysis of many philosophical issues regarding its testability. This chapter outlines the philosophical foundations governing scientific and ecological testability.

Popperian Falsificationism

In his 1989 paper, "The Gaia Hypothesis: Can it be tested," Kirchner explains "the minimal criteria of testability can be stated concisely" (226). He continues:

In order to be testable a hypothesis must be clear, and its terms must be unambiguous. It must be intelligible in terms of observable phenomena. And most importantly, it must generate predictions of two kinds: confirmatory predictions (phenomena that should be observed if the hypothesis is true and that would not be predicted by the existing body of accepted theory) and falsifying predictions (phenomena that should be observed if the hypothesis is false) (226).

Kirchner's ideas regarding testability stem from the early works of Karl Popper, a notable philosopher of science. Kirchner quotes and paraphrases Popper extensively in "The Gaia Hypothesis: Can it be tested.." Popper is one of many philosophers who has attempted to create a definition of science. Throughout much of his career, Popper was concerned with a method of systematically distinguishing science from pseudoscience. He viewed the study of physics as the epitome of science, and Marxism and Freudism as examples of pseudoscience.

Popper's method of scientific inquiry was entitled 'falsificationism,' and considered a theory scientific as long as it: (1) was liable to be falsified by data (2) was testable by observation and experiment and (3) made valid predictions. The ideas expressed in Popper's 'falsificationism' have become mainstream and are currently accepted and labeled 'the scientific method' by numerous textbooks and bureaucratic establishments.

Falsificationism is not universally accepted, however, and has received substantial criticisms from philosophers of science and scientists alike, namely biologists. Many of these criticisms stem from the fact that in his early writings, Popper strongly argued that evolutionary theory was unfalsifiable and therefore (Popper 230). Popperian critics argue that biological theories are inherently different from the theories of chemistry or physics and therefore cannot be tested by the same means. Later in life Popper recanted his arguments against evolutionary theory and altered his scientific philosophy to incorporate biological theories; however, many misconceptions of his position still linger from his early writings.

Ernst Mayr, a notable biologist and philosopher of science from the Technical University of Munich, refutes many aspects of Falsificationism. In his 1988 book, *Towards a New Philosophy of Biology*, Mayr argues against the notion that falsificationism can be equally applied to all of the sciences. He states:

Popper's claim...allows one rather neatly to delimit science from nonscience: any claim which in principle cannot be falsified is outside the realm of science...Falsification, however, is sometimes as difficult to provide as absolute proof. It is therefore not considered the only measure for obtaining scientific acceptability (26).

Concerning the applicability of falsificationism to Gaia, Lovelock writes:

Geophysiology is about the evolution of a tightly coupled system whose constituents are the biota and their material environment, which comprises the atmosphere, the oceans, and the surface rocks. Self-regulation of important properties, such as climate and chemical

composition, are seen as a consequence of this evolutionary process. Like living organisms and many closed-loop self-regulating systems, it would be expected to show emergent properties, that is the whole will be more than the sum of its parts. This kind of system is notoriously difficult, if not impossible, to explain by cause and effect logic, as practicing inventors know to their cost. It is doubtful also if the fashionable and trendy use of Popperian falsification tests, so valuable for theories in physics, is really appropriate for such systems (Geophysics, 170).

Reductionism and Holism

Reductionism

As summarized by Lovelock, Popperian falsificationism ideally applies to the study of physics. Popper's ideas were formulated during a period when most scientists held a reductionist view of science. Reductionism is the idea that a system can be explained in terms of its component parts. The biological reductionist viewpoint, for example, states that all biological theories can, at least in principle, be reduced to and described by the laws of physics.

Like Gaia, the term 'reductionism' has been used to describe many different logically distinct ideas. In an attempt to clarify the resulting confusion, Ernst Mayr divided reductionism into three distinct theories: constitutive reduction, explanatory reduction, and theory reduction (Towards a New Philosophy 10).

Mayr describes constitutive reduction as "any dissection of phenomena, events and processes into the constituents of which they are composed" (Towards a New Philosophy 11. Of explanatory reduction, he states "all phenomena and processes at higher hierarchical levels can be explained in terms of the actions and interactions of the components of the lowest hierarchical level." (11). Finally, of theory reduction, he states "theories and laws formulated in biology are only special cases of theories and laws formulated in the physical sciences, and...such biological theories can thus be reduced to physical theories" (11).

Different versions of reductionism cause different reactions from the scientific community. Mayr states that few scientists oppose constitutive reduction since all organic processes can ultimately reduce to physico-chemical processes; "No processes encountered in the world of living organisms is in any conflict with a physico-chemical explanation at the level of atoms and molecules" (11).

Explanatory reduction is met with criticisms from Organicists who claim: "...new properties and capacities emerge at higher hierarchical levels and can be explained only in terms of the constituents at those levels. For instance, it would be futile to try to explain the flow of air over the wing of an airplane in terms of elementary particles. Almost any phenomenon studied by a biologist relates to a highly complex system, the components of which are usually several hierarchical levels above the level studied by physical scientist's (11).

Theory reduction receives the harshest criticisms from biologists. Concerning theory reduction, Mayr states "All authors in recent years who have studied this claim, including even several former reductionists, have come to the conclusion that such theory reduction is vitally never successful...none of the more complex biological laws has ever been reduced to and explained in terms of the composing single processes" (The Growth of Biological Thought 11).

Holism

Whereas theories of reductionism tend to split apart scientific methodologies into component parts, theories of 'holism' tend to view complex systems as whole, integrated, systems. Holism is the idea that the components of a system can only be understood in context of that system. A holistic approach to science is opposite a reductionist approach and scientists tend to favor either reductionism or holism, rarely both. The division between reductionists and holists in science is pronounced, and especially so in the study of ecology. Since Gaia can be viewed as a planetary ecosystem, it is necessary to examine the following philosophical aspects of ecology.

The Implications of Reductionism and Holism to the Study of Ecology

The science of ecology has undergone significant paradigm shifts since its origin towards the end of the last century. Ecology began as a very holistic science that studied communities, or associations of organisms. As part of this early holistic approach, communities of organisms were not studied in isolation, but in context of the whole system or their environment. Both Frederick Clements and Victor Shelford, two prominent early American ecologists defined ecology as the 'science of communities'. In the early 1930's, the Oxford ecologist Arthur Tansley coined the term 'ecosystem', defining it as a "community taken together with its abiotic environment" (Goldsmith 64).

Around 1950 however, Ecology (along with many other scientific disciplines) shifted from a primarily holistic science to a reductionist science. According to Edward Goldsmith:

Ecology has undergone, about a half century later than genetics and evolution, a transformation so strikingly similar in both outline and detail that one can scarcely doubt its debt to the same materialistic and probabilistic revolution. An initial emphasis on a similarity of isolated communities replaced by concern about their differences: the examination of groups of populations largely superceded by the study of individual populations; belief in deterministic succession shifting with the widespread introduction of statistics into ecology, to realization that temporal community development is probabilistic: and a continuing struggle to focus on material, observable entities rather than ideal constructs" (Goldsmith 65).

Although the development of systems theory and numerous 'bottom-up' methods of viewing ecology have emerged in the last twenty years, since the 1950's reductionism has pervaded as the dominant paradigm in the sciences of ecology and biology. Within this reductionist paradigm, Gaia, as a holistic approach to science, received staunch criticisms since its first proposal.

Many scientists and philosophers are currently extremely unsatisfied with the reductionist paradigm of ecology. According to Edward Goldsmith:

Ecology has in fact been perverted – perverted in this interests of making it acceptable to the scientific establishment and to the politicians and industrialists who sponsor it...it is unlikely that those ecologists who view the biosphere in purely reductionistic and mechanistic terms can understand the implications of the devastation being wrought by the modern industrial system, and hence they can understand what action is required to bring this devastation to an end. (65).

Numerous scientists and philosophers of science doubt the wisdom of applying reductionist principles to the life sciences. In *The Growth of Biological Thought* Ernst Mayr writes:

This discussion of reductionism can be summarized by saying that the analysis of systems is a valuable method, but that attempts at a "reduction" of purely biological phenomena or concepts to

laws of physical sciences has rarely, if ever, led to any advance in our understanding. Reduction is at best vacuous, but more often a thoroughly misleading and futile, approach (63).

Summarizing the applicability of reductionism to the life sciences, Stephen Jay Gould states: First nothing in biology contradicts the laws of physics and chemistry; any adequate biology must be consonant with the "basic" sciences. Second, the principles of physics and chemistry are not sufficient to explain complex biological objects because new properties emerge as a result of organization and interaction. These properties can only be understood by the direct study of whole, living systems in their normal state. Third, the insufficiency of physics and chemistry to encompass life records no mystical addition, no contradiction to the basic sciences, but only reflects the hierarchy of natural objects and the principles of emergent properties at higher levels of organization (From Barlow, 103).

General System Theory as it Relates to the Study of Ecology

It was these ideas concerning the hierarchical organization within the life sciences that spawned general system theory (GST) in the late 1960's. Under the framework of GST, a holistic approach to science, ecosystems are examined as complex, integrated systems. Recent developments in GST have revolutionized the study of ecology and numerous other complex systems. A 'systems' approach to ecology and other complex systems offers an alternative approach to the traditional reductionist methods of evaluating ecosystems. GST is therefore important to the study of ecological modeling and Gaia.

The notions of 'systems' science first became widespread in the 1960's as the limitations of reductionist science became apparent. Since then, GST has been applied to all disciplines of science. In relation to ecology, GST regards every organism as a system, or a "complex of elements in mutual interaction...circumscribed in space and time" (Bartlow 12).

The major ecological implications of GST can be summarized by two basic premises. First, it is impossible to resolve the phenomena of life completely into its elementary units because each individual part depends not only on conditions within itself, but also to the conditions within the whole. Therefore, the behavior of an isolated part is inherently, different from its behavior within the context of the whole. Secondly, the whole shows emergent properties, or properties that are not merely the sum of its parts. As a result, as long as we single out individual phenomena, we do not discover any fundamental difference between the living and the non-living (112).

The introduction of GST was important to ecology because it provided an alternative framework for viewing complex systems. GST paved the way for scientifically acceptable, holistic interpretations of ecological phenomena. Another theory which dramatically altered the foundations of ecology was chaos theory. By illustrating that complex systems exhibit unpredictable or chaotic behavior, chaos theory greatly modified the concept of scientific and ecological testability.

Chaos Theory as it Relates to the Study of Ecology

Chaos theory is the notion that complex systems exhibit inherently random or unpredictable behavior. This behavior was first noticed by Edward Lorenz, a meteorologist at the Massachusetts Institute of Technology, in 1960. Lorenz, while manipulating, a computerized weather model noticed that small changes in input data resulted in unusually large changes of output data. This

principle, termed "sensitive dependence on initial conditions" led to the formulation of chaos theory.

Chaos theory is important to the study of ecology because it describes the unpredictable nature of complex systems. When Lorenz first noticed these properties in his weather models, he realized that due to the complexity of the weather, accurate long-term weather forecasting was impossible. Since the weather is a complex system (i.e. influenced by an infinite number of factors), it cannot be accurately modeled. Ecosystems, like the weather, are complex systems and therefore cannot be modeled to a large degree of precision.

An Introduction to Ecological Modeling

Gaia is ultimately a global ecosystem and can therefore be best tested under the framework of ecological modeling. From the first population studies of Thomas Malthus to the most recent applications of chaos theory, ecological models have served as an indispensable tool for evaluating the complex relationships between communities of organisms.

Many practical and theoretical problems hinder the potential accuracy of ecological models. Ecosystems are inherently complex, chaotic systems and therefore have an infinite number of components which are not easily defined or characterized. As a result, when modeling an ecosystem, it is impossible to account for all of its component parts and contributing variables and thus accurately portray the system as a whole. Because of this, ecosystems, like long-term weather forecasts, are impossible to predict to a high degree of certainty.

The complex nature of ecosystems does not, however, mean that ecological modeling is futile or devoid of meaning. Referring to the importance of ecological modeling, Edward Rykiel states: It is perfectly valid to ask the ecologist to describe the rules by which ecological systems operate. Science is after all a search for the rules that describe the way nature behaves. We have no clear evidence at this point in time that there is a simple set of rules for ecological systems. Ecological systems are complex and it is not unreasonable to think that there may be hundreds or thousands of rules needed to describe, for example, the behavior of a salt marsh. Theoretical development is hampered by the limited mental capacity we have for figuring out the consequences of even small knowledge bases. Why not take advantage of any technology that can assist us in determining the logical consequences of complicated ecological chains of reasoning (7).

Ecological models provide scientists with a tool for evaluating the biological relationships of ecosystems and are thus necessary for an in-depth understanding of ecosystems. Ecological models vary greatly in complexity and scope, and have evolved significantly since the first Malthusian population models. In order to determine the best method of testing a global ecosystem such as Gaia, it is necessary to understand the historical developments of ecological modeling.

Historical Developments in Ecological Modeling

In his 1994 book entitled "Fundamentals of Ecological Modeling", Sven Jørgensen outlines the major historical developments in ecological modeling. Table #2 is a schematic diagram illustrating the historical development of ecological and environmental models. Jørgensen groups these developments into five major stages or "generations" of ecological modeling. The following discussion describes that developmental history.

First Generation Models

The earliest ecological models, termed by JÆrgensen as the "first generation" of ecological modeling, were created to describe human populations, oxygen balance in streams, and predator prey relationships.

Table #2 the development of ecological and environmental models shown schematically. From JÆrgensen 105)

Streeter - Phelps Lotka - Volterra	1920
	1950
Population Dynamics River Models	1960
	1970
Eutrophication models Complex river models	1975
	1980
Fixed procedure Balanced complexity More Ecology	1990
Ecotoxicological models More case studies Validation of prognosis	
Structural dynamic Models, ecological Constraints, new Mathematical tools.	

The first true ecological model was based upon the population studies of Thomas Malthus. In his 1798 "Essay on the Principal of Population," Malthus argued that although (human) populations grow exponentially, the resources sustaining these populations grow either arithmetically or not at all. He argued that the demand for the earth's resources would eventually exceed the supply and become a limiting factor for an otherwise unlimited human population growth.

In 1838, P. F. Verhulst formulated Malthus's "principle of population" into a derivative based mathematical model describing single-species population dynamics. In Verhulst's logistic equation:

$$dN / dt = aN (1 - N/K)$$

N is the biomass density of the population in question, a is the maximum per-capita rate of change, or the intrinsic rate of increase, and K is the equilibrium density, often called the carrying capacity of the environment. This equation, although simplistic in nature, provides a generalized framework for the dynamics of numerous single-species populations in both the laboratory and the field (Berryman 1530).

Aside from the population studies of Malthus and Verhulst, it was not until the development of predator-prey theory in the early 20th century that scientists actively turned to ecosystem modeling as a means of understanding the natural world. In 1925, A.J. Lotka was the first to use a logistic equation to model the interactions between predators and prey in a given ecosystem and thus began the next major advance in population dynamics theory. Instead of applying his logistic equation to numerous species, Lotka, and later V. Volterra (1928) applied the chemical principle of mass action to predator-prey theory. This implies that the response of populations would be proportional to the product of their biomass densities. In what are commonly known as the Lotka-Volterra Equations:

$$dN/dt = aN - bNP,$$

$$dP / dt = cNP - dP,$$

N and P represent the biomass densities of prey and predator (respectively) and a and d are their per-capita rates of change in the absence of each other, and b and c are their respective rates of change due to interaction (Berryman 1531).

Many other similar models comprise the first generation of ecological modeling. These first generation models are very simplistic in nature and primarily model single or double-species variations within their environment. These models do not provide an accurate description of the "real world", but they were the first attempt at doing so. These first models are significant because they provided scientists with a mechanism for quantitatively describing ecological systems. It is interesting to note that Volterra, one of the first to publish on ecological modeling, concludes his 1926 paper, *Fluctuations in the Abundance of a Species Considered Mathematically*, with the statement "Seeing that a great number of biological phenomena are characteristic of associations of species, it is to be hoped that this theory may receive further verification and may be of some use to biologists (558)."

Second Generation Models

The second generation of ecological modeling spanned from approximately 1950 to 1970. The modeling of this period primarily focused upon more complex population dynamic models and river models. Increased developments within these models allowed for a more accurate, yet still primitive, depiction of the ecological features in question. The developments within predator prey models will be analyzed to illustrate the increased complexity of second generation models.

By the beginning of the 1950's, the functional responses of predators' were incorporated into predator prey models. Solomon (1949) and Holling (1966) argued that because predators can only handle a finite number of prey during a given unit of time, the prey mortality rate should be a nonlinear function of prey density; i.e.,

$$dN / dt = aN(1 - N / K) - b(N)P$$

Where $b(N)$ is the functional response of the predator to prey density. Based on a series of behavioral experiments, in which "predators" (blindfolded students) searched for different densities of prey (sandpaper disks), Holling derived his famous "disk" equation which turned out to be identical to the well-known Michaelis-Menton equation of enzyme kinetics (Real 1977); i.e.,

$$b(N) = mN/(w + N),$$

where m is the maximum predator attack rate and w is the prey density where the attack rate is half-saturated. The functional response introduces ratio-dependence into the prey equation because, when w is set at zero, the per-capita death rate becomes mP/N (Berryman 1983). Regarding the argument that prey deaths can be directly translated into predator births, functional responses are often employed in predator equations; i.e.

$$dP/dt = cP[mN/(w+N)] - dP$$

The major difference between first and second generation models is the increased level of sophistication present in second generation models. Second generation models include more complicated parameters than first generation models, allowing more explanatory power. Certain inaccuracies are of course inherent within these types of models; yet it is obvious that there is an increased complexity of second generation ecological models.

Third Generation Models

The third generation of ecological models emerged in the 1970's in conjunction with the rise of the environmental movement. The models of this generation consist of very complex river models and the first lake eutrophication models. With many newly developed computer modeling procedures, it suddenly became much easier to write and handle complex ecological models. Because of these developments, third generation models are often characterized as being "too complex" (Jørgensen 1982).

According to Jørgensen it became clear among modelers during the mid-seventies that the limitations in modeling were no longer based on computer or mathematical controls, but on the data and our knowledge about ecosystems and ecological processes (1982). Modelers became more critical of the models they deemed acceptable. These ideas evolved in accordance with the understanding that the basis for a sound ecological model was an in depth understanding of the ecosystem and its ecological components.

Jørgensen, a very influential academic in the field of ecological modeling, provided a list of modeling recommendations based on this third generation of ecological models. The following recommendations serve as a framework for creating ecological models in accordance with the "rules" of third generation ecological modeling.

Ø Follow strictly all steps of the procedure, i.e., conceptualization, selection of parameters, verification, calibration, examination of the sensitivity, validation etc.

Ø Find a complexity of the model, which considers a balance between data, problem, ecosystem and knowledge,

Ø Make parameter estimations by using all the methods, i.e., literature review, determination by measurement in laboratory or in situ, use of intensive measurement and calibration of submodels and the entire model (JÆrgensen 104).

Fourth Generation Models

From the mid-seventies to the mid-eighties, out of needs arising from environmental management, ecologists became increasingly quantitative in their approach to evaluating the environment and ecological problems. JÆrgensen termed these developments the fourth generation of ecological modeling. The conclusions from this period may be summarized as the following:

Ø Provided that the recommendations given above were followed and the underlying database was of good quality, it was possible to develop models that could be used as prognostic tools.

Ø Models based upon a database of questionable quality should possibly not be used as a prognostic tool, but could give an insight into the mechanisms behind the environmental management problem, which could be most valuable. Simple models are often of particular value in this context.

Ø Ecologically sound models, i.e. models based upon ecological knowledge, are powerful tools in understanding ecosystem behavior and as tools for setting up research priorities. The understanding may be qualitative or semi-qualitative, but has in any case proved to be of importance for ecosystem theories and better environmental management (JÆrgensen 106).

Fifth Generation Models

Conceptual and technological developments from the mid-eighties until today spawned the fifth generation of ecological modeling. This generation of models is holistic in approach and was formulated from recent scientific developments including systems theory, chaos theory, complexity theory, catastrophe theory, artificial intelligence, cellular automata, and fuzzy logic. Inherent in fifth generation models is the notion that ecosystems are infinitely complex, extremely adaptive, capable of self-organization, and can only be truly understood in context of their surroundings (JÆrgensen 483). For a complex system such as Gaia to be most accurately tested, it is best done so under JÆrgensen's fifth generation of ecological models.

Fifth Generation Models and the Testability of Gaia

James Lovelock's notion of Gaia can most be effectively tested using fifth generation ecological models. Fifth generation models, commonly known as structural dynamic models, are created with a holistic, 'systems' approach to ecology and take into account the limitations of scientific inquiry. According to the principles of chaos theory, Gaia, like any other ecosystem, is infinitely complex and cannot currently be modeled to any degree of long-term accuracy. Fifth generation models, however, can be used to test the self-regulating mechanisms of Gaia as they test other ecological mechanisms.

Prior to the fifth generation of modeling, ecological models were designed with fixed parameters, allowing no change or replacement of components within a system. From the study of systems theory and chaos theory, however, it is known that system parameters constantly change and are in

a state of flux. Because of this, fifth generation models are designed with changeable parameters, allowing systems to fluctuate freely from their thermodynamic equilibrium (JÆrgensen 493).

JÆrgensen illustrates the theoretical framework of these models stating:

We cannot capture the complexity (of an ecosystem)...with all its details, but we can understand how ecosystems are complex and we can set up a realistic strategy for how to get sufficient knowledge about the system – not knowing all the details, but still understanding and knowing the mean behavior and the more important reactions of the system. It means that we can only try to reveal the basic properties behind the complexity. We have no other choice than to go holistic. The results from the more reductionistic ecology are essential in our effort to "go to the root" of the system properties of ecosystems, but we need systems ecology, which consists of many new ideas, approaches, and concepts to follow the path of the roots of the basic system properties of ecosystems by analyzing all the details, because they are simply too many, but only by trying to reveal the system properties of ecosystems by examination of the entire systems (JÆrgensen 487).

Many different types of models comprise JÆrgensen's fifth generation ecological models.

These models incorporate the influences of systems theory, chaos theory, complexity theory, expert systems, cellular automata, and fuzzy logic and are the best mechanism for testing Gaia. The following section provides an overview of numerous fifth generation models that can be utilized to test Gaia.

Chaos and Complexity Models

In contrast to the traditional, deterministic mathematical, models, chaos models explore the unpredictable aspects of complex systems. Testing complex systems via chaos theory is radically different from traditional modeling methods and has thus provided new methods of modeling throughout the sciences. According to JÆrgensen, "Chaos theory has eliminated the Laplacian illusion of deterministic predictability and can therefore be conceived as a ticking bomb under reductionistic science" (JÆrgensen 506).

Robert May and George Oster were some of the first biologists to apply the principles of chaos and complexity theory to biology and ecological modeling. In their 1976 article, "Bifurcations and Dynamic Complexity in Simple Ecological Models," May and Oster explain the dynamic behavior of many biological functions. Illustrating the non deterministic nature of ecological systems, they describe the phenomena of bifurcations, stability points, fixed points (attractors), and other chaos phenomena in relation to ecological modeling (May and Oster 1976).

The implications of this research to ecological modeling are paramount. May and Oster note that ecosystems are infinitely complex, non-linear, and chaotic, and therefore cannot be modeled by simple, deterministic models. It is therefore currently impossible to make long term ecological predictions with any degree of accuracy. These models do however provide a sound, scientific method for testing the non-linear properties of ecosystems. Since ecosystems are inherently complex and non-linear, these models are essential to understanding their behavior.

Most standard methods of modeling dynamic systems account for system parameters in one or two-dimensional space. Chaos modeling allows system parameters to be modeled in

three-dimensional space. This is critical because many chaos parameters can only occur in three dimensional space and thus could not be recognized in one or two dimensions (Hilborn 136).

Fuzzy Logic Models

The principles of fuzzy logic originated from the study of complex systems. In complex systems such as ecosystems, widespread, accurate data is difficult, if not impossible, to attain; scientists, however, continually strive to test and model these systems. From this desire to model complex systems using inherently imprecise quantitative data arose the fuzzy logic approach to modeling.

Fuzzy logic evolved from fuzzy set theory, developed by L. Zadeh in the 1960's. Rather than using imprecise, 'real-world' quantitative data for modeling, fuzzy logic models utilize 'approximated data' and 'approximated reasoning' to generate 'approximated models' of complex systems (Zadeh 1965). Fuzzy logic is beneficial in describing complex systems because it allows the modeler to utilize imprecise knowledge to create models based strictly upon qualitative data (Salski 106).

Cellular Automata Models

Cellular Automata (CA) is a general term referring to a series of easily computable rules used to mimic physical laws or phenomena. Strictly speaking, a cellular automaton consists of a "simulation which is discrete in time, space, and state" (Ermentrout and Edelstein-Keshet 1993). CA simulations provide quick, often iterative, calculations and graphic representations of the data. These features make CA useful in modeling complex phenomena such as theoretical biology and ecology.

CA models differ greatly from traditional ecological models in that they are not "bottom up" or designed to test specific, observable phenomena. Instead, CA models are created to examine certain generalized traits of complex systems. In doing so, CA models tend to mimic biological features such as flocking patterns, population fluctuations and extinctions, and the evolution of neural networks. These models are important because they provide a "top-down," or theory-driven, approach for evaluating ecological and biological processes.

Catastrophe Theory Models

Catastrophe theory is generally regarded as a theory of equilibria. In contrast to chaos theory, which deals with unpredictable, nonlinear phenomena at an individual level, catastrophe theory deals with shifts in equilibrium or attractor points at a 'systems' level. In context of this theory, a 'catastrophe' is not necessarily a negative event; it is simply a sudden shift in the properties of a system. Catastrophes typically occur in cases where two or more non-linear processes are interacting, and cause ecosystems to evolve, as natural selection favors the stronger elements of a system and eliminates the weaker ones (JÆrgensen 518).

According to JÆrgensen, catastrophe theory is not widely accepted in ecology "because reductionistic ecology does not believe that it is possible to look through 'the mist of complexity'" (524). JÆrgensen criticizes this position however, arguing that certain phenomena, indescribable by other theories, can be explained and modeled by the use catastrophe theory. He also argues that, in an ecological context, catastrophe theory should be viewed less as a theory of equilibria, and more as a theory describing sudden changes in steady state (524).

Artificial Intelligence and Expert System Models

Artificial Intelligence (AI) is a branch of computer science that uses computational models to mimic the processes of the human brain. The term AI, is a generic term referring to developments in expert systems, search methods, knowledge representation, logical and probabilistic reasoning, learning, natural language understanding, vision, and robotics (Rykiel 4). Expert Systems are a specific type of AI specifically designed to display a high degree of knowledge about specific, limited subjects. Usually these are capable of making inferences or decisions based on that knowledge and are normally implemented as a collection of if-then production rules (Caudil and Butler 280). Expert system models, as well as numerous other forms of AI can be applied to the study of complex systems.

Applying Holistic Models to Gaia

As previously stated, Gaia, as a whole, is untestable in the same way that long-term weather forecasts are untestable. Gaian regulatory mechanisms can, however, be studied and tested using holistic ecological models. When testing a complex system such as Gaia, there is no one definitive method for achieving optimal results. Certain steps, however, are recommended for best results. Modeling with fifth generation, holistic ecological models is different from modeling with traditional reductionist models. JÆrgensen illustrates this process of holistic modeling:

If a relation is found here between two or more variables by, for instance, the use of statistics on available treatment of data, the relationship is afterward tested on several additional cases to increase the scientific certainty. If the results are accepted, the relationship is ready to be used to make predictions and it is examined whether the predictions are wrong or right. If the relationship still holds, we are satisfied and a wider scientific use of the relationship is made possible (9).

Holistic models increase in complexity in this fashion as they are extrapolated to encompass more ecosystem parameters.

When modeling complex ecosystems like Gaia, it is necessary to choose numerous, applicable ecological models. Individual holistic ecological models yield high degrees of abstraction and therefore utilizing additional models results in decreased levels of abstraction.

In addition to applying modeling techniques to Gaia, other methods are also beneficial. In his *Fundamentals of Ecological Modeling*, JÆrgensen outlines these alternative methods of study. These methods are:

Ø Empirical studies where bits of information are collected, and attempts are made to integrate and assemble these into a complete picture.

Ø Comparative studies where a few structural and a few functional components are compared for a range of ecosystem types.

Ø Experimental studies where manipulation of a whole ecosystem is used to identify and elucidate mechanisms.

Ø Modeling or computer simulation studies (JÆrgensen 16).

All of the preceding strategies can be applied to modeling complex ecosystems such as Gaia.

Conclusion

James Kirchner provides convincing arguments illustrating the untestable nature of Gaia. It is naïve, however, to brand Gaia as "untestable" without thoroughly exploring the philosophical foundations of scientific testability. A complex system like Gaia cannot simply be accepted or rejected based upon simple verification or falsification tests. The testability of Gaia can only be determined by careful examination of the philosophical foundations governing its testability.

Gaia, as a whole, is untestable in the same way that long-term weather forecasts are untestable. If real, Gaia, is an infinitely complex, chaotic system and cannot be tested by traditional reductionist methods. However, like other chaotic systems, its components may be tested to some degree of certainty by means of holistic, fifth generation models.