HOW DOES THE TEILHARDIAN VISION OF EVOLUTION COMPARE WITH CONTEMPORARY THEORIES?

by Lodovico Galleni

Abstract. Teilhard de Chardin's ideas about the mechanisms of biological evolution are revised and their connections with contemporary theories are reported. Teilhard de Chardin's main contribution is the proposal of a new scientific discipline, geobiology—the science of the biosphere evolving as a whole. The main fields of interest of geobiology are reported, and its relationships with contemporary hypotheses, such as Lovelock's Gaia, are discussed. The consequences of this kind of approach are the parallel evolution described as orthogenesis and the presence of canalization phenomena. These Teilhardian hypotheses are discussed in relation to those of the process structuralists and to the novelties of the molecular evolution of the genome. Conclusions are that the mechanisms discussed by Teilhard are presently taken into consideration by contemporary evolutionists in order to construct a new theory of biological evolution.

Keywords: biosphere; complexity; evolution; evolutionary landscape; Gaia hypothesis; geobiology; noosphere; orthogenesis; Pierre Teilhard de Chardin.

Pierre Teilhard de Chardin is very well known for his synthesis of science and theology. His mind was open to what was good in the modern world. He saw his own vocation in recovering for Christianity the novelties proposed by natural science; in his diary he traced back this vocation to John Henry Newman (JT 1977).[1] Professionally, he was actively engaged in paleontology, geology, and finally, anthropology. For these reasons he was aware that the main contribution of these sciences to the contemporary vision of the

Lodovico Galleni is Professor of General Zoology, Faculty of Agricultural Science, University of Pisa, Via San Michele degli Scalzi 2, I 56124 Pisa, Italy. This paper was presented at the twelfth annual Cosmos and Creation Conference at Loyola College in Maryland, Baltimore, 27–29 May 1994. Support for this conference was provided by the John Templeton Foundation and the Humanities Foundation at Loyola College.

[*Zygon,* vol. 30, no. 1 (March 1995).]
 ISSN 0591-2385

world was the discovery of biological evolution. He had to confront this novelty and assimilate it into his worldview.

TEILHARD DE CHARDIN AND THE MODERN SYNTHESIS

Teilhard's confrontation with scientific ideas, in particular the revision of Darwinism often called the modern synthesis (Huxley 1942), occurred mainly during his own scientifically active period. During his long stay in China, he was faced with many aspects of the modern synthesis, and he attempted to integrate his scientific work and his cultural background with those of the Darwinists. This integration has been analyzed by many authors (Dodson 1984, 1993; Birx 1991; Galleni 1992a). Teilhard worked hard to formulate lawful reasons for the emergence of thinking beings, an event that classic Darwinism attributes to random mechanisms. In searching for trends in evolutionary development, he postulated some kind of preferential movement toward more complex and conscious forms. I have described modes and methods elsewhere (Galleni 1992a) and summarize them here. As a paleontologist, Teilhard thought in terms of evolutionary lines that lasted a long time (on the scale of paleontology) and covered a large area (on a continental scale). In doing so he identified evidence of events that could be considered examples of directionality in evolution. Directionality was evidenced by the emergence of similar characteristics in separated phyletic lines; Teilhard referred to it as *orthogenesis*, redefining the term. Preferential lines were described, the most important among them leading to increased cerebralization.

In a 1947 Paris colloquium of paleontologists of different cultural origins, Teilhard encountered one of the authors of the modern synthesis, George G. Simpson. Teilhard presented a case of directionality of evolution in a small group of rodents: the mole-rats of the Pleistocene of China (PT).[2] In the discussion that followed, Simpson stressed that the element capable of introducing directionality was still natural selection: "Therefore it seems that the directing element, the effect not based on chance which appears in this example of evolution, cannot be otherwise but natural selection, and I don't see any reason to look for another explanation where that one is sufficient" (Simpson, in Piveteau 1949, 179). Indeed, this example seems to support the conclusion that orthogenesis, if in fact it really exists, is orthoselection (Simpson, in Piveteau 1949, 179).

At the congress, Teilhard de Chardin's views were to some degree interpreted with those of the modern synthesis (Galleni 1992a). But now we are ready for another step. Actually, many novelties related to the theories of evolution proposed since the sixties are difficult to integrate into the modern synthesis. It will be useful to compare these novelties with some aspects of Teilhard's scientific papers that could be interpreted as their forerunners.

TEILHARD DE CHARDIN'S CONCEPT OF THE BIOSPHERE

In a paper published posthumously in a book edited by William Thomas, Jr., and devoted to the problem of the rise and development of human culture, Teilhard de Chardin (MRE) summarized the rise of the concept of Noosphere:

> More than a half-century ago the great geologist Suess took a bold and lucky step when, in addition to describing our planet by the classical sequence of concentrical, spherical shells (barysphere, lithosphere, atmosphere, etc.), he decided to add the biosphere, in order to affirm, in a concise and vivid way, that the frail but superactive film of highly complex, self-reproducing matter spread around the world was of decided geological significance and value. Since Suess's times, the notion of a special planetary envelope of organic matter distinct from the inorganic lithosphere has been accepted as a normal basis for the fast-growing structures of geobiology (a new branch of science). But, then, why not take one step more and recognize the fact that, if the appearance of the earth has undergone a major alteration by turning chlorophyll-green or life-warm since the Paleozoic period, an even more revolutionary transformation took place at the end of the Tertiary time, when our planet developed the psychically reflexive human surface, for which, together with Professor Edouard Le Roy and Professor Vernadsky, we suggested in the 1920's the name "noosphere"? (MRE, 103)

This quotation is of fundamental importance in comparing some of the lesser-known Teilhardian views on evolution with some of the novelties that have recently emerged. As a matter of fact, Teilhard refers to relationships he developed in the twenties in Paris with Le Roy and Vernadsky and to Suess's concept of biosphere, and he links this concept to a new branch of science: geobiology. In a more widely known paper, reported in the anthology *The Future of Man*, he referred again to the concept of the biosphere as a step toward Noosphere:

> We must enlarge our approach to encompass the formation, taking place before our eyes and arising out of this factor of hominisation, of a particular biological entity such as has never before existed on earth—the growth, outside and above the biosphere, of an added planetary layer, an envelope of thinking substance, to which, for the sake of convenience and symmetry, I have given the name of the Noosphere. (FM, 163)

And in a footnote he explains his concept of biosphere with a reference to that of Vernadsky: "This term, invented by Suess, is sometimes interpreted [Vernadsky] in the sense of the 'terrestrial zone containing life.' I use it here to mean the actual layer of vitalised substance enveloping the earth" (FM, 163).

This paper is not the occasion to further analyze Teilhard de Chardin's and Vernadsky's concepts of biosphere, analysis partially carried out by Grinevald (1988) and Serafin (1988). However, an essential part of this contribution is strictly related to the development of the concept of the biosphere acting as a whole, as recently proposed by J. Lovelock in his Gaia hypothesis (Lovelock 1988). For this reason it is necessary to go further into Teilhard's concept of biosphere.

I recently noted the development of a new branch of science—geobiology, originally proposed by Teilhard de Chardin and his coworkers in Beijing during the Second World War (Galleni 1984, Galleni 1992a)—I attempted to integrate it with the modern synthesis. But now we can take another step: we can consider whether geobiology might be considered the science of the biosphere as a whole. And in this case, can Teilhard de Chardin be considered one of the anticipators of the Gaia hypothesis? In a paper Teilhard presented in 1940 to the Institute of Geobiology, which can be considered the very manifesto of this new science, it is clearly stated:

> We had come to the conviction that China was the place for an Institute devoted to the systematic development of what might be called the Science of "continental evolution." From both geological and biological points of views, Continents represent a kind of natural unit. Either in their building under tectonical and eruptive forces, in the nature of their sediments—in the formation and the shifting of their basin—in the modelling of their topographical surfaces—in the variations of their climates—or in the development and the distribution of special vegetal and animal groups, they can only by studied "as a whole." And, if understood as a whole, they may introduce us to a renewed and better conception of the mysterious "concrescence" of Land and Life which is the Earth around us. (Teilhard de Chardin et al. 1940, 1–2)

From these sentences emerges the idea that geological and biological elements have to be studied as a whole, and this idea is clearly related to the concept of biosphere linked as a unity to the other spheres. To integrate such concepts, life must be studied on a large scale. This requirement is emphasized many times; the publications of the institute presented it as follows: "Its purpose is to study the interdependent Evolution of Land and Life on the Asiatic Continent considered as a semi-independent nucleus of the Earth's Crust. Therefore in its publications the Institute specializes in those geological and biological facts that have continental significance" (PIG, 3638).

When the institute started to publish, not only single papers, but its own journal, entitled, of course, *Geobiologia*, it had more occasions to develop this science. In 1943, Teilhard wrote:

> What exactly is Geobiology?
> To answer that question, it should first be remembered that from year to year a double line of evidence has been growing up around us, contributed by scientists of all disciplines, showing that:
> 1. First, the world of life, taken as a whole, forms a single system bound to the surface of the earth; a system whose elements, in whatever order of association they may be considered, are not simply thrown together and moulded upon one another like grains of sand, but are organically interdependent like the streamlines of a hydrodynamic system, or like molecules caught in a capillary surface.
> 2. Second, this organic sheet which is spread over the whole surface of what is often called the "crust" but is in fact chemically the most active "sphere" of our planet, is not, either in its genesis or in its duration, physically separable from the general mass of the earth it covers. The earth is not merely a spatial support for, but the very "matrix" of this living envelope.
> Hence the growing importance Science attaches to the notion of the *biosphere*, considering it not a mere metaphoric entity but as a physical reality, as objective and as essential to the earth as the various other "spheres" (mineral, liquid, gaseous) whose concentric structures constitute our planet.
> The notion that the inorganic matter of the earth constitutes a natural whole whose elements, far from forming an accidental aggregate, manifest in their proportions and arrangement a definite structure and composition bound up with the atomic and sidereal architecture of the universe, is one long since accepted by chemists and physicists. Hence today the remarkable individualization of a chemistry and physics of the earth.
> And now the same current of thought manifests itself in the domain of Life, leading to the same results.
> On the one hand, taking shape and gaining momentum (as I have just said), is the movement which tends to bring the biosphere within the range of the greatest scientific realities known to us.
> And simultaneously on the other, the need is becoming felt for a specific discipline dedicated to the investigation of the biosphere.
> We already have Geophysics and Geochemistry.
> Now, completing the triad, appears Geobiology. (GG, 5-6)

This initiative to study living beings *in their totality as a single closed system* is emphasized again in the text. Continental evolution is again proposed as a focus for study of the biosphere as a whole, *on a reduced scale but without distortion*: the reference point is still the biosphere as a whole and the mutual relationships between living and nonliving environments. The technical methods to be used by geobiology, along with examples, were discussed by Teilhard de Chardin (GG 1943) and Pierre Leroy (1943) as well as briefly reported and discussed by Galleni (1984, 1992a).

THE SCIENCE OF THE WHOLE AS THE SCIENCE OF COMPLEXITY

To take something into consideration as a whole means going further into the problem of complexity. This problem, basic to understanding the development of Teilhard de Chardin's ideas, is today one of science's greatest challenges. Teilhard identified the tendency toward complexity as one of the characteristics of the evolution of the universe and of life. In light of Ludwig Von Bertalanffy's general theory of systems (Von Bertalanffy 1968; see also Freguglia 1994) and the mathematics of chaos (Gleick 1987), it seems that the study of complexity requires a unique approach that is dramatically changing our vision of science. An important discussion of Teilhard's view of complexity can be found in *Man's Place in Nature* (MPN). His insights are clearly summarized by Karl Schmitz-Moormann (1994):

> Teilhard wants to limit the term exactly to "*the combination*—that is, this particular and superior form of grouping whose property is to tie together in itself in a certain fixed number of elements (a few or many, that is without importance) with or without the additional help of aggregation and repetition—in a closed whole with a well-defined radius: such as the atom, the molecule, the cell, the metazoon, etc."
>
> The two essential points meriting the term of complexity are thus the fixed number of elements and the closed whole. Teilhard insists on this: the crystal is always open to further growth, there is no natural limitation to it (except that some crystals will burst due to the inner tensions). In the stars, some matter can always be added: it might change the lifetime of a star, but the star is not defined by a certain quantity of matter that could not be added to it without changing it fundamentally. Crystals and stars, in Teilhard's view, are accidentally limited systems, while a cell or any living being has, like the molecule, essential limits. One cannot add an atom to a molecule without changing it, making it quite another. One even cannot change the position of an atom in a molecule without changing the latter in its essence. (Schmitz-Moormann 1994, 240)

Hence complexity, in Teilhard's view, is the combination of elements into a whole with a well-defined boundary. But the modern science of complexity has added new insights to Teilhard's vision. The general theory of systems pointed out that the whole has characteristics that are different from the sum of the single parts: properties emerge from the interactions of the parts when they are acting as a whole. As noted by Roger Lewin, "From the interaction of the individual components *down here* emerges some kind of global property *up here*, something you couldn't have predicted from what you know of the component parts" (Lewin 1933, 12–13).

Emergence of properties when parts act as a whole is a characteristic of the complex system. The emergence of properties such as life and consciousness is, in Teilhard's view, characteristic of the evolution of the universe. So the modern science of complexity develops Teilhard's ideas about complexity: living organisms are to be considered evolving complex objects, and their evolution is characterized by the emergence of new properties. Another characteristic of complex systems is the presence of self-organizing systems that are subject to environmental influence: slight disturbances may have catastrophic consequences. According to Stuart Kauffman (1993, 30–31), life exists on the edge of chaos, where critical states and threshold effects are present. Interestingly, a central insight seen repeatedly in the papers of Teilhard de Chardin is the presence of threshold effects. Among them is the appearance of the Noosphere: the birth of the thinking creature. In Teilhard's opinion, humans appeared in essentially the same way as every other species, but their advent presented a threshold effect. Here we refer to one of Father Teilhard's most famous passages, from *The Phenomenon of Man*:

> By the end of the Tertiary era, the physical temperature in the cellular world had been rising for more than 500 million years. From branch to branch, from layer to layer, we have seen how nervous systems followed *pari passu* the process of increased complication and concentration. Finally, with the primates, an instrument was fashioned so remarkably supple and rich that the step immediately following could not take place unless the animal's entire psychic being were recast and consolidated on itself. Now this movement did not stop, for there was nothing in the structure of the organism to prevent its advancing. When the anthropoid, so to speak, had been brought mentally to a boiling point some further calories were added. Or, when the anthropoid had almost reached the summit of the cone, a final effort took place along the axis. No more was needed for the whole inner equilibrium to be upset. What was previously only a centered surface became a center. By a tiny "tangential" increase, the "radial" was turned back on itself and, so to speak, took an infinite leap forward. Outwardly, almost nothing in the organs had changed. But in depth, a great revolution had taken place: consciousness was now leaping and boiling in a space of supersensory relationships and representations; and simultaneously consciousness was capable of perceiving itself in the concentrated simplicity of its faculties. And all this happened for the first time. (PM[c] 168–69)

The fundamental step of the law of complexity of consciousness is represented by a threshold event.

So we can conclude that the present study of complexity will be one of the fruitful arenas of confrontation between contemporary science and Teilhard's contribution to theories of evolution.

Complexity, starting from Von Bertalanffy's general theory of systems, takes into consideration not only the quality and quantity of a system's components, but their relationships. The properties of the whole emerge from these relationships—not from single components: there is an emergence of properties, which could be related to threshold effects. But according to Teilhard one more characteristic is necessary in order to have true complexity: the parts of the system must not only act together, but they have to be confined in a whole with a well-defined boundary. This is the starting point for a new kind of inquiry, which may develop some of Teilhard de Chardin's most discussed contributions to the modern theory of evolution: those related to the problem of the directionality of evolution.

Taking the Biosphere as a Whole

The concept that the biosphere acts as a whole and interacts with the other earthly spheres is the very basis of geobiology. This concept is also the basis of one of the most interesting and fruitful elements of the contemporary scientific debate: J. E. Lovelock's Gaia hypothesis.

The Gaia hypothesis was first proposed by Lovelock in the seventies (Lovelock 1979). He traced his concepts back to the English geologist J. Hutton (Lovelock 1991) and to the concept of biosphere proposed by Suess and then developed by Vernadsky (Grinevald 1988). This is why previous attempts have been made to trace the relationships between Teilhard and Vernadsky, with emphasis on Teilhard's efforts to take into consideration the biosphere as a whole.[3]

According to the Gaia hypothesis, the biosphere should be considered as a whole, and this entity has a function: to maintain homeostasis. The notion that the biosphere acts as a whole is congruent with Teilhard de Chardin's notion of complexity. But the congruency is even more extensive. Teilhard, unlike such radical Darwinists such as G.G. Simpson, perceives that the evolving biosphere has a preferential direction leading to more complex and cerebralized forms and finally to the formation of Noosphere. Similarly, Lovelock maintains that the biosphere, acting as a whole, has a well-defined task: to maintain dynamic homeostasis. These assertions reintroduce teleological concepts; their relationships are worthy of discussion (for more on the Gaia hypothesis, see, *inter alia*, Lovelock 1988, 1990, 1991).

According to the Gaia hypothesis, the biosphere maintains homeostasis through mechanisms of negative feedback that connect living systems with nonliving ones. According to general systems theory, the different objects constituting the biosphere are determined fundamentally by these types of relationships (in this case negative feedback). According to Teilhard de Chardin's definition of complexity, they are concentrated in a well-defined arena with definite boundaries. Under these conditions, Lovelock's Gaia is strictly related both to the science of complexity and to Teilhard's ideas. But is this system evolving? Can a single object evolve? This is a central question that lies behind many criticisms of the hypothesis by Darwinian evolutionists. According to a simulation presented by Watson and Lovelock (1983) and Lovelock (1988), it is possible to demonstrate that on a hypothetical planet, Daisyworld, different species of daisies, which are able to control atmospheric temperature through negative feedback, are able to maintain temperature homeostasis for long periods. Stability is better maintained when more species are present: the number of interactions is positively correlated with stability. This is intuitively clear: more species mean more feedback mechanisms and thus more stability. At this point we can add a new concept to the Gaia hypothesis: homeostasis is reached through a process of diversification and increasing complexity. The objects that interact through feedback in a closed system increase both in numbers and in connections, thus moving toward stability. Like Teilhard's biosphere, Gaia is evolving toward complexity.

FROM LOVELOCK TO TEILHARD DE CHARDIN: WORKING ON METAPHORS

The use of metaphor is a way of getting information about a system in which an unknown or lesser-known object is working on a better-known object. This is possible thanks to an "**as a**" relationship, and it can be used in biology if the metaphor, this is, the "**as a**" connection, suggests an experimental pathway. In Lovelock's Gaia hypothesis, the metaphor is present: The biosphere acts "**as an**" organism.

This kind of metaphor is of great importance from an epistemological point of view because it allows one to reintroduce some levels of Aristotelian finalism. The organism of a mammal (e.g., a mouse, a dog, or a monkey) tends to maintain a constant temperature. We can say without great epistemological problems that the organism acts as a whole in order to maintain its constant temperature. Many of its organs work together with the goal of thermic homeostasis. Of course they have an internal program originated by processes that can be studied by evolutionary biologists, but the result is that the organism acts in a teleological manner. Thus some kinds of teleology might at least be discussed at the level of biosphere homeostasis. But how might this metaphor, still a static one, be connected with the continuing transformations and complexification typical of evolving life?

Here we have to introduce new metaphors—first of all, that of

Waddington: an organism "**as a**" landscape. Waddington developed this idea in the belief that ontogenetic development is clearly represented by the path of a ball moving in a landscape of valleys and hills. According to Waddington (1953), "the epigenotype of an animal can best be visualized as a branch system of development pathways, each of which leads to one component of the adult form. Each path is to a greater or lesser extent canalized or buffered."

The metaphor implies that the development of an organism is *canalized.* The epigenetic landscape is a landscape of parallel valleys and branch points. What happens depends on peculiar factors: morphogenes that at branch points direct the development "ball" into the appropriate valley. According to this model, "the sequences of gene reactions must be described in terms of branching tracks, and . . . the presence or absence of particular genes acts by determining which path shall be followed from a certain point of divergence" (Gilbert 1991, 146).

The existence and action of morphogenes, whose existence was foreseen by the theoretical works of Waddington, is one of the major discoveries of contemporary biology (Edelmann 1988).

Moreover the epigenetic landscape is predetermined, and when environmental stress alters the epigenetic landscape, the ball moves, not casually, but in a parallel valley.

We are now ready to discuss some aspects of Teilhard's evolutionary theory in light of these considerations.

THE METAPHOR OF PIERRE TEILHARD DE CHARDIN

Teilhard also proposed a metaphor: Evolution may be seen "**as a**" landscape. This metaphor is useful in discussing parallelism and canalization in evolution.

The Gaia hypothesis reintroduces into the science of the biosphere an organismic approach and some kind of teleology at a level above that of the organism. Waddington's theory of the epigenetic landscape introduces the concepts of canalization and parallelism. We have discussed how Lovelock's organismic approach could be related to Teilhard de Chardin's concept of the unity of the biosphere (and a task for the future will be to compare Teilhard's geobiology with Lovelock's geophysiology). Now we will discuss Teilhard's scientific papers in regard to parallelisms and canalization in evolutionary phenomena. As I stated in a previous paper,

> Teilhard de Chardin . . . was aware of the Darwinian interpretation that "life does not advance except when it is groping among the effects of large numbers

> and the game of change" . . . but he also was convinced that "one evolutionary phenomenon involved the whole universe and that it had a precise goal. It represents the convergent path of matter toward more conscious forms." . . . He spent a large part of his scientific research looking for evolutive trends which can explain the emergence of the Noosphere from an experimental standpoint and to look for laws or at least tendencies in evolutive orientation. In so doing he gave a peculiar contribution to evolutive theories with the foundation of a new discipline: geobiology, the science of continental evolution, with the redefinition of the term "orthogenesis" which explains the directionality of evolution looking for parallelism and finally with the proposal of the "scale" phyletic trees. These contributions were strictly related to his scientific problem: "to discover the laws of a most general process, the process of constituting, on cold stars, even more complex material units, from atoms to supermolecules, from supermolecules to cells, from free cells to metazoans and to social groups." (Galleni 1994a, 122)

These arguments have been widely discussed (Dodson 1984, 1993; Galleni 1984, 1992a, 1992b, 1994a), and they will not be mentioned here again apart from those aspects that throw new light upon the theory of evolution.

I earlier referred to the Paris *Colloquium sur Paleontologie et Trasformisme* (Galleni 1992a), which could be considered the moment when Teilhard de Chardin's ideas about evolution and the interpretations of evolution proposed by the authors of the modern synthesis reached a state of interpretation or at least of cohabitation. Teilhard de Chardin developed a wider approach in his last scientific paper, prepared for presentation to a second Paris *Colloquium sur Palentologie et Trasformisme*. This paper is of fundamental importance because while the first colloquium was the place for integration with the modern synthesis, the second should have been the place to discuss differences. These differences, based on the entire scientific corpus of Teilhard, are rich in suggestions for present research on evolutionary theories.

Teilhard used the term *orthogenesis* in its etymological meaning of "oriented evolution." I attempted to demonstrate that he was able to maintain all the scientific significance of this term while redefining it as parallel evolution (Galleni 1992a); this claim was questioned by many authors (see Ruse 1969). In his last paper he reintroduced with intensity his belief that preferential factors exist that explain the presence of parallel and directional phenomena in evolution. In this way, orthogenesis is presented as depending on both orthoselection and other mechanisms. And at this point Teilhard refers explicitly to canalization phenomena: "The dominant feature in the phylogenesis of the best-known groups is not, in the last resort, the dispersion but the *canalization* of forms" (VP, 272). And here he proposed a new mechanism that could be added to orthoselection, in order to explain canalization of evolution:

This is a proof that, followed along major tracts of time, chromosomic characteristics are not the inert "grains" and "isotropes" that geneticists suppose, but in fact elementary vectors, consisting of very short oriented segments, reacting additively, always in a single favoured direction, to the complex "topography" of the geographical and biological milieu in which they find themselves. (VP, 272)

The idea of gene additivity was developed by Teilhard in correspondence with his friend and colleague Pierre Leroy, a zoologist and geneticist. As a Jesuit, Leroy worked with Teilhard in Beijing and was one of the cofounders of geobiology (Leroy 1992). In letters Teilhard wrote to him between 1948 and 1955, this idea is often discussed, proof that Teilhard was actively reflecting upon the problem. In the postscript of a letter written in New York, dated 6 March 1952, Teilhard explicates again his ideas about orthogenesis: "All genetic explanation notwithstanding, orthogenesis (as I conceive it) is the established fact that a morphologic "additivity" in a certain direction does exist (for reasons perhaps opposed and variable). Are they a result of inertia or of preference? What, for instance, have hypsodonty and cephalization in common? I'll take the question up again in another letter" (Teilhard de Chardin, in Leroy 1976, 134).

This letter sparked a discussion about orthogenesis that demonstrates the changes in Teilhard's thought. As we can see, Teilhard is no longer satisfied by a definition of orthogenesis as the emergence of similar characteristics in different groups (parallelisms of hypsodontization and cephalization.[4]

He is not satisfied by Simpson's proposal of orthoselection; he believes canalization of evolution means that evolution runs along parallel paths due to factors other than selection—which amounts to some kind of additivity. But what are these different factors? In the following letter, dated New York, 16 March 1952, Teilhard is back to the problem:

Here are some more notes to be put with my letter in which I touched on the question of orthogenesis—a subject that interests you at the moment, and about which, as I noticed . . . many scientists are now asking questions.

In my opinion, this is the very place where the problems of evolution arise in their liveliest and most concentrated form. The word "orthogenesis" disturbs and frightens us because we identify it with particular formulas and interpretations or because the phenomenon is not easy to interpret in terms of genetics. . . . As I told you, "orthogenesis" . . . simply means that, historically, life developed and continues to develop (in ourselves, for instance) by *addition*, or (what comes to the same thing) by continually reaffirming itself along certain definite lines. In my opinion, this is a fact of pure experience. (Teilhard de Chardin, in Leroy 1976, 135–36)

Here orthogenesis is attributed to the more general laws of the evolution of the universe, in the way we have previously described (Galleni 1984, 1992a). But for the purposes of the present paper we wish to emphasize that the problem of additivity of characteristics is again underlined and, in the rest of the letter, the example of hypsodonty is again reported. Another letter, dated New York, 6 May 1953, gives us the final clues. Here Father Teilhard goes further in a discussion about chromosomes and genetics, subjects not often developed in his papers. Here he proposes a difference between characteristics acquired and transmitted culturally, with no effect on the chromosomes, and characteristics that in some way, after some generations, are assimilated into the genome.

In the case of insects in particular, where instinct (if I'm not mistaken) is admittedly of a hereditary chromosomic nature, it seems to me that only a real gambler would hold that certain behaviors (hunting, nest-making, etc.) among adults who never see their parents are not acquired habits before being "chromosized." In other words, one absolutely must distinguish between individual *acquired* characteristics which are not there already, and acquired characteristics which are absorbed into the "baggage" of the species.

As far as I can see, the real weak point of present genetics lies in the fact that everything is explained, except the genesis of the genes . . . . The essence of evolution is that it is *additive*; in other words, it accumulates certain acquired traits. (Teilhard de Chardin, in Leroy 1976, 192)

Here again we are back to the problem of additivity and also to some kind of genetic assimilation, a theory discussed in that period by Waddington (1953). Leroy (1976, 178) clearly refers to Waddington in his response to this letter; in my opinion this is Teilhard's proof of my idea that some aspects of Teilhard's thought may be correlated with those of Waddington. At this time Teilhard is actively considering the idea of additivity of genes in genome evolution.

And in one of his last letters, dated Now York, 22 January 1955, he refers to the Paris symposium being organized by Jean Piveteau, where he will not go for reasons related to his residence in the United States:

Again, there's nothing new in my life.—I'm still a little tangled in my visa troubles. Yesterday, at last, I got a six-month extension of it. In July I'll have another X ray, and then we'll see about a permanent visa. Meanwhile, I don't want to risk leaving the U.S.A. for fear of not being allowed back in. And for this reason, I shall regretfully decline Piveteau's kind invitation to join his symposium at the Sorbonne. (Its subject: "The Present Problems of Paleontology.") The voyage would be paid for. So it's a shame in a sense to miss the opportunity. But after all, it's perhaps better not to repeat the "hectic" experience of a month in Paris.—Finally, in all honesty, I'm not particularly excited by anyone's new impressions of the origins of the *Tetrapods,* or by discussion of the exact position of the *Australopithecines.* (Teilhard de Chardin, in Leroy 1976, 244)

And finally, he proposed his plan to send only a communication: "As a sign of sympathy and good will, however, I have written down a few pages to be read apropos of orthogenesis, taken in the general and rigorously experimental-phenomenal sense of 'the drift of lower Complexity-Consciousness'" (Teilhard de Chardin, in Leroy 1976, 245).

As we previously noted, it is this paper that all these considerations on additivity of orthogenesis are related to additivity in genes.[5] Such gene additivity is actually one of the major discoveries in genetics in recent years.

Problems of Darwin and Genes

Modern genetics, based on Mendel's laws, and modern theories about evolution, based on Darwin's theory of natural selection, were proposed at about the same time, in the 1850s and 1860s. Their connections were established later, in the early years of the twentieth century. Although natural selection was demonstrated to be the main force capable of introducing changes in allele frequencies, natural selection actually acts on phenotypes, while genes are the components of the genotype. The mechanism proposed by the authors of the modern synthesis would work if the connection between genes and phonotypic characteristics were linear and without complications. The great results of molecular biology obtained after World War II—that is, the discovery of the structures of DNA and the genetic code—seemed to confirm this simplified model. Further proof was apparently found in variations of characteristics in natural populations, seen as related to the action of selection (see the ecological genetics of E.B. Ford [1981]). The structure of DNA was summarized by the phrase "one gene, one enzyme," emphasizing the easy relationship between phenotype (realized by proteins) and genotype (constituted by DNA and considered to be a sequence of single genes). But what is presently curious is that many novelties of DNA organization point in a completely different way. Summarizing these novelties, Barbara McClintock wrote:

Because I became actively involved in the subject of genetics only 21 years after the rediscovery, in 1900, of Mendel's principles of heredity, and at a stage when acceptance of these principles was not general among biologists, I had the pleasure of witnessing and experiencing the excitement created by revolutionary changes in genetics concepts that have occurred over the past sixty-odd years. I believe we are again experiencing such a revolution. It is altering our concept of the genome: its component parts, their organizations, mobilities, and their mode of operation. (McClintock 1984, 793)

Many are the novelties to take into consideration. First of all, the genes coding for proteins are only a small part of DNA, at least of the eukaryotic cell, and in contrast, the large majority of DNA is made of repeated sequences whose role in DNA organization and physiology is still to be clarified. Moreover, genes are often mobile elements (transposones), and they can be amplified—that is, one single sequence may be repeated many, many times. Gene amplification is presently correlated with structural functions in DNA (centromere and telomere regions); it may have adaptive functions (gene amplification, for example, can enhance insecticide resistence in insects. Finally, dispersion and amplification of repeated sequences has been correlated with speciation (Dover 1982, Galleni 1994b). The significance of the revolution described by Barbara McClintock is that genes are not the "inert grains and isotropes that geneticists suppose, but in fact elementary vectors, consisting of very short oriented segments, reacting additively" (VP, 272).

And here we are back to our main problem: DNA amplification and repetition of sequences, at least in some cases, could be considered a kind of self-organization of DNA, a self-organization toward more stable structures, which could be considered another force responsible for canalization of evolution (see Kauffman 1993).

Another factor related to canalization in evolution concerns morphological constraints. They are taken into consideration by scientists known as "process structuralists" (Smith 1992) or "rational morphologists" (Kauffman 1993). They embody Waddington's ideas on canalization of development referred to an evolutionary landscape. We have briefly discussed some of these proposals in relation to Teilhard's ideas (Galleni 1992a, 1994a); here we emphasize that the metaphor "evolution may be seen "**as a**" landscape" is useful to clarify his thought. He clarifies his metaphor by considering evolution as a river that is creating its course from the mountains to the valley thanks to gravity (VP).

Many aspects of this metaphor are clearly related to that of Waddington. However, they deal not with the vicissitudes of individual development, but with the totality of biological evolution. This enlargement is possible because Teilhard de Chardin is taking biosphere as a whole. And actually, gene additivity is related to the metaphor: genes are acting in an additive manner because they react additively to

> the complex "topography" of the geographical and biological milieu in which they find themselves.
>
> No "mysticism" . . . is implied in the recognition of this phenomenon which inevitably reminds us of the entirely material phenomenon of a river gradually establishing its course to conform with the terrain over which it flows.
>
> But just as, in the example I have chosen of the river tracing its bed, there is (whatever the breadth and the form of the basin under consideration) the same *gravity* acting everywhere and always on the flowing water; so in the case of "speciating" matter also (that is to say in order to explain the formation of any phylum), is there not—must we not inevitably postulate—the existence of a single basic factor in operation? (VP, 272)

This metaphor implies two different factors. The first, represented by gravity, is a force moving life whose result is evolution. To Teilhard de Chardin, this force is the law of complexity consciousness. Lovelock sees the force manifested in the maintenance of dynamic homeostasis in the face of external disturbances or internal factors (errors that according to John Von Neumann [1963] are present in every replicating machine; in this case, they are related to errors in the reproduction of the DNA program [Omodeo 1992]). All these factors induce the continuous change in life that we call evolution. In this interpretation, evolution has *per se* adaptive value, as the biosphere maintains homeostasis in spite of the factors that tend to alter it. In Teilhard's river metaphor, gravity represents these factors. An attempt to demonstrate that gene additivity has adaptative value and is not only a casual consequence of other factors (as in the theory of junk DNA or the concept of the selfish genes) is a way of developing Teilhard's ideas with the aid of modern molecular biology. And actually, as we have said, seeing gene amplification as an answer to stress reinforces this line of research. Although gravity moves the river, the river is tracing its course in relation to the landscape, and in Waddington's metaphor the landscape is in some way predetermined. Is it also predetermined in some way in Teilhard's metaphor? According to the neo-Darwinists there are many possibilities in evolution, and only some of them are realized through the blind action of natural selection. According to the process structuralists, on the contrary, there are morphological constrictions that introduce few and well-defined possibilities. And finally the mathematics of chaos proves that many events that were considered purely random are actually moving toward an attractor. So the development of such a complex object as the biosphere may look casual but in fact may be influenced by attractors. Here we are again discussing canalization phenomena: not all results are possible, only those allowed by the many canalization factors of evolution. Here again, we perceive echoes of Teilhard's suggestions. As Goodwin said,

> To a neo-Darwinist, every point in that space is realizable as an organism, as long as the environmental conditions favor its expression. In other words, any kind of biological form is possible, within certain mechanical limits. I am saying that's not correct, that the organizational dynamics of morphogenesis define a limited number of points in that space, that the possible range of biological form is restricted in a fundamental way. Species as attractors in a dynamical system: it's a provocative notion, quite outside conventional biological thought. (in Lewin 1993, 40)

In this view, the rule of evolution is not dispersion of types but canalization of types toward morphological attractors. And canalization of types is a fundamental issue in Teilhard's ideas on biological evolution. We can emphasize here that the presence of attractors and of "landscapes" that are determining many aspects of evolution has been widely proposed and is further discussed by Kauffman (1993) in a book that represents the future of evolutionary theories.

Finally, canalization of development is in Waddington's metaphor mediated by morphogenes. Do morphogenes also play a role in evolution? In an unpublished paper dated New York, May 1952, Teilhard clearly refers to the presence of morphogenetic factors in evolution:[6]

> And in animal life . . . we are warned that, in spite of the remarkable and useful efforts made by the geneticians and the neo-Darwinists to reduce to an automatic arrangement the gradual development of zoological types, the existence of some internal factors of morphogenesis (in addition to the external action of changes and selection) must perforce be suspected as supplying, even at the earliest stages of evolution, the roots of the human power of *self-arrangement* through choice and planned invention. (Teilhard de Chardin, in N. and K. Schmitz-Moormann 1971, 4428)

Conclusion: A New Scientific Research Program in Evolution Following Teilhard's Perspective

In conclusion, I affirm that Teilhard de Chardin believed that the biosphere acts as a whole, and so he can be considered one of the precursors of the Gaia hypothesis. But taking into consideration the biosphere as a whole suggests that evolution has *per se* adaptive value, and that trends toward complexity are in way related to the maintanence of homeostasis. Complexification, in other words, is an adaptive answer of the evolving biosphere. A biosphere evolves due to many factors other than chance and natural selection. Genes evolve in an additive manner, and this mechanism also has *per se* adaptive value. Finally an "evolutionary landscape" canalizes the process toward some well-defined morphological results, as the process structuralists are proposing. The final conclusion is that a true scientific research program (in the sense of Lakatos [1978]) is emerging from Teilhard's scientific papers, and it may serve to unify many recent novelties in evolutionary theory:

The biosphere evolving as a whole is the object of the science of evolution. Evolution has *per se* adaptive value because it is the way the biosphere maintains dynamic homeostasis. The trend toward complexity is one of the mechanisms used by the biosphere in order to maintain homeostasis. Evolution is not moving in every direction but in those allowed by a morphogenetic landscape determined by morphological attractors or by the self-organizing forces of DNA. In such a complex system as an evolving biosphere, properties are emerging as a result of relationships between the interacting components, and threshold effects characterize biosphere evolution. The Noosphere is the result of these forces: increasing complexity related to stability, the additivity of genes, the local action of natural selection, the presence of morphological constraints of the evolutionary landscape, and threshold effects.

NOTES

1. Initials refer to abbreviations used throughout this issue of *Zygon*, as shown in the key on pp. 7–8.
2. It is to be emphasized that, among other considerations, Teilhard de Chardin suggests the presence, in the evolution of *Siphneidae*, of two different evolutionary speeds: "The actual division of the primitive *Siphneidae* . . . corresponds apparently to a rather sudden transformation (of a dispersive type) distinctly different from the slow orthogenetic changes in size and dentition observable throughout each individual radiation" (PIG 1942, 78). And these models of evolution with rapid changes followed by long period of stasis or of slow evolution are at the very basis of the description of the so-called theory of punctuated equilibria" (Eldredge and Gould 1972).
3. Lovelock presents a new concept, that of the task of the biosphere: acting as a whole, the biosphere *maintains earth in homeostasis*. This concept is lacking in the writings of Teilhard de Chardin. Investigating the reasons for this absence leads us further into Teilhard's ideas about evolution. Here our intellectual path brings us back to the nineteenth century in Italy. As John H. Newman did in the English cultural environment, a strong movement developed in Italy aiming to reconcile the novelties of modernity and the Roman Catholic faith.

One of the philosophers active in this movement was Antonio Rosmini. One of his followers was a geologist named Antonio Stoppani, who was active in the second half of the nineteenth century and who can be considered the founder of modern regional geology in Italy. He was, of course, well aware of the transformation of the geological landscape over long periods and consequently knew that the geological history of the earth was one of continuing change. But he was not able, in spite of his open mind, to accept the idea of the evolution of living beings. He considered theories of evolution to be strongly influenced by materialism and therefore not in agreement with the Bible (Stoppani 1893). But of course a clear antinomy rises here. If the geological history of the earth is one of continuing change, why is the history of life one of stability and the nontransformation of species? To solve the problem he introduced some of Lovelock's concepts a century earlier. At a group of conferences held in Milan in 1873 (Stoppani 1882) he clearly referred to the concept of biosphere: living beings must be considered to act as a whole in relationship to the other elements of the earth, and *they have to be considered as another atmosphere. This sphere is surrounding the earth and is the force that is able to condition all the geological phenomena.* The task of this peculiar kind of atmosphere (actually the biosphere of Suess, Vernadsky, and Teilhard) is to maintain stability. Living beings do not evolve, because they interact with geological events in order to maintain stability; life is a result of stability and not of transformation. This idea of stability is also present at least in the first interpretation of Lovelock's Gaia hypothesis. Of course this idea was not acceptable to Father Teilhard, who saw the whole as one of movement and of continuing change. Homeostasis was, on the contrary, an element of stability and even of immobility. Nonetheless, we will follow a line of reconciliation between these different interpretations of biosphere, going further into the problem of the biosphere considered as a whole.

4. At this point I emphasize that hypsodontia is one of the most evident characteristics Teilhard used to exemplify his concept of orthogenesis as parallel emergence of characteristics. In his fundamental paper of 1942, "New Rodents of the Pliocene and Lower Pleistocene of North China" (PIG 1942), whose importance to the theory of orthogenesis I discussed previously (Galleni 1992a), he used hypsodonty as one of the characteristics that emerged many times in rodents' history. So he looked for hypsodonty, not only in the well-discussed *Siphneidae* but also in the genus *Neotoma* and in the family *Castoridae*. In his discussion of this family, he actually wrote:

Considered as a whole, these various Pliocene forms curiously duplicate in the structure of their teeth the main evolutionary stages observed in the Mole-rats (*Siphneidae*) at approximately the same time. . . .

Whereas, however, a regular process in hypsodonty can be traced in the case of the Mole-rats from the Lower Pliocene upward, the dental stages in the Beavers are much mixed (the fully hypsodont *Dipoides*, for instance, being already found in the Pliocene).

This difference is probably due to the different phylogenetic structure of the two groups: a narrow and comparatively simple branch in the case of the *Siphneidae* . . . but a complicated and extensive tree in the case of the *Castoridae*. (PIG, 26)

Taking a group as a whole is, then, the key to each of Teilhard's interpretations of phyletic evolution. In his report (written with Pierre Leroy) on the *Felides* of China, he again concluded: "So limited, and on the whole, so uniform are the cats of China in their morphological types, however complex and exotic their origins can be, they do not form an aggregate but a recast and organized biological whole in accordance with the need and with the size of the continent" (Teilhard de Chardin and Leroy 1942, 54).

But taking phenomena as a whole means again to discover directionalities and parallelisms: "Observed as a group, the diverse types of *Machairodus*, described above, build a clearly defined organic assembly, the principal feature of which being indeed, as we showed, a division into two independant branches . . . which has been persisting side by side since the beginning of the Pliocene to the middle of the Pleistocene. Besides, on this long interval, each branch . . . continues still to evolve in an appreciable and parallel way (gradual reduction of the deuterocone and of the anterior premolar)" (Teilhard de Chardin and Leroy 1942, 17).

A final consideration on orthogenesis and Teilhard can here be made: a wide discussion of orthogenesis was presented in a book written by Lucien Cuenot, a friend of Teilhard's and one of the best known French evolutionists (Cuenot 1925). Actually these ideas were present in Teilhard's mind during his reflections on orthogenesis.

5. Teilhard presented his final ideas on orthogenesis to Madame Mortier as a repetition but also as a clarification: "In the meantime, I sent again to Piveteau a few pages on *Paleontology and Orthogenesis* (for his seminar in April). A little repetition. But is it not necessary to say the same time over and over to gain attention? And then, in telling things again and again, we imperceptibly focus the issue" (LJM, 172).

6. This is probably the test he presented at Harvard and to which he referred in a letter to Pierre Leroy dated New York, 5 June 1952 (Leroy 1976, 144).
The leters to Father Leroy suggest that this is the period when Teilhard was seriously thinking about new and different mechanisms of evolution and where his distance from the authors of the modern synthesis was clearly emerging.

REFERENCES

Works by Pierre Teilhard de Chardin are indicated by abbreviations of the title. For a list of these abbreviations, see pp. 7-8.

Note: Numbers between brackets at the end of some references are those of the pages on which the papers are reported in N. and K. Schmitz-Moorman 1971.

Birx, James H. 1991. *Interpreting Evolution. Darwin and Teilhard de Chardin.* Buffalo: Prometheus Books.

Cuenot, Lucien. 1925. *L'Adaptation.* Paris: Gaston Doin.

Dodson, Edward O. 1984. *The Phenomenon of Man Revisited.* New York: Columbia Univ. Press.

———. 1993. "The Teilhardian Synthesis, Lamarckism, and Orthogenesis." *Teilhard Studies* 29: 1-16.

Dover, G. 1982. "Molecular Drive: A Cohesive Mode of Species Evolution." *Nature* 299: 111-17.

Edelmann, Gerald M. 1988. *Topobiology. An Introduction to Molecular Embryology.* New York: Basic Books.

Eldredge, Niels, and Stephen J. Gould. 1972. "Punctuated Equilibria; An Alternative to Phyletic Gradualism." In *Models in Paleobiology*, ed. T.J. M. Schepf. San Francisco: Freeman.

Ford, E.B. 1981. *Ecological Genetics.* London: Chapman and Hall.

Freguglia, Paolo. 1994. *Dai modelli matematici in Biologia alla teoria generale dei sistemi.* Roma: Instituto Enciclopedia Italiana.

Galleni, Lodovico. 1984. "La Geobiologa, un contributo di Pierre Teilhard de Chardin allo studio dell'Evoluzione." *Il Futuro dell'Uomo* 11(1): 11-18.

———. 1992a. "Relationships between Scientific Analysis and the World View of Pierre Teilhard de Chardin." *Zygon: Journal of Religion and Science* 27 (June): 153-66.

———. 1992b. *Scienza e teologia.* Brescia: Queriniana.

———. 1994a. "Teilhard de Chardin's Search for Laws in Evolutive Orientation: A Philosophical and/or a Scientific Challenge." *Studies in Science and Theology* 2: 121-26.

———. 1994b. "Speciation in the Savi Pine Vole, *Microtus savii* (De Sel. L.) (Rodentia, Arvicolidae): A Theoretical Biology Approach." *Bull. Zool.* In press.

Gilbert, S.F. 1991. "Epigenetic Landscaping: Waddington's Use of Cell Fate Bifurcation Diagrams." *Biology and Philosophy* 6: 135-54.

Gleick, James. 1987. *Chaos.* New York: Viking Penguin.

Grinevald, J. 1988. "A History of the Idea of the Biosphere." In *Gaia: The Thesis, the Mechanisms and the Implications*, ed. P. Bunyard and E. Goldsmith. Wadebridge, Cornwall: Quintrell.

Huxley, Julian. 1942. *Evolution: The Modern Synthesis.* London: Allen and Unwin.

Kauffman, Stuart A. 1993. *The Origins of Order.* New York: Oxford Univ. Press.

Lakatos, Imre. 1978. "The Methodology of Scientific Research Programmes". In *Philosophical Papers.* Vol. 1, ed. John Worrall and Gregory Currie. Cambridge: Cambridge Univ. Press.

Lewin, Roger. 1993. *Complexity.* London: J.M. Dent.

Leroy, Pierre. 1943. "Biogéographie et géobiologie." *Geobiologia* 1: 9-16 (3761-68).

———. 1976. *Lettres familières de Pierre Teilhard de Chardin mon ami 1948-1955.* Paris: Le Centurion.

———. 1992. *Un chem non tracé.* Paris: Desclèe de Brouwer.

Lovelock, J. E. 1979. *Gaia: A New Look at Life on Earth*. Oxford: Oxford Univ. Press.
———. 1988. *The Ages of Gaia. A Biography of Our Living Earth*. London: W. W. Norton.
———. 1990. "Hands Up for the Gaia Hypothesis." *Nature* 34: 100–102.
———. 1991. "Geophysiology—The Science of Gaia." In *Scientists on Gaia*, ed. S. H. Schneider and P. J. Boston. Cambridge Mass.: MIT Press.
McClintock, Barbara. 1984. "The Significance of Responses of the Genome to Challenge." *Science* 226: 792–801.
Omodeo, Pietro. 1992. "Phylogenetic Concepts of the Nineteenth Century and the Fundamental Biogenetic Law." *Bull. Zool.* 59: 17–21.
Piveteau, Jean, ed. 1949. *Paléontologie et transformisme: Rapports et discussions du colloque international de paléontologie*. Paris: Albin Michel.
Ruse, Michael, 1969. "Confirmation and Falsification of Theories of Evolution." *Scientia*, 7th ser., vol. 104, 329–57.
Schmitz-Moormann, Karl. 1994. *The Concept of Complexity Seen in the Light of the Evolution of Complexes*. Studies in Science and Theology 2: 236–41.
Schmitz-Moormann, Nicole, and Karl Schmitz-Moormann. 1971. *Pierre Teilhard de Chardin, l'oeuvre scientifique*. Freiburg: Walter-Verlag.
Serafin, Rafal. 1988. "Noosphere, Gaia, and the Science of the Biosphere." *Environmental Ethics* 10: 121–37.
Smith, K. C. 1992. "Neo-Rationalism Versus Neo-Darwinism: Development and Evolution." *Biology and Philosophy* 7: 431–52.
Stoppani, Antonio. 1882. *Acqua ed Aria ossia la purezza del Mare e dell'Atmosfera fin dai primordi del mondo animato*. Milano: Ulrico Hoepli.
———. 1893. *L'Exemeron: Nuovo saggio di una esegesi della Storia della Creazione secondo la Ragione e la Fede*. Torino: Unione Tipografico-Editrice.
Teilhard de Chardin, Pierre, and Pierre Leroy. 1942. "Chinese Fossil Mammals." *Publications de l'Institut de Géobiologie* 8: 1–167 (3461–3634).
Teilhard de Chardin, Pierre, P. Leroy, M. Trassaert, and J. Roi. 1940. *The Institute of Geobiology in Peking*, 3216–18. Beijing: Institut de Géobiologie.
Von Bertalanffy, Ludwig. 1968. *General System Theory*. New York: George Braziller.
Von Neumann, John. 1963. *Collected Works*. New York: Pergamon Press.
Waddington, C. H. 1953. "Epigenetic and Evolution." In *Evolution*, ed. R. Brown and I. F. Danielli. New York: Academic Press.
Watson, A., and J. E. Lovelock. 1983. "Biological Homeostasis of the Global Environment: The Parable of Daisyworld." *Tellus* 35B: 284–89.