David Beerling

The Emerald Planet

'One of the greatest stories ever told.' *New Scientist*

OXFORD LANDMARK SCIENCE

THE EMERALD PLANET

David Beerling is the Sorby Professor of Natural Sciences and Director of the Leverhulme Centre for Climate Change Mitigation at the University of Sheffield. He has published numerous articles in learned academic journals. *The Emerald Planet* is his first popular science book and formed the basis of a major three-part BBC Two television series, How to Grow a Planet. He was elected to the Fellowship of the Royal Society, London, in 2014.

Praise for *The Emerald Planet*

'My favorite nonfiction book this year. A minutely-argued but highly readable history of the last half-billion years on earth. The story Beerling tells could not have been put together even ten years ago, for it depends upon the latest insights from palaeontology, climate science, genetics, molecular biology, and chemistry, all brilliantly and beautifully integrated together. I got a special deep, quiet pleasure from reading *The Emerald Planet*—the sort of pleasure one gets from reading Darwin.'
Oliver Sacks, Books of the Year, *Observer*

'Within these pages is one of the greatest stories ever told: the story of the way plants have shaped our planet and how they will shape its future as the climate changes more rapidly than ever before. It is as fascinating as it is important.'
Stephanie Pain, *New Scientist*

'A beautifully detailed account of the puzzles of reconstructing Earth's climatic history . . . a gorgeous book about plants and the fantastically complex way they can be used to deduce past climatic events.'
Steven Poole, *The Guardian*

'Here at last is David Beerling as the Green Knight, revealing the extraordinary story of the construction of our emerald planet. Rigorous science joins hands with an enthusiastic delivery to re-awaken our fascination in plants, while engaging anecdotes provide a thrilling background to an extraordinary story of climate change and our current environmental crisis.'
Professor Simon Conway-Morris, author of *Life's Solution*, University of Cambridge

'A fascinating, ambitious and well-written book [on] how the pursuit of plants promises to unlock greater riches from their fossil record . . . a fresh form of critical analysis on some of the major issues of Earth's history. Beerling makes a compelling case for the power of plants and for research on living systems as a way of unlocking the potential of the fossil record.'
Paul Kenrick, Natural History Museum, London

'David Beerling's fascinating new book offers a new global perspective on the evolution of our planet . . . [a] vivid account . . . The environmental legacy of the plant kingdom upon our world can only be better appreciated after reading this book.'
Louis Ronse De Craene, Book of the Month, *Geographical*

'Beerling uses evidence from the plant fossil record to reconstruct past climates and to help explain mass extinctions. Too often this evidence has been disregarded, but Beerling gives it its due, and then some. [He] introduces us to the scientists of the past and their contributions to today's hypotheses . . . and successfully conveys the incremental nature of science and that new hypotheses often emerge from a combination of observations and syntheses of previous work.'

Pamela Soltis, Florida Museum of Natural History

'David Beerling tells two stories in parallel. Both are eloquently and engagingly merged in a scholarly, yet generally accessible book . . . Beerling provides for the reader a fascinating history of the discovery of fossils and the inferences drawn from them . . . this book is a wonderful example of the nascent field of Earth systems science.'

Paul Falkowski, *Nature*

'Beerling gives us the big picture of how plants have changed our planet—and poses the key question of how we will manage the emerald planet to ensure the kind of future we desire.'

Professor Sir Peter Crane, University of Chicago

'*The Emerald Planet* is a serious talking to about why plants must not be ignored. Everyone should appreciate this . . . and also know, Beerling argues, how plants fit into the global picture.'

Jonathan Silvertown, *Times Literary Supplement*

'[A] fascinating overview of green evolution.'

Karl Dallas, *Morning Star*

'Reads like a novel . . . but is constructed solidly on a foundation of diverse scientific literature. The stars are the scientists from the past, the present and the near future, pushing back ignorance, racing against each other and sometimes against impending natural threats . . . The coverage is sweeping. An engaging historical narrative in which science seems to be a fast-paced enterprise. Provocative, well written and well researched.'

William A. DiMichele, Smithsonian Institution, Washington DC

'David Beerling is to be congratulated on producing a highly readable account of an underappreciated aspect of Earth history—the role of plants in shaping today's planet, and our views of it. Palaeobotany has probably never been so topical.'

Nigel Chaffey, *Annals of Botany*

‘Of great value and relevance to all interested in plants, climate and, equally, the future of our “emerald planet”.’
John MacLeod, Royal Horticultural Society

‘Refreshingly novel... a thought-provoking book... by better understanding the role that plants played during extreme episodes in Earth history we are better equipped to understand the changes that might occur in response to global warming.’
Howard Falcon-Lang, University of Bristol

‘His account interweaves hard scientific facts with rich anecdotes about the scientists who have pieced together the evolutionary record over time. The result is a book that is fascinating and exciting to read. *The Emerald Planet* is beautifully written, fresh and provocative.’
Jennifer McElwain, *American Scientist*

THE EMERALD PLANET

How plants changed Earth's history

DAVID BEERLING

OXFORD
UNIVERSITY PRESS

OXFORD
UNIVERSITY PRESS

Great Clarendon Street, Oxford, OX2 6DP,
United Kingdom

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide. Oxford is a registered trade mark of
Oxford University Press in the UK and in certain other countries

First published 2007
First published in paperback, 2008
Revised impression, as Oxford Landmark Science 2017

The moral rights of the author have been asserted

First Edition published in 2017
Impression: 1

Published in the United States of America by Oxford University Press
198 Madison Avenue, New York, NY 10016, United States of America

British Library Cataloguing in Publication Data
Data available

Library of Congress Control Number: 2016955210

ISBN 978–0–19–879832–3

Printed in Great Britain by
Clays Ltd, St Ives plc

For Juliette

FOREWORD

The Emerald Planet is one of those books that makes you think differently about the world you live in. Or at least it certainly did that for me. I had been used to thinking of how the Earth worked in terms of those big physical processes you can see—shuddering earthquakes, belching volcanoes, grinding glaciers. But what unfolds in the pages of this book is the story of a silent force that has shaped our planet and almost everything living on it, one that is hidden in plain sight: plants.

I'm not sure what your feeling about plants is, but mine had always been rather ambivalent. Plants seemed... well... dull. Even a brief childhood phase of force feeding insects to my Venus Fly Trap simply highlighted how little plants did. Animals were far more exciting. Even rocks were more impressive, courtesy of the spectacular landscapes they helped sculpt. True, plants could be beautiful too, even extravagant, but they were passive—bit players in the workings of a natural world that elsewhere was bristling with shock and awe. Then, I read *The Emerald Planet.*

I came to the book just as I was finishing a television series called 'Earth: The Power of the Planet', which celebrated the wonderfully intricate interplay between our land, ocean, ice and atmosphere. It showcased the new geological perspective of Earth System Science, which brought together insights from all aspects of science to understand how the planet we call 'home' came to be. For me, the revelation of *The Emerald Planet* was that when you are interested in those planetary scale machinations, and when you have hundreds of thousands or millions of years to play with, that's when plants come to the fore. That's when they become a planetary force in their own right - orchestrating the evolution of our climate, our landscapes and our animal life. It is true that plant power is a slow and almost imperceptible force, but set against a backdrop of creeping continents or the measured rise and fall of mountains, the actions of the plant world become dramatic and fundamental. The result is an epic story that deserved to be told, and so the seeds of a television series were sown: *How to grow a planet*.

The Emerald Planet opens with a humorous but telling remark from the book *Science made stupid* which states 'The history of plants is an important chapter in the story of life. Unfortunately it's a pretty dull chapter, so we'll skip it.' David Beerling's achievement with this engaging book is that no reader will ever think that way ever again.

Iain Stewart

PREFACE

The great evolutionary biologist J.B.S. Haldane (1892–1964), on being asked by a cleric what biology could say about the Creator, entertainingly replied, 'I'm really not sure, except that the Creator, if he exists, must have an inordinate fondness of beetles.' Haldane was referring to the fact that approximately 400 000 species of beetles make up roughly 25% of all known animal species. Current estimates for the total number of species of flowering plants in the world (300 000–400 000), had they been available to him at the time, may have given Haldane pause for thought about his riposte.

Plants and beetles may be tied, stem and thorax, in the global biodiversity stakes but when it comes to capturing our own fascination, plants are way ahead, clear winners in the popularity stakes. We have been collecting, classifying, and cultivating floras worldwide for centuries. Not only do plants provide us with fuel, food, shelter, and medicines that sustain the human way of life, but they also uplift and inspire us. Irrespective of the season, we flock to fine gardens, elegantly sculpted landscapes, botanical gardens, and arboreta to pay homage to the plants and trees.

But how many of us have stopped to wonder how remarkable plants are, how profoundly they have altered the history of life on Earth, and how critically they are involved in shaping its climate? Only now are we unlocking vital information about the history of the planet trapped within fossil plants. My aim in writing this book has been to provide a glimpse of these exciting new discoveries because they offer us a new way of looking and thinking about plant life. It recognizes—indeed emphasizes—

that plants are an active component of our planet, Earth. At the global scale, forests and grasslands regulate the cycling of carbon dioxide and water, influence the rate at which rocks erode, adjust the chemical composition of the atmosphere, and affect how the landscape absorbs or reflects sunlight. In this book, I reveal how plant activities like these have added up over the immensity of geological time to change the course of Earth history. Never mind the dinosaurs, here is a revisionist take on Earth history that puts plants centre stage.

My hope is that the book will further stimulate readers' natural fascination with plants—both the living and the long dead—by revealing their activities in this new light. Each chapter leads the reader through a scientific detective story describing a puzzle from Earth history in which plants have played a starring role. Occasional linkages with themes from other chapters are pointed out as they arise. This format allows individual chapters to stand alone or be read in sequence. I provide a short summary at the start of each chapter to help readers quickly grasp the nature of the puzzle and glimpse the scientific excitement ahead. In writing a popular science book like this, it is true that, in Mark Twain's words, I have got 'wholesale returns of conjecture out of … a trifling investment in fact'. All sources of the 'facts' taken from the published scientific literature are given in the notes, and where my ideas and conjecture are more speculative, I hope I have clearly signposted them as such. I have made every effort to keep the text free of scientific jargon, but admit that the odd word or term has proved indispensable. These are defined or explained where they occasionally crop up.

> *He had been eight years upon a project for extracting sunbeams out of cucumbers, which were to be put into vials hermetically sealed, and let out to warm the air in raw inclement summers.*
>
> Jonathan Swift (1726), *Gulliver's travels*

Humankind continues to take liberties with our planet, although not, of course, in the gentle manner Jonathan Swift described in *Gulliver's travels*. By consuming fossil fuels and destroying tropical rainforests, we are undertaking a global uncontrolled experiment guaranteed to alter the climate for future generations. Plants and vegetation are major actors in the environmental drama of global warming now as they have been in the recent and more distant past. This book focuses on the distant past, Earth history from millions of years ago. As we shall see, though, this investigation of the past has much to teach us about our present predicament. It offers us cautionary lessons about the current mismanagement of our planet's resources we would be wise to heed.

July 2006, Sheffield D.B.

ACKNOWLEDGEMENTS

This book had its genesis in discussions with colleagues over a beer in a sushi bar in San Francisco, in December 2002. San Francisco is home of the fall meeting of the American Geophysical Union, an annual gathering of several thousand scientists from a host of disciplines who congregate for a science feast. At the 2002 meeting, I had the prospect of delivering a belated inaugural lecture the following spring hanging over me, and was searching for an effective way to present some of the findings of my research group over the past decade in an engaging way to a lay audience. One idea was to present them as a series of short stories, each beginning with a seemingly straightforward question, an approach used to good effect by Paul Colinvaux in his admirable 1980 book *Why big fierce animals are rare* (Penguin, London). The basic concept of individual stories, each with plants playing the starring role, worked well on the night, and I subsequently adopted that format here, although in all but one case the inclusion of a question-in-the-title has been abandoned.

Many people have been instrumental in helping to put this book together. I extend warm thanks to Bill Chaloner (University of London) and Colin Osborne (University of Sheffield) for patiently and critically reviewing earlier drafts of the text. Many other colleagues also kindly gave of their time to critically read and comment on various chapters, provide data, ideas, and images, and engage in detailed discussions about the different scientific issues and queries raised during the writing process. I have benefited greatly from their input and special thanks must go to Paul Kenrick (Natural History Museum, London), Karl

Niklas (Cornell University), Charles Wellman, Doug Ibrahim, Barry Lomax, Peter Mitchell, Andrew Fleming, and Ian Woodward (University of Sheffield), Robert Berner (Yale University), Jon Harrison (Arizona State University), Robert Dudley (University of California, Berkeley), Don Canfield (Odense University, Denmark), Henk Visscher (Utrecht University), Dana Royer (Wesleyan University), Charles Cockell (Open University), Kevin Newsham and Jonathan Shanklin (British Antarctic Survey), Virginia Walbot (Stanford University), Sheila McCormick (University of California, Berkeley), Lee Kump (Pennsylvania State University), Michael Benton and Paul Valdes (University of Bristol), John Pyle and Michael Harfoot (University of Cambridge), Tim Lenton (University of East Anglia), Paul Wignall, Jane Francis and Jon Lloyd (Leeds University), Gavin Schmidt (NASA/Goddard Institute for Space Studies, New York), Barry Osmond (Australian National University) and Govindjee (University of Illinois). The corrective feedback of all of these individuals trapped numerous errors of interpretation, and crucial omissions. Any remaining errors and over-enthusiastic interpretations of datasets and published papers remain my own responsibility.

The groundwork for my thinking about plants as a geological force of nature was laid in large part during my tenure of a Royal Society University Research Fellowship held between 1994 and 2001. I am extremely grateful to the Royal Society for funding my research through this mechanism. These fellowships continue to offer unsurpassed opportunities to young scientists by giving them the most valuable commodity in their armoury—time to think, free from the usual burdens of administration and teaching that normally accompany academic life. I am also grateful to the Leverhulme Trust and the Natural Environment Research Council, UK for their financial support of my research.

Popular science writing requires a step change in style from the more turgid prose used in writing scientific papers. Francis Crick (1916–2004), the British molecular biologist and co-discoverer of the structure of DNA, commented in his 1990 book *What mad pursuit: a personal view of scientific discovery* (Penguin, London) that 'there is no form of prose more difficult to understand and more tedious to read than the average scientific paper'. I am extremely grateful to my editor, Latha Menon, for her wise counsel and suggestions on earlier drafts that have eased the transition, and which have been instrumental in shaping the current direction of the book. Whether I have been successful in this endeavour or not is another matter; any failings remain my own. I also thank the production team at Oxford University Press for efficiently shepherding me through the production process, especially Michael Tiernan the copy-editor and Sandra Assersohn for efficiently sourcing some delightful images.

Finally I thank my partner Juliette for her forbearance far above and beyond the call of duty. The time that writing this book has stolen from us over the past three years astonished me as well.

CONTENTS

ILLUSTRATIONS

PLATES

(*Upper image*: Leibniz Institute of Marein Sciences (IFM-GEOMAR). Reproduced with permission. *Lower image*: courtesy of Tom Pantages.)

Plate 11 Scott's party at the South Pole.

(Scott Polar Research Institute. Reproduced with permission.)

Plate 12 Albert Seward.

(National Portrait Gallery, London. Reproduced with permission.)

Plate 13 Fossil remains of polar forests discovered in Axel Heiberg Island in the Canadian High Arctic and on the Antarctic Peninsula (top left). The tree stump (top left) is thought to be of dawn redwood (*Metasequoia*), a deciduous species with feathery leaflets still widely planted today (top right). The substantial fossil tree trunk discovered on Antarctica (bottom left) belongs to the southern beech (*Nothofagus*) family, the relatives of which form extensive natural forests in New Zealand (bottom right).

(*Top left*: Eocene fossil stump, courtesy of Jane Francis, University of Leeds. *Top right*: Ming Li/Photolibrary. *Bottom left*: courtesy of Jane Francis, University of Leeds. *Bottom right*: courtesy of Ian Woodward, University of Sheffield. All photos reproduced with permission.)

Plate 14 John Tyndall.

(© Getty Images. Reproduced with permission.)

Plate 15 Martin Kamen and Samuel Ruben.

(*Kamen image*: AIP Emilio Segre Visual Archives, Segre Collection. *Ruben image*: Ernest Orlando Lawrence Berkeley National Laboratory. Both photos reproduced with permission.)

Plate 16 The complex web of feedbacks between biology and the climate system, linked by fire, which might have accelerated the global expansion of C_4 savannas some 8 million years ago.

(Photo courtesy of Doug Ibrahim, University of Sheffield. Reproduced with permission.)

Plate 1 A fossil of *Cooksonia,* the earliest vascular land plant. Fragile and leafless, *Cooksonia* heralded the start of greater things to come.

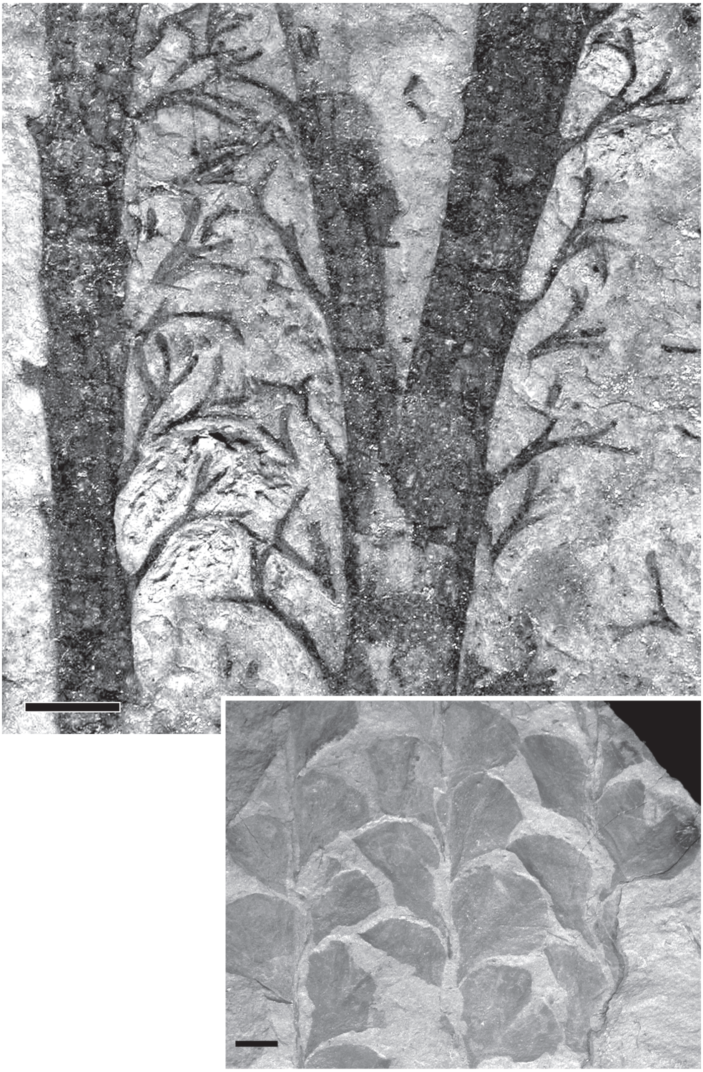


Plate 2 The leafless and the leafy. *Top*: a branch of the 380-million-year-old fossil species *Calamophyton primaevum* from Goé in Beglium. Its forking side shoots are considered to be the ancestors to leaves. Scale bar = 10 mm. *Above*: a typical example of large leaves that developed after carbon dioxide levels plummeted. This image illustrates those of *Archaeopteris obtusa,* dating to late in the Devonian, around 370 million years ago. Scale bar = 10 mm.

Plate 3 The brilliant French chemist Antoine Lavoisier.

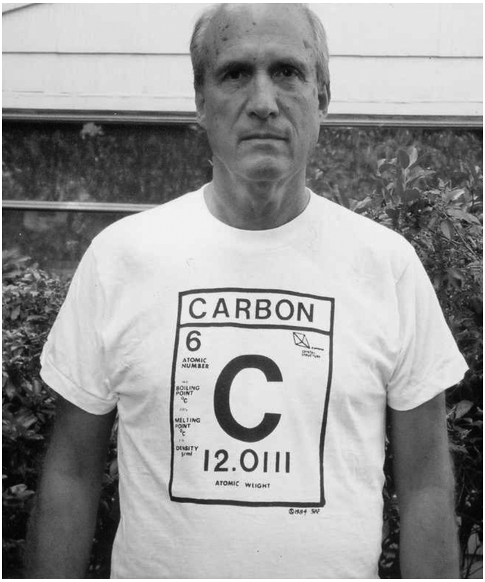


Plate 4 Robert Berner of Yale University, who played a pivotal role in uncovering Earth's atmospheric oxygen history over the last half billion years. Berner is sporting a tee-shirt displaying the atomic details of his favourite element, carbon (C), which is number six in the periodic table.

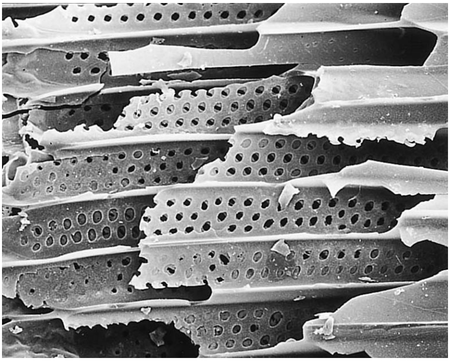


Plate 5 Fossil charcoal of gymnosperm woods from wildfire in Nova Scotia, occurring 300 million years ago. Note that the outstanding cellular preservation detail of the water-conducting cells (tracheids) is still visible. Scale bar = 100 μm.

Plate 6 Robert Strutt, 4th Baron Rayleigh, a pivotal figure in the discovery of the ozone layer.

Plate 7 Mutated fossil plant spores dating to 250 million years ago. Notice the cluster of individual spores stuck together in unusual unseparated clumps. Scale bar (top left) = 50 μm (1 mm = 10–6 m, that is, one millionth of a metre).

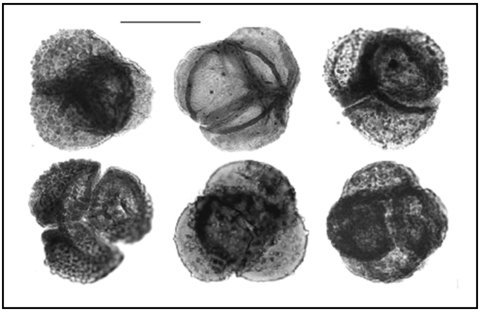


Plate 8 William Buckland in 1833. Buckland was described in the early nineteenth century as 'cheery, humorous, bustling, full of eloquence, with which he too blended much true wit; seldom without his famous blue bag, whence, even at fashionable evening parties, he would bring out with infinite drollery, amid the surprise and laughter of his audience, the last "find" from a bone cave.'

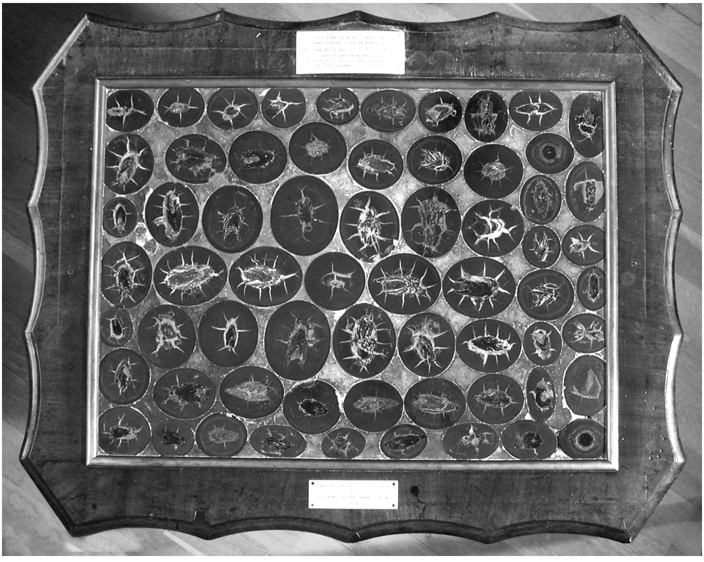


Plate 9 Buckland's table, with inlaid polished coprolites, displayed at the Philpot Museum, Lyme Regis.

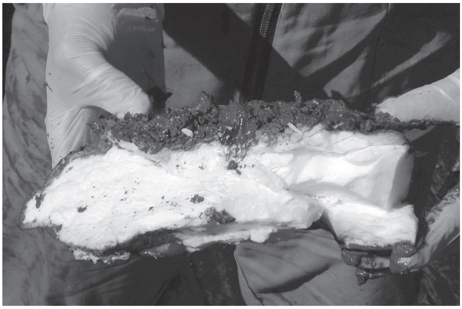


Plate 10 *Left*: solid methane hydrate brought up from the depths of the ocean. *Below*: small fragments of icy hydrate burning in air.

Plate 11 *Below*: Scott's party at the South Pole. From the left: Lieutenant Bowers, Captain Scott, Dr Wilson, Seaman Evans, and Captain Oates. They stand beside the Union Jack presented by Queen Alexandra, given with the instructions to erect it if and when the South Pole was reached. The photograph was produced from the negative found inside the tent in which Scott and his companions perished.

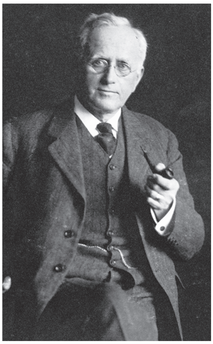
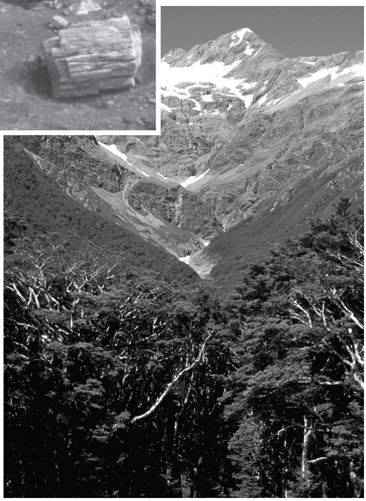


Plate 12 Albert Seward. Seward was the palaeobotanist who examined the fossils collected by Scott's party. He conjectured that trees could have survived perfectly well growing in an ancient polar environment, regardless of whether they were evergreen or deciduous.

Plate 13 Eocene-aged fossil remains of polar forests discovered in Axel Heiberg Island in the Canadian High Arctic and on the Antarctic Peninsula.

The tree stump (*above*) is thought to be of dawn redwood (*Metasequoia*), a deciduous species with feathery leaflets still widely planted today (*right*).



The substantial cretaceous fossil tree trunk discovered on Antarctica (*above*) belongs to the southern beech (*Nothofagus*), the relatives of which form extensive natural forests in New Zealand (*right*).

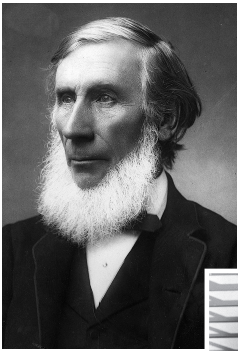


Plate 14 Renowned Irish physicist John Tyndall in around 1884.

Plate 15 Martin Kamen in 1947 (*left*) and Samuel Ruben (*above*) in the late 1930s or early 1940s. Kamen and Ruben were co-discovers of the long-lived radioactive isotope of carbon, 14C.

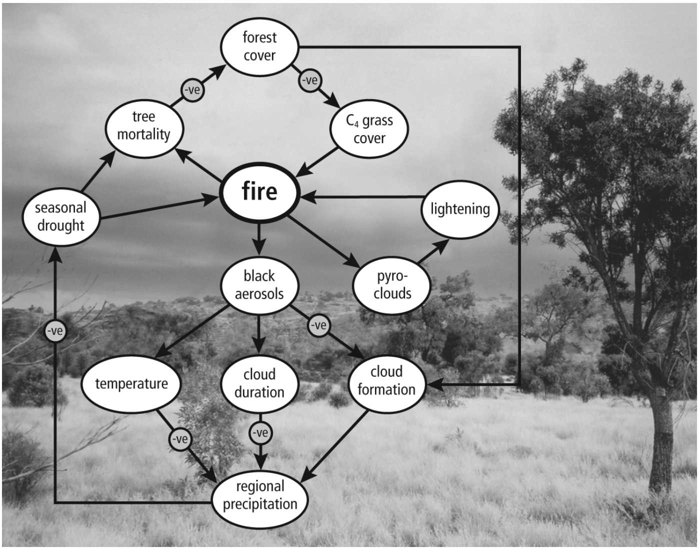


Plate 16 The complex web of feedbacks between biology and the climate system, linked by fire, which might have accelerated the global expansion of C4 savannas some 8 million years ago. The background photograph shows a C4 savanna near Mt Winter, Northern Territory, Australia, in June 2000.

1

Introduction

This book tells for the first time stories of the evolution of plants. It illuminates the exciting role fossil plants are playing in unravelling the history of our planet. The illumination is made possible thanks to the emergence of an exhilarating new discipline, one that integrates unprecedented knowledge of plants as living organisms with their fossil record and the role they play in driving global environmental change. As we do so, we can see clearly that plants are not 'silent witnesses to the passage of time' but dynamic components of our world that shape and are, in turn, shaped by the environment. The power of the new science is that it brings to life the plant fossil record in previously hidden ways to offer a deeper understanding of Earth's history and pointers to our climatic future.

The evolution of plants is an important chapter in the history of life. However, it's a pretty dull chapter, so we'll skip it.

Tom Weller (1985), *Science made stupid*

CHARLES Darwin (1809–82), the greatest naturalist of all, was fascinated by them, Richard Dawkins all but ignored them.[1] The world, it seems, is divided about the charms of the plant kingdom. The opening quotation of this chapter is from the American popular science author Tom Weller's witty and provocative 1985 book *Science made stupid*, and sums up the malaise afflicting those on one side of the great divide. To these folk, plants have an unexceptional evolutionary trajectory leading up to the emergence of our modern floras and play no appreciable role in unravelling Earth's history. Too often, this view is reiterated, reinforced, in Earth science textbooks, where it is palmed off on the unwary reader as received wisdom. Many such scholarly tomes devote a few pages to Earth's first green spring, that decisive moment of our past when terrestrial plants turned the continents green. A few graciously give more space—an entire chapter, perhaps—to the progression of plants up the evolutionary ladder from their earliest beginnings through to the appearance of the first forests, the emergence of seed plants, and the blooming of the Earth with the rise of flowering plants. Fewer still recognize plants as important players in the game of life.[2]

In this book I argue that Weller's viewpoint, and the conventional view of textbooks, is now outdated, redundant even, and misguided. The scientific investigation of fossil plants is on the threshold of an exciting new era, a grand synthesis illuminating new chapters in the inseparable stories of plant evolution and Earth's environmental history. This book is about that new science. It is an endeavour that has emerged unnoticed in the last two decades but which is proving a powerful tool for clearing a path through the dense, sterile thicket of entrenched orthodoxy. It advocates fossils not as the disarticulated remains of ancient plant life gathering dust deep within the basements of museums, but as exciting, dynamic entities brought to life in new ways by the scientific investigation of their living counterparts. The *Emerald planet* is not a textbook, nor an attempt at describing, blow-by-blow, the detailed evolutionary history of plant life over the ages in a manner accessible to the general reader. Neither will the reader find a classical treatment of the detailed history of the Earth, with its shifting continents, the opening and closing of ocean gateways, and the changing climate of the past 4.5 billion years. To be sure, plant evolution, global climate change, and the theory of plate tectonics are all elements that form a crucial part of what the new science is about. But the argument is that we must marry these traditional elements of geology with a focus on plants as living organisms to mount a frontal attack on the citadels of received wisdom and orthodoxy and reach a deeper understanding of Earth history.

The endless fascination of reaching for this deeper understanding of Earth history is that it has already happened. It establishes the sparkling intellectual adventure of unravelling the what, why, and how of it all. Ancient fossils and rocks document it, and by decoding the different languages they are written in we find that they often betray the processes involved in shaping Earth's history. The grand challenge is piecing it all together from a fragmentary record of events. Unlike the science of the future, the science of the past holds out the ultimate reward—the exciting prospect of understanding the causes of things to better comprehend how the world works. Projections of future climates and ecology, like the retreat of mountain glaciers and the polar ice caps, the migration of forests, and so on, are really just proposals, made in spite of real ignorance about the critical physical and biological processes involved, and the difficulty of actually evaluating them.[3]

The key to it all lies in recognizing the urgent need to understand how the environment shapes plants, and how plants shape the environment, over the immensity of geological time. My intention is to show that with this recognition come two new ideas. First, that plants exquisitely record previously hidden features of Earth history, and second, that plants are a geological force of nature, one to be added to the pantheon of mighty forces traditionally thought to have moulded and recycled the Earth's landscape and climate throughout its 4.5 billion years. Yet the underlying rocks of our familiar modern world, weathered by the action of climate, so obviously govern the character of the landscape around us, and influence the formation of soils and the nature of agriculture and natural vegetation, that it seems an impossible task to think of the reverse situation.

But for this scientists have a trick up their sleeve. It has been likened in significance to the Copernican revolution, the seminal moment in history that properly put Earth, and the other planets in our solar system, in orbit around the Sun some five hundred years ago. The second 'Copernican' revolution is emerging in the form of a general class of mathematical models, grandly dubbed 'Earth system' models.[4] Earth system models vary enormously in complexity, forming a dynamic hierarchy that ranges from those that run in seconds on desktop computers to state-of-the-art examples demanding weeks of processing time on the world's fastest supercomputers. It is axiomatic that even the most sophisticated models are incomplete; their value lies in their capacity to simulate how the biological and physical components of our planet—the atmosphere, oceans, and biosphere—interact with each other across a very wide range of timescales, from days to millions of years. When the newly discovered activities of plants are included in such models, we glimpse their capacity to shape the global environment of our planet.

Before we embrace these new ideas, it is perhaps time to say something about the thorny issue of the Gaia hypothesis of James Lovelock and colleagues. The Gaia hypothesis originally stated that the Earth's environment is regulated 'at a state comfortable for life by and for the biosphere.'[5] Many scientists were understandably aghast at such an extravagant claim and took issue with the implied teleological suggestion that life could consciously bend the climate to its collective will to improve its lot. Indeed, less than a decade later Lovelock abandoned the idea, writing 'It is important to recognize that the Gaia hypothesis so stated is wrong'.[6] In its place, rising phoenix-like from the ashes, is a revised concept called 'Gaia theory', in which 'active feedback processes operate automatically and solar energy sustains comfortable conditions for life. The conditions are only constant in the short-term and evolve in synchrony with the changing needs of the biota as it evolves'.[7] Again the language hints at the uneasy notion that living organisms regulate the environment to maintain conditions comfortable for themselves. I show in several chapters that this is often not the case at all, but there are many other examples.[8]

The problem is that if we look around us, life seems to be supremely adapted to its environment and this simple observation tempts us to the false conclusion that organisms orchestrated things this way. Yet the logic is flawed by the obvious fact that, as Darwin observed, natural selection ruthlessly weeds out those life forms that are poorly adapted to their environments. Douglas Adams (1952–2001), author of the *Hitchhiker's guide to the galaxy*, commented on the Gaia hypothesis with characteristic flair, 'imagine a puddle waking up one morning and thinking, "This is an interesting world I find myself in—an interesting *hole* I find myself in—fits me rather neatly, doesn't it? In fact it fits me staggeringly well, must have been made to have me in it!"' Suspended uncomfortably between tainted metaphor, fact, and false science, I prefer to leave Gaia firmly in the background.[9]

In the chapters that follow, I show how plants are painting a vivid and revealing picture of the dramas in Earth's history. The timeframe for this ambitious venture is the last 540 million years, a thick slice of Earth history known as the Phanerozoic eon, characterized by the evolution of complex plants and animals that define our modern world. The chapters documenting the lifting of our 'veils of ignorance' are organized along a timeline, from the oldest events discussed in Chapter 2 to the youngest in Chapter 8. Figure 1 outlines where each chapter slots into the geological timescale.[10] Although I have tried whenever possible to keep the use of geological names to a minimum, a passing familiarity with the different eras and periods will be helpful (Fig. 1).

My other intention in writing this book, besides casting the spotlight sharply on plants' proper place in Earth history, is to place these stories in their proper historical context by highlighting the brilliant achievements of the generations of scientific pioneers and adventurers who have shaped scientific thought. I have attempted to do this by bringing to life key figures with biographical sketches, and by occasionally outlining historical scientific developments and events. These are not intended in any way to be complete but rather to give the reader a flavour of the personalities of the pioneers and the excitement

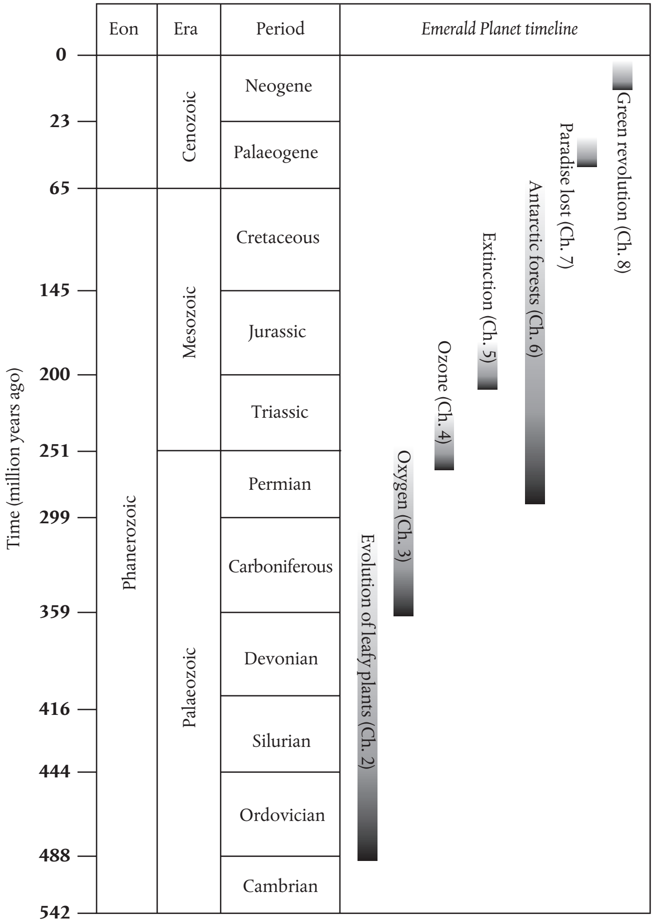


Fig. 1 How the geological timescale relates to the chapters in the book.

of their discoveries on which a particular story builds. Some may be familiar while others, I hope, will be less so. We will learn of the contributions of pioneering chemists and physicists who laid the foundations of modern chemistry, discovered the stratospheric ozone layer, deduced the presence of greenhouse gases in the atmosphere, discovered the long-lived radioactive isotope of carbon, and invented the first atom-smashing machines, cyclotrons, which ushered in the nuclear age. Sitting alongside these scientists are eccentric Victorian fossil hunters, who amazed the world with discoveries of giant prehistoric animals and the weird-looking remains of the early plant life, and heroic polar explorers who lost their lives extending the boundaries of human knowledge.

The English mathematician, physicist, astronomer, and one-time alchemist Isaac Newton (1643–1727) famously penned the words 'If I have seen farther, it is by standing on the shoulders of Giants.' The meaning of this famous phrase is often misunderstood and the comment was actually coaxed from him after he was cajoled into making a public reconciliation with his sworn enemy, the formidable polymath Robert Hooke (1635–1703), following several years' acrimonious dispute between the two men. It seems likely Newton deliberately phrased this comment as a dig at Hooke, who was a small man with a twisted spine, and certainly no giant.[11] Nevertheless, the underlying sentiment is that he borrowed from the ancients to formulate his ideas. I have no pretensions to have seen further or have greater insight than anyone else; rather my point in placing modern scientific debates in their proper historical context is to emphasize that the scientific enterprise progresses through the efforts of generations who have gone before. It has become almost a cliché to point out that scientific progress is an incremental affair, a journey not a destination, characterized by being wrong as often as being right. Too often the historical flesh of discovery documenting this progress is filleted from the textbooks, and yet clearly those involved, either by luck, judgement, or special insight, at significant moments deserve proper credit.

The stories I describe selectively illustrating the new science can be classified into three broad non-exclusive categories. First, there are those in which fossil plants contribute to the debate as we come to appreciate that they record previously unrealized facets of Earth history (Chapters 4 and 5). In this category, I introduce the idea that fossil leaves can 'breathalyse' the ancient atmosphere for its carbon dioxide content. Here we will also find the contentious notion that mutated fossil spores, which suddenly appear in rocks dating to the 'mother of mass extinctions' towards the end of the Permian, may be signalling significant disruption to the ozone chemistry of the atmosphere. Second, there is a group of four chapters (2, 3, 7, and 8) that reveal plants to be powerful agents of global environmental change. These chapters describe how the evolution and spread of plants inexorably altered the composition of the atmosphere with, in some cases, dramatic consequences for their own ecological success, that of the animals, and the Earth's climate. Finally, a third group document remarkable stories about the evolutionary history of a particular vegetation type and its surprising interaction with the environment (Chapters 6 and 8). In these chapters, I revive the flagging fortunes of several forgotten heroes of palaeobotany and photosynthesis research whose pioneering efforts paved the way for a deeper understanding of the forests that once clothed the polar regions millions of years ago and of the dramatic appearance of our modern savannas onto the evolutionary stage.

Several chapters can be collected into yet another important category, one offering lessons from the past for our own climatic future (Chapters 5, 6, and 7). We live in an age when the escalating influence of humankind on the environment is only too apparent. In fact, so dramatic is the overprint of human society on the environment that a new term has been assigned