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On Gaia: A critical investigation of the relationship between life and Earth, by Toby Tyrrell, Princeton University Press, Princeton and Oxford, 2013, 311 pp, £24.95, hbk, (ISBN 978-0-691-12158-1).

Central London on the 8th of April 2014 dawned cold and sunny. Across the road from the Albert Hall the golden statue of Prince Albert shone in full Victorian overstatement in the low-angled early morning sunshine. A short walk down Exhibition Road leads to several of the capital's most important museums and in the Science Museum people were gathering by invitation at the breakfast launch event for a new temporary exhibition on the life and work of James Lovelock. Few scientists achieve a level of eminence that causes their archive to be acquired by a major national museum and very few are the subject of a substantial exhibition – especially in their own lifetime (Lovelock, aged 94, gave one of the opening talks that morning).

Clearly Lovelock is in some way special. He is arguably best known for his ideas on Gaia (the subject of Toby Tyrrell's book and this review) but has made significant contributions to many other areas of science. For example, he is credited with giving a 'rather definitive answer' to the question of how freezing damages cells in the early 1950s [1]. This is a process of crucial importance to many areas of science but especially to reproductive medicine; think of the safe freezing of eggs, sperm and embryos. His work on the development of various important innovations in gas chromatography led to him becoming involved with the design of life detection experiments at NASA during the 1960s when this area was especially well funded and rapidly growing [2]. This work also catalysed the development of Lovelock's ideas on Gaia.

Gaia is hard to define, a task that is made harder by the fact that the definition has evolved since its original conception in the late 1960s. In this respect, Gaia is very like the concept of Darwinism which, according to Gould [3, p.146], 'like most comprehensive and complex concepts, defies easy definition'. In the early definitions of Gaia the emphasis was on 'homeostasis by and for the biosphere' resulting in conditions that were in some way ideal for life [4]. A more recent version (which is currently my preferred definition) is that 'organisms and their material environment evolve as a single coupled system, from which emerges the sustained self-regulation of climate and chemistry at a habitable state for whatever is the current biota' [5, p. 769].

This difficulty in defining Gaia is clearly a problem when it comes to trying to answer the deceptively simple looking question of 'Is the idea of Gaia right or wrong?' These difficulties are beautifully highlighted in Toby Tyrrell's recent book *On Gaia* which is subtitled 'A critical investigation of the relationship between life and Earth' [6]. His ultimate conclusion is that while some parts of the idea are correct the concept of Gaia as a whole can now be seen to be incorrect. It is clear that Tyrrell sees Gaia as an important idea. Indeed Tyrrell has long been interested in this area; he has a longstanding interest in the factors which regulate ocean nutrients, clearly a rather Gaian topic [7,8]. In addition, successful mid-career scientists tend to be chronically short of time and don't write 300 page books on subjects which they consider to be of no interest or importance! In part this book is its author's attempt to understand Gaia for himself. In the preface he suggests that at the start of the writing processes, he did not know if he was going to reach a favourable or negative opinion of the plausibility of Gaia.

Certainly anyone with an interest in Gaia would benefit from reading and – potentially – arguing with this book. This essay is one such argument and I use a discussion of the ideas in Tyrrell's book as a way of organising my own thoughts on Gaia. In so doing I attempt to highlight areas of agreement and, perhaps more crucially, areas where the jury is still out and where I believe Tyrrell has been too certain of some of his conclusions. In addition I try to suggest how we should

view Gaia: more as a complex concept like Gould's view of Darwinian evolution than a straightforward theory amenable to simple test and falsification.

In his book Toby Tyrrell follows Kirchner [9] and others [10] in pointing out that the Gaia hypothesis (or theory) is actually composed of a number of different ideas. In Kirchner's classification there are five forms of the Gaia hypothesis. The least provocative is 'Influential Gaia' where the biota is rather trivially just thought to influence the abiotic biosphere. At the other extreme are 'Teleological Gaia' (the regulation of the biosphere by and for the biota) and 'Optimising Gaia' (the biota manipulates the biosphere to make it optimal). As described above, these are close to the original idea of Gaia in some of the early 1970s publications. In between these extremes are 'Coevolutionary Gaia' where the biota and biosphere are thought to influence each other and 'Homeostatic Gaia' where the biotic influences on the biosphere impart some level of stability. There is now a consensus that the early versions of Gaia which viewed the biota as controlling the biosphere for their own ends were 'wrong because it is not life alone but the whole Earth system that does the regulating' [11, p166].

In addition, Tyrrell's book documents a range of other reasons why this view fails to match what we now know about the nature of our planet. Tyrrell views what others have called 'coevolutionary Gaia' not as one of the several ideas comprising the overarching concept of Gaia but as an alternative theory which should be seen as a scientific rival to Gaia. Yet this coevolutionary aspect was clearly a novel (but not completely original) component of Gaia when it was first put forward. For example as Tyrrell himself points out 'When Lovelock first formulated the Gaia hypothesis there were many scientists who would have defended an abiotically determined world; now there are hardly any' [6, p 114]. Kirchner [9] took a similar view. He agreed that this coevolutionary idea was correct but questioned its novelty. He pointed out that several people had written things which could be interpreted as somewhat Gaian in the 19th and early 20th centuries. Kirchner named Herbert Spencer and T.H. Huxley; but several other names could be added such as Charles Lyell, Adolphe Brongniart and especially Vladimir Vernadsky. It is usually possible to find plausible precursors to almost any scientific idea if one trawls through the literature in search of apparently 'ahead-of-their-time' statements [12]. Lovelock, and his early ideas on Gaia, do seem to have been extremely influential in establishing this coevolutionary idea in Anglophone science – although related ideas have a much longer history in Russian science [13]. This coevolutionary aspect of Gaia probably deserves more emphasis than either Kirchner or Tyrrell have given it, and I certainly see it as part of Gaia – not a rival explanation. This coevolutionary aspect was a fundamental influence of Gaian ideas on my own book on Earth Systems ecology some 8 years ago [14]. But, I agree with Tyrrell that it is the Gaian ideas about regulation that are particularly provocative and interesting and clearly move beyond anything suggested by Vernadsky and other proto-Gaians.

Homeostatic Gaia – a well-established term used by Kirchner [9], and many others - is the regulative effect due to the combined life and abiotic environment which imparts stability to planetary conditions. The term homeostasis is borrowed from physiology and was coined by Walter Cannon for the process by which an organism maintains favourable conditions for its own function. As Tyrrell points out (on his page 30) this is a fine and potentially useful analogy for thinking about the world, but it raises an important problem. As many people, such as Richard Dawkins [15], have noted, it is in principle easy to see how natural selection creates homeostasis in an organism but very hard to see how this could happen at a planetary level. The problem can be appreciated by thinking about an organism that is performing some useful Gaian function (say producing a chemical of use to the global environment). If this is of no direct use to the organism but produced at some cost to itself then any mutant that did not produce the chemical would presumably be more successful and over time its descendents would come to dominate the population. For this reason many evolutionary biologists were very sceptical about the idea of Gaia. Indeed this is a general problem with arguments that a particular organism does something 'for the good of the species' (with 'for the good of the planet' being even more unlikely!). Evolutionary biologists had largely realised during the 1960s that for the

reasons outlined above ‘good of the species’ arguments were unlikely to be correct and so were sceptical when the early papers on Gaia were published during the 1970s [16].

Nevertheless, there are some possible ways around this evolutionary impasse. Towards the end of the 1990s several people independently suggested that these problems vanish if the Gaian effects of organisms are by-products of their actions rather than having evolved directly for their Gaian effects. For example, plants and many microbes produce oxygen as a by-product of photosynthesis rather than to be of service to oxygen hungry animals like ourselves. This point – obvious with the benefit of hindsight – was made in greatest detail by Tyler Volk [17], but because his arguments were developed in a popular science book their impact in the scientific literature may have been somewhat lessened. I made similar points in a paper in the ecology journal *Oikos* [18] while Tim Lenton also made the point in passing in his well cited *Nature* paper of 1998 [19]. This idea of the importance of by-products apparently solves one problem, but as Tyrrell (and many others) point out it raises another difficult issue. ‘If the biologically driven feedbacks occur incidentally (rather than being specifically selected for because they have beneficial effects on the global environment) then needless to say they can be either positive or negative, either sustaining or destructive’ [6, p 45].

One possible answer is to import the idea of the anthropic principle from cosmology. As defined by Penrose [20, p 757] the anthropic principle ‘takes as its starting point the fact that the universe we perceive about us must be of such a nature as will produce and accommodate beings who can perceive it’. In other words, if it could not support human beings then we would not be here to worry about the nature of the cosmos! Penrose goes on to point out that we ‘could use this argument to explain why the planet upon which we live has such a congenial range of temperatures, atmosphere, abundance of water, etc, etc.’ Indeed at the end of the 1990s several authors [18, 19, 21, 22] pointed out this latter point; i.e., the idea of the anthropic principle is very relevant to Gaia. As I explained it a few years later ‘Any planet which is home to organisms as complex as James Lovelock and Lynn Margulis must have had a long period of time during which conditions were always suitable for life, and thus must give the impression of regulation for life-friendly conditions [23, p 72]’. Watson [24] called this Gaia due to the anthropic principle ‘lucky Gaia’ and contrasted it with what he called ‘innate Gaia’ where regulation is an expected emergent property of planets with abundant life.

Tyrrell [6] discusses the application of the anthropic principle to Gaia in some detail (his fig 9.1 is especially clear and likely to be very useful to anyone trying to explain this idea to their students). He implies that the anthropic principle rather undermines the idea of Gaia and because of it ‘Earth cannot be typical’ of planets with life [6, p 198]. This is indeed true, but as Watson [24] pointed out the Earth may well be typical of planets with advanced intelligent life. By taking an approach based on Bayes’ theorem of conditional probabilities, it is possible to argue that although the presence of intelligent observers does indeed mean that the Earth is unlikely to be typical of all planets with life, one can consider it likely to be typical of the subset of planets with observers. In other words, there are no good reasons to assume any other *a priori* constraints other than the presence of ourselves and so no reason to assume the Earth is not typical of planets with observers (as typical planets are by definition going to be commoner than atypical ones).

This suggests that the idea of the anthropic principle and lucky Gaia is much more significant than suggested in Tyrrell’s book. Since it is now uncontroversial that life has a major effect on the global environment and that life friendly conditions have existed continuously for several billion years on Earth (otherwise we would not exist), the feedbacks in the Earth system must be effectively Gaian; i.e., at least partly stabilizing and with life playing a major role as it has such large effects on many aspects of the Earth system. In short, *the Earth system is Gaian*, and based on the arguments made by Andy Watson [24] it also follows that any planet which evolved intelligent observers should be Gaian too.

From an applied point of view this is all we need to know. It does not matter if all planets with life can be expected to be like this or not when we are thinking about approaches to managing the Earth. What matters are the conditions on our planet. Yet, from the standpoint of a general scientific understanding of the universe, it is clearly interesting to ask if there is more to it than the 'luck' of lucky Gaia. Indeed from a philosophical point of view and even perhaps a theological perspective, this is also an important question (cf. Ruse [25]). I think Tyrrell and many other commentators have been too quick to define a Gaia based purely on the anthropic principle as uninteresting – it tells us something very important about the world.

It follows from these anthropic arguments that homeostatic Gaia must be a reasonably accurate description of the Earth. The open question is what is the mechanism? Is it just the anthropic principle (luck) or are there emergent properties of a planet with abundant life that make the long term persistence of life more likely? This second option is what Watson [24] called innate Gaia or 'probable Gaia' in the terminology of Lenton and Wilkinson [26] and Free and Barton [10]. Tyrrell [6] effectively equates homeostatic Gaia with probable Gaia. I agree with the analysis of Free and Barton [10] who suggest that a homeostatic Gaia could be produced by either 'lucky' and/or 'probable' mechanisms (see their insightful Fig 1). There are a range of mechanisms involving life which could potentially increase the survival time of life friendly conditions on a planet and *may* apply more widely than just on Earth. For example, Tyrrell discusses the role of silicate weathering on global climate in some detail – indeed this is commonly discussed in a Gaian context. Another possibility – not discussed by Tyrrell – is the potential role of life in creating conditions that helped in preserving water on the planet, preventing its loss to space in the form of hydrogen [27, 28].

The difficulty with all these mechanisms (and Tyrrell does a very useful job of discussing many more in detail in his book) is that they are all exceedingly complex processes open to a variety of interpretations. Our current understanding of Earth history – which has advanced substantially since the idea of Gaia was first proposed – makes it clear that any regulation must be far from perfect. Just like an old bathroom shower whose water temperature fluctuates while you are standing under it, imperfect regulation is very different from no regulation (which could give you near icy or scalding hot water in your shower). For example the 'snowball Earth' events discussed in Tyrrell's book demonstrate apparent 'failures' in regulation which may be due in part to life; but the system recovers and life (e.g., through its putative role in preserving water on the planet) may also be active here too. To summarise: although we only know one planet with life it may be impossible to be sure if 'probable Gaia' is a correct explanation. Drawing firm conclusions from a sample size of one is usually impossible. If this was not so, we would have no need of statistics textbooks.

The key differences between Tyrrell's analyses and mine appear to focus on two points. He is certainly right to focus on regulation (probably best thought of as processes that prolonged the life span of the biosphere) as central to Gaia. On the other hand, he views a homeostatic Gaia based on the anthropic principle as not Gaia; but, as far as I can see for all practical earth bound purposes such as system is fully Gaian. Further, although we both agree that the evidence is not conclusive for the mechanism of probable Gaia, we differ in our best guesses. Tyrrell thinks it is unlikely to be correct while I would guess that it is at least partly true. Without other planets to study this may be hard to establish fully and I have no idea how many other planets with life would make a suitable sample. If probable Gaia is a strong effect, then a handful of planets may do. But if it is a relatively weak effect which just slightly biases things in favour of a longer time span of biosphere survival then it may take hundreds of planets to have the statistical power to show the effect. I currently see no easy way of telling between these alternatives.

Since it is a long time before we will be able to follow the history of a sample of extra-terrestrial Gaias (always assuming there is life outside our solar system!), are there any other approaches that could be tried? Experiments are usually seen as a particularly important approach to

gaining scientific knowledge, but there are few Gaian experiments. After all, how do you experiment on a whole planet? Unfortunately we are now doing this with climate and other anthropogenic changes to the Earth, but it is not a very well planned experiment! As Free and Barton [10] pointed out, however, because for most of the history of life on Earth all life was microbial it would be reasonable to use simple microbial microcosms to make a start, at least, with experimental Gaian research. The work of Alaxandru Milcu, Phil Ineson and colleagues on small carbon cycle microcosms provide examples of possible approaches and also illustrate the challenges of such an approach [29, 30]. There may be questions about the universal generality of such experiments as they can only use organisms from a Gaian planet with a history of over three billion years of continuous life.

Tyrell argues at the end of his book that it matters if Gaia is a correct idea as it may affect how we approach managing the Earth system. He suggests that a belief in Gaia could tend to make people less worried as they may think that a Gaian planet can sort out any damage we do to it. Therefore in Tyrrell's view it is important to be clear that Gaia is wrong. On the other hand, I have argued above that the long term persistence of life on Earth means that the Earth system must be somewhat Gaian, although it is unclear if this is just luck or an expected property of a planet with life. What Gaia means in this context is that on average the main feedbacks in the Earth system have tended to be regulating (or at least not profoundly destabilizing) and that life has played a major role in this. Rather than suggesting to me that all is well and the planet can look after itself this seems to suggest at least great caution in making significant modifications to the abundance and diversity of life on Earth as this may alter its ability to continue to contribute to important feedbacks. The moral philosopher Mary Midgley [31] has also drawn very different lessons from Gaia, and what it means for our behaviour towards other life forms, in contrast to those suggested by Tyrrell. Clearly, Gaia need not lead to an 'all is well' view of our planet.

To conclude, I think I view Gaia somewhat differently from Tyrrell (and possibly also Lovelock). I think of Gaia as an explanatory framework (in the sense of Vepsäläinen and Spence [32]) rather than a single theory open to a simple test. In this, it is similar to the concept of Darwinian evolution which is composed of a number of different theories [33] and is best judged by its overall utility in making sense of a complex world. Another recent book provides a neat sound bite that summarises the current position. In his book 'Oxygen' Donald Canfield [34] wrote of Gaia that 'Few working geobiologists would refute the importance of life in influencing the chemical environment. The role of life in actively regulating this chemistry is a frontier research area and a topic of intense discussion'. As the discussion in this review makes clear, Tyrrell and I agree on much detail but differ in some of our best guesses about the best way to make sense of it all.

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