Box 2.6. Gaia

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The Gaia concept arose in the 1960s when James Lovelock was employed by NASA to help design means of detecting life on Mars. Lovelock took a general approach to the problem of life detection and suggested that if a planet harbours abundant life, it will have an atmosphere shifted many orders of magnitude away from thermodynamic equilibrium (Lovelock 1965). Earth has a remarkable atmosphere, whilst Mars and Venus have atmospheres more modestly shifted from equilibrium by the predictable action of photochemistry (Hitchcock and Lovelock 1967). Earth's atmospheric composition is also stable, in the sense that the concentrations of major gases have varied relatively little over time periods many times the residence time of their constituent molecules. This indicated to Lovelock that the composition of Earth's atmosphere was being regulated and he suggested that life was doing the regulating. The fact that life has persisted on Earth for at least 3.5 billion years, despite a ~25% increase in the luminosity of the Sun, led him to propose that the climate has also been regulated, in concert with the atmospheric composition. The concept and the system to which it refers were named Gaia (Lovelock 1972) after the Greek Goddess of the Earth.

The microbiologist Lynn Margulis played a key role in developing the Gaia concept and framing it as a hypothesis of "… atmospheric homeostasis by and for the biosphere" (Lovelock and Margulis 1974). The Gaia hypothesis postulated that "… the climate and chemical composition of the Earth's surface are kept in homeostasis at an optimum by and for the biosphere" (Lovelock and Watson 1982). A number of observations were given in support, for example, the concentration of oxygen (the product of past photosynthesis), at 21% of the atmosphere by volume, is sufficient to support the activities of large animals but below the threshold as which frequent fires threaten the persistence of slowly regenerating forests, and it has remained within these bounds for at least the last ~350 million years. Gaia had already proved successful as a hypothesis generator; Lovelock proposed that the biologically important elements sulphur and iodine would have gaseous forms produced by marine life and he then discovered dimethylsulphide (DMS) (Lovelock et al. 1972) and methyl iodide (Lovelock et al. 1973). In the late 1970s, the Gaia hypothesis was extended to encompass regulation of aspects of the composition of the ocean, including its salinity (Lovelock 1979) and the concentration of some biologically important elements (Whitfield 1981), including phosphorus and nitrogen, which had been discussed prior to Gaia (Redfield 1958).

Once the Gaia hypothesis had appeared in book form (Lovelock 1979), it attracted strong and constructive criticisms (Doolittle 1981; Dawkins 1983). These led to some of its tenets being altered or abandoned, and in the late 1980s, the original hypothesis was replaced with what Lovelock named the Gaia theory. Unfortunately, the changes are often overlooked and the outdated Gaia hypothesis continues to draw new critiques (Crutzen 2002). Hence the key changes are spelt out here:

- The notion of regulation "by and for the biosphere" was rejected with the realisation that it is the *whole system* of life and its material environment at the surface of the Earth (Gaia) that *self-regulates*. Regulation "for the biosphere" had implied teleology to some readers, although this was never intended, and regulation "by … the biosphere" had wrongly implied that life was doing the regulating. Lovelock's invention of the Daisyworld model (Watson and Lovelock 1983) demonstrated that a tightly coupled system of life and planetary temperature can automatically self-regulate (without teleology) in a manner consistent with natural selection. (The introduction of a mathematical framework is what inspired the term Gaia *theory*.)
- The notion of regulation in an *optimum* state was broadened to regulation in a *habitable* state, because different types of organism can have very different optima (e.g., temperature optima), but there are shared habitability bounds for all known life (e.g., the required presence of liquid water on the planet).
- The notion of *homeostasis* was restricted to specific cases and time intervals and *self-regulation* adopted as a more general term. Homeostasis is often interpreted as maintenance of constant conditions, although this is not strictly what it means in physiology. Constancy is not a valid generalisation of Earth history, for example, atmospheric oxygen has undergone large and possibly stepwise changes in the past (Lovelock 1988), prior to the current broadly homeostatic regulation. Both *homeorhesis* (regulation around a moving point) and *punctuated equilibria* (a series of different stable regimes) were early suggested as more accurate descriptions of Earth history, but neither term caught on. Homeostasis has also often been misunderstood as implying a system dominated by negative feedback. In fact, as in cybernetics, engineering and physiology, it was always intended to imply a system with a combination of positive and negative feedbacks.

With these changes, the Gaia theory was presented as a framework for understanding the Earth as a system and its development over time (Lovelock 1988). The effects of life within the system continued to be emphasised, but the focus shifted to understanding emergent properties of the whole system, including self-regulation. Four properties of life were identified as the basis for generating biota-environment feedbacks: First, all organisms alter their environment. Second, organisms grow and multiply, potentially exponentially (a positive feedback intrinsic to life). Third, the state of the environment constrains the growth of life (for each environmental variable, there is a level or range at which growth of a particular organism is maximum and constraints outside of which it cannot grow). Finally, natural selection determines that the types of life that leave the most descendants come to dominate their environment.

The different types of biotic feedback that can emerge from this life-environment coupling have been classified (Lenton 1998) and new examples of planetary-scale feedback mechanisms continue to be identified and quantified (Lenton and Watson 2000a, 2000b). Amongst the best established now is the proposal (Lovelock and Watson 1982; Lovelock and Whitfield 1982) that biological amplification of silicate rock weathering is part of a respon-

ing of the Earth System, knowledge of the overall nature of this role remains elusive. On balance, does the biosphere work in ways that influence the abiotic environment in directions of benefit to the biosphere? Does the biosphere provide an overall stabilising influence on the dynamics of the planetary machinery? Is the Earth System a strongly Gaian world or not (Boxes 2.6 and 2.7)?

Connectivity in space and time. Processes in far distant corners of the planet are linked in ways that could hardly be conceived of 10–20 years ago. The great conveyor belt of the ocean moves energy and nutrients in a slow waltz around the planet. Atmospheric circulation picks up dust from the continents and deposits it on the ocean surface thousands of kilometres away, triggering planktonic blooms and thus directly linking terrestrial with marine ecosystems. The combination of climate change and human hunting over 10 000 years ago has stamped northern Eurasian ecosystems with a signature still readable today in the patterns of trace gas emissions.

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sive negative feedback on long-term carbon dioxide and global temperature change (Schwartzman and Volk 1989). Much ongoing research was generated by the proposal (Charlson et al. 1987) that emission of dimethylsulphide gas from surface ocean ecosystems generates sulphate aerosol, an increased number density of cloud condensation nuclei and hence more reflective (higher albedo) clouds, with a consequent reduction in insolation and cooling at the surface of the ocean. It was suggested that this could generate negative feedback on the growth of dimethylsulphide producers. It is now understood that above the temperature at which the surface ocean stratifies (~10 °C) the sign of feedback is likely to switch to positive (warming leading to less dimethylsulphide emission thus amplifying the change). This and other biogenic positive feedbacks can amplify changes in the system, for example, at the termination of ice ages. Such behaviour is taken to indicate that at present, over-arching negative feedbacks are nearing the limits of their operation and the system may be approaching a major transition/reorganisation (Lovelock 1991; Lovelock and Kump 1994).

From the outset Gaia has referred (implicitly or explicitly) to a system. Initially this system was described as a quasi-living organism (Lovelock 1979), and later as a super-organism (Lovelock 1988). Both descriptions generated understandable resistance from biologists, whilst appealing to a general readership. The term *Earth System* arose later (NASA 1986) and it is worth asking whether it refers to the same thing? The Gaia system has been defined (Lenton and van Oijen 2002) as the thermodynamically open system at Earth's surface comprising life (the biota), atmosphere, hydrosphere (ocean, ice, freshwater), dead organic matter, soils, sediments and those parts of the lithosphere (crust) and mantle that interact with surface processes (including sedimentary rocks and rocks subject to weathering). The Earth's internal heat source is considered (like the Sun) to be outside of the influence of the system. In practice, the *surface* Earth System as studied by the IGBP and illustrated in the Bretherton diagram (NASA 1986) is the Gaia system minus some of the slowest processes. In contrast, geologists sometimes consider the Earth System to include the entire interior of the planet, and to include states without life, including those before the origin of life, whereas Gaia refers to a system with abundant life. Thus Gaia may be considered a sub-system of the *geologic* Earth System, with a shorter life span.

The Amsterdam Declaration (Box 6.11) has as its first bullet point: "The Earth System behaves as a single, self-regulating system comprised of physical, chemical, biological and human components" (B. Moore et al. 2001). This adopts the central notion of a "self-regulating system" from the Gaia theory. It doesn't say what is regulated, at what level, or what is meant by self-regulation, but these issues continue to be explored in depth in the Gaia literature (Lenton 2002) and in this volume. Thus a common theoretical framework for understanding the system now seems to be emerging, whatever we choose to call it.

Much research on global change and the nature of the Earth System has focused on the vertical fluxes of water, energy and materials between the land and the atmosphere and between the ocean and the atmosphere. While such fluxes are undoubtedly important, there is a growing awareness of the absolutely essential role that lateral flows and transformations play in the functioning of the Earth System. The central importance of the planetary circulation of the two great fluids – the atmosphere and the oceans – is obvious, although much remains to be understood about the nature of these circulations and their coupling. More recent is the appreciation of the critical connectivity of the land to the ocean through riverine systems for global biogeochemical cycling. Even more recent is the evidence that connectivity between land and ocean and between continents via the atmosphere is a surprisingly important part of the natural Earth System. Every place on Earth is downwind of someplace else, and almost every point on the continents is downstream of someplace else.

Thresholds, non-linearities and abrupt change. The behaviour of the Earth System is typified not by stable equilibria but by strong non-linearities, whereby relatively small changes in a forcing function can push the System across a threshold and lead to abrupt changes in key functions. Some of the modes of variability noted above contain the potential for very sharp, sudden changes that are unexpected given the relatively small forcing that triggers such changes. For example, the speed and amplitude of the movement of the Earth System from its glacial to its interglacial state is massively out of proportion to the small change in the distribution of incoming solar radiation that set the transition in motion. Even more dramatic are the sudden swings in temperature in the northern hemisphere, oscillations of up to 10 °C in only a decade, that appear to be associated with changes in the salinity of the surface waters in the North Atlantic Ocean sufficient to trigger major changes in deep water formation and ocean circulation.

The potential for abrupt change is a characteristic that is extremely important for understanding the nature of the Earth System. The existence of such changes has been convincingly demonstrated by palaeo-evidence accumulated during the past decade. Unravelling the triggers of such changes and the internal dynamics of the Earth System that connect the trigger to the outcome is one of the most pressing challenges to improving understanding of the planetary machinery.

Although much more is now known about the functioning of the Earth System in its state prior to significant human influence, much of this knowledge is still fragmentary. There are many examples of individual features of Earth System dynamics and many case studies showing feedbacks and other interactions. Yet, the patterns revealed by the Vostok ice core (Fig. 1.3) demonstrate without a doubt that the Earth behaves as a single, interlinked, self-regulating system in which all of these processes and connections work together to define the behaviour of the System. Thus, in terms of understanding the Earth System in its pre-human dominated form, one of the biggest challenges is to explain the Vostok patterns. Many attempts have been made (see Prentice et al. 2001 for a summary) but none has achieved a convincing explanation; the challenge remains.

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