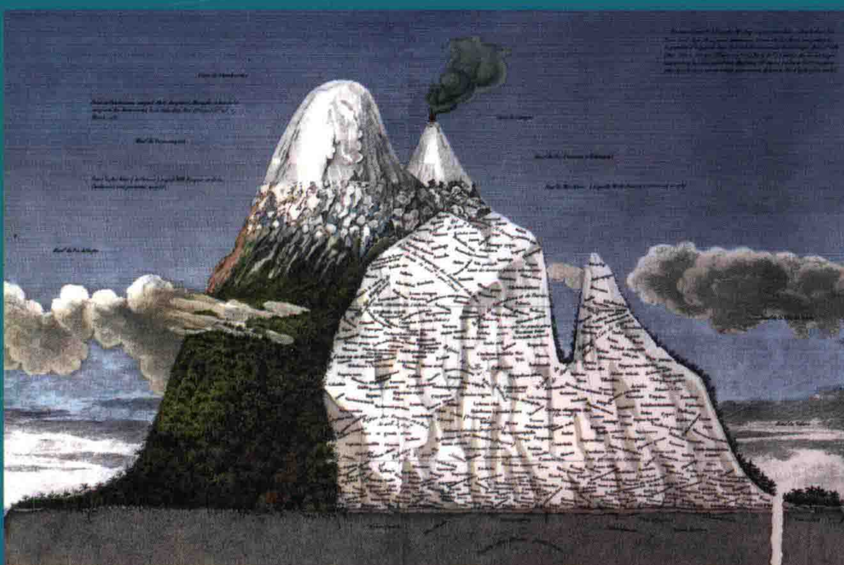
GLOBAL CHANGE AND THE TERRESTRIAL BIOSPHERE

Achievements and Challenges



H. H. Shugart and F. I. Woodward

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Global Change and the Terrestrial Biosphere

Preface

Global climate change in modern times frames a big question for ecologists. It challenges us to synthesize what we know or think we know, to identify what we need to know, and to solve a problem with deep historical roots in our discipline. Science as a way of knowing is built upon large central questions. These questions work as a fulcrum allowing leverage for the great compilations of ideas and observations of scientists to lift our inquiry to new and hopefully higher levels. In ecology, 'How do terrestrial ecosystems interact with the other Earth systems to produce planetary change?' is such a question. That the changes that we may be manifesting upon our planet's systems of land, sea, air and ice also can have potential consequences for the future of civilization[1–3] only sharpens this question.

Since the early 1960s there has been an organized attempt on the part of Earth-systems scientists to better understand the interactions of the major Earth systems of oceans, terrestrial surface and atmosphere. This was brought about by the alignment of several significant events. The Manhattan Project to build the atomic bomb, the International Geophysical Year to obtain synoptic measurements across the planet, the International Biological Programme to develop broad-scale ecological models, and numerous other projects gave impetus to the idea that 'big science' could solve an important class of large and important scientific questions. Computers were developed and then expanded their computational power exponentially for decades. Environmental measurements revealed the effects of humans on their planet in terms of changes in the levels of carbon dioxide in the atmosphere and indications of the fragility of the planet's stratospheric ozone under the influence of anthropogenic chemical effluents. Satellite remote sensing revealed a planet whose terrestrial surface was being changed by human action. Radioactive isotopes, chlorinated-hydrocarbons and other human-created novelties were found to spread thousands of miles from their release point. These and a myriad of other examples are the contents of a portmanteau term called 'Global Change'.

One of the most significant topics involving global change is in the potential of human actions to change the planet's climate. This is the principal topic of this book. It is a central issue to understanding many of the other planetary changes.

We will focus on the terrestrial surface and its vegetation. This surface and its dynamics have been a challenge to other Earth scientists. Atmospheric and oceanographic scientists represent the dynamics in their systems using the equations of motion for liquid flow. The winds flow across the world according to the same mathematics as the ocean currents with the differences in the model parameters and not the equations. The terrestrial surface is the odd-man out in the planetary triangle of air, ocean and land. Land systems are heterogeneous. Their processes interact in complex, non-fluid ways. They have long-memories of past events that influence their present responses. Nonetheless, understanding the interaction of the land systems with the atmosphere and oceans is central to the understanding of global change and our focus here, climate change.

Global change is such a current topic that one might think its study and origin is also recent. It is not. We intend to inform the reader of this book of the depth of the history of global ecology. Each chapter starts with a brief narrative about a scientist whose work traces forward into the issue of global ecosystems, today. Our motivation is not to write a hagiography in praise of scientific saints. It is to illustrate the depth of the ideas being studied today. In doing so, we also will introduce the diversity of ecological modelling approaches that are the basis of evaluations of climate changes and are providing the initial insights into the nature of the dynamic feedback between land and atmosphere. Our discussions are framed in a growing realization that we may be altering the way our planet functions almost before we have gained much knowledge of how it works at all.

Ecology is a young science in the sense of its formal definition – the word is from the German word, Ökologie (from Greek *oikos* or house) and was coined by the Prussian zoologist Ernst Haeckel[4] in 1873. In this sense, the people whose ideas we discuss are, in many cases, older than ecology as a formal scientific discipline. In another sense, ecology is a very old discipline in content if not in name – it was surely a topic of campfire conversations of prehistoric hunter–gathers and discussed by our earliest historic great thinkers, Theophrastus in the 3rd century BC being a notable example.

Our principal objective is to provide our reader with scientific background on the prediction of the consequences of change on terrestrial ecosystems. In the chapters that follow, the origins of the current science in relating climate and vegetation (Chapter 1), in appreciating the magnitudes of past climate changes (Chapter 2), and in reconciling the broad ranges of temporal and spatial considerations that attend the domain of terrestrial ecosystem change are presented as the roots of the scientific challenges we currently face. The intrinsic heterogeneity of the land surface at multiple spatial scales and the complex dynamics deriving from this heterogeneity are particularly challenging. We will discuss this complexity and its consequences as the 'scaling problem' in Chapter 3.

Chapter 4 gauges the simultaneously topical and historical issue of anthropogenic changes in climate on natural systems and their function (Chapter 4). From Chapter 4 onwards the book basically treats four questions.

1. *Are the expected changes in climate large enough to have a meaningful effect on the world's vegetation?*
2. *If the vegetation change is meaningful and detectable in the face of all the other things we are doing to the vegetation, how rapidly might it occur?*
3. *How might the change in vegetation interact with the atmosphere with climate change?*
4. *Are there other factors that might significantly alter our conclusions in trying to answer the first three questions?*

The changes we will consider largely stem from the complex interactions between atmosphere and the terrestrial surface. The progress that we have made in understanding this multiscale complexity is remarkable, as is its historical depth. There is a great deal more work to be done.

We are introducing a field of great innovation and challenge. It is also a field where scientific practice can be quite different from other sciences and from familiar scientific methodologies. A planet is not a natural experimental unit. All the more so, if one inhabits the planet that is being changed. Understanding planetary ecosystem dynamics is often gained by developing, exercising and testing ecological models. Theories and scientific conjecture are exercised for testable consequences that can actually be observed. Robust conclusions, which can be reached from a range of different assumptions, reveal theoretically rich generality not found by inspecting more fragile conclusions, which may be model or assumption specific. Deciding that a given phenomenon is important creates a rationale that will imply other phenomena are also important. Much of modern science is framed on the operational position that reduction and disassembly will provide insight into the ways a system works. Planetary ecology has a strongly holistic and synthetic theme of assembling what we know into the consequences of what we think will be.

Most of all the intellectual challenge of planetary ecology is invigorating to the instinctive desire of scientists to know the true nature of nature. We hope in this text to convey to you, the reader, some of the excitement of working in understanding the ecology of Earth at the planetary level. This work has fascinated scientists in the past and, in a changing planet, it is all the more important today.

We would like to thank Jack Ewel for comments on Chapter 8. Peter Cox kindly provided information of the levels of atmospheric CO_2 in the Little Ice Age. Mark Lomas implemented the many model simulations presented in Chapters 6 to 8. Lyndele von Schill helped in more ways than we can list. We could not have pulled this together without her willing help. Alan Crowden was a great supporter of this project from its inception. Thanks once again, Alan. H.H. Shugart thanks the NASA grants 127561-GG10906, 128765-GP10124, 131465-GO10825, 134696-GF12269 and 121303-GP10083 for support of his research over the time of the writing of this book. F.I. Woodward similarly expresses his appreciation to the Natural Environment Research Council for their research support. The writing of a book is a strain for the writers but it is all the more so for spouses and families – thank you for everything, Ramona and Pearl.

Finally, we would like to dedicate this book to some of those of the coming generation who will hopefully inherit a much better understood planet: To our grandchildren – Pascal and Chaerin; Abigail and Charlie; Robin and Chloe.

H.H. Shugart
and
F.I. Woodward
July 2010

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Contents

1

Climatic change: ecology's big question

Ich werde Pflanzen und Foßilien sammeln, mit vortreflichen Sextanten von Ramsden, einen Quadrant von Bird, und einen Chronometer von Louis Berthoud werde ich nüzliche astronomische Beobachtungen machen können; ich werde die Luft chemisch zerlegen, – dieß alles ist aber nicht Hauptzwek meiner Reise. Auf das Zusammenwirken der Kräfte, den Einfluß der unbelebten Schöpfung auf die belebte Thier- und Pflanzenwelt, auf diese Harmonie sollen stäts meine Augen gerichtet seyn.

[I shall collect plants and fossils, I shall be able to make useful astronomic observations with an excellent sextant by Ramsden, with a quadrant by Bird, and a chronometer by Louis Berthoud; I shall conduct chemical analyses of the air, – but all that is not the main purpose of my expedition. Above all, I will observe the interactions of forces, the influence of the inanimate environment on plant and animal life. My eyes will constantly focus on this harmony.]

Alexander von Humboldt (1799)
in a letter to Karl Ehrenbert von Moll
before his 5-year exploration of the Americas[1].

Science is driven by substantive questions that organize and focus the intellectual efforts of researchers. In Astronomy, how did the Universe begin? In Physics, what comprises matter? In Biology, how are genes duplicated over generations? In Ecology, how do ecosystems change when climate changes? Answering this substantive ecological question, particularly when climate alteration includes an increase in the amount of carbon dioxide in the atmosphere, requires a synthesis of all we think we know – from the physiology of plants and animals to population and community ecology to ecosystem productivity and element cycling – and we still do

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not have a complete answer. Answering this climate–ecosystem question is given urgency by the implications of global climate change for life on Earth.

The climate–ecosystem question is in today's news but it springs from deep roots in Ecology's history. Relationships between climate and vegetation are among the earliest ecological observations and most relevant to our big question. As early as the 3rd century BC, Theophrastus, a Greek philosopher sometimes called the 'Father of Ecology,' conducted experiments by transplanting species to areas outside their natural range to determine if they would grow (or flower). He documented systematic changes in patterns of deciduousness and evergreenness with different climate conditions. Theophrastus also observed the positive relationship between altitude and latitude with respect to their climates and vegetation[2,3]. Two millennia later, these early observations and the long history of others were codified by the great exploratory biologists of the 18th and 19th centuries. Alexander von Humboldt stands out as the most conspicuous example. He was a holistic thinker with a unique capacity to record biological and cultural details coupled with a fascination with diverse environmental data.

Alexander von Humboldt was **the** intellectual giant of the early 18th century. He developed an observation-based, detail-rich approach to scientific inquiry that fuelled his remarkable capacity to synthesize the underlying generality from details. His 'Humboldtian Science', the detailed measurement of the planet with the goal of understanding how physical and biological processes shape and sustain the world, was the guide to a scientific great-generation to follow[4]. Certainly, Alexander von Humboldt's life and work make him the pathfinder in the scaling-up of the consequences of finer scale observations of processes and patterns to larger consequences – the essential challenge in predicting climate change effects on ecosystems. He saw as one of his principal accomplishments the understanding of how the environment influences ecosystems[5]. Today, two centuries later, 'scaling-up' and quantifying vegetation–climate relations remain as the kernel needed to understand the ecological workings of Earth, a planet that we are actively changing.

In 1804, when he returned from his extended travel to the Americas, Alexander von Humboldt had laid the foundation that would make him the most celebrated intellect of his time. He had performed dramatic deeds. By a dangerous boat journey, particularly so as he could not swim, von Humboldt first demonstrated that, uniquely among the major rivers of the world, the Orinoco drainage exchanged waters with the Amazon basin. Along with Aimé Bonpland and Carlos Montúfar, he climbed to 5875 m on the tallest mountain in Ecuador, Mount Chimborazo. Blocked by a crevice, they could not reach the 6268 m summit. At that time, Chimborazo was thought to be the tallest mountain on Earth. Theirs was the highest altitude reached by any European mountaineer, a record that would stand for decades[6].

He brought new and novel observations of the new world tropics. In New Granada (now Colombia), he observed mud volcanoes in Turbaco and inspected mastodon fossils on the Campo be Gigantes. Through all of this and much more, he withstood pestilence, disease, and the rigours of travel in unexplored regions. He collected notes on plants, animals, geology, the environment and the human condition. While returning to Europe in 1804, he met with President Jefferson at the White House and later was his guest at Monticello. Jefferson wrote in a letter to Casper Wistar on 7 June 1804[7]. 'I have omitted to state above the extreme satisfaction I have received from Baron Humboldt's communications. The treasures of information which he possesses are inestimable ...' The two men corresponded for years hence[6].

Returning to Paris in 1804 with crates of notes on geological, astronomical and biological 'treasures', he began his life work of writing and synthesizing this knowledge[8]. Humboldt was Prussian, but he lived in Paris for the next 23 years and spent his fortune publishing maps and reports[9]. One of these publications is shown in Fig. 1.1, part of von Humboldt's[10] *Tableau des Régions équinoxiales* published in 1807. It shows the distributions of plants with elevation on a cross-section through the Andes. On the original diagram to the left and right of this cross-section, there are two tables (not shown in order to enhance the detail in Fig. 1.1). These flanking tables were arranged by elevation and listed (as a function of elevation): the heights of Andean mountains as well as the distance these mountains should be visible at sea, bending of light by the atmosphere, the appearance of electrical phenomena, vegetation, loss of weight as evidenced by change in pendulum swing in a vacuum, blueness of the sky, humidity of the atmosphere and atmospheric pressure, minimum and maximum temperatures, the chemical composition of the atmosphere, the height of the lower snow line, the animals found at different altitudes, boiling points of water with altitude, geological notes and the amount of the weakening of sunrays while passing through the atmosphere. This is but an indication of the breadth of his observations and his capacity for synthesis of large volumes of data.

Over his life time, von Humboldt produced 44 books and reports[11], several with multiple volumes, including the five volume *Kosmos* with its fifth volume published in the year of his death at age 90 in 1859. Luminaries of his time – Honoré de Balzac, Lord Byron; Victor Hugo, Gustave Flaubert – praised him and his remarkable intellect[6]. His friend,

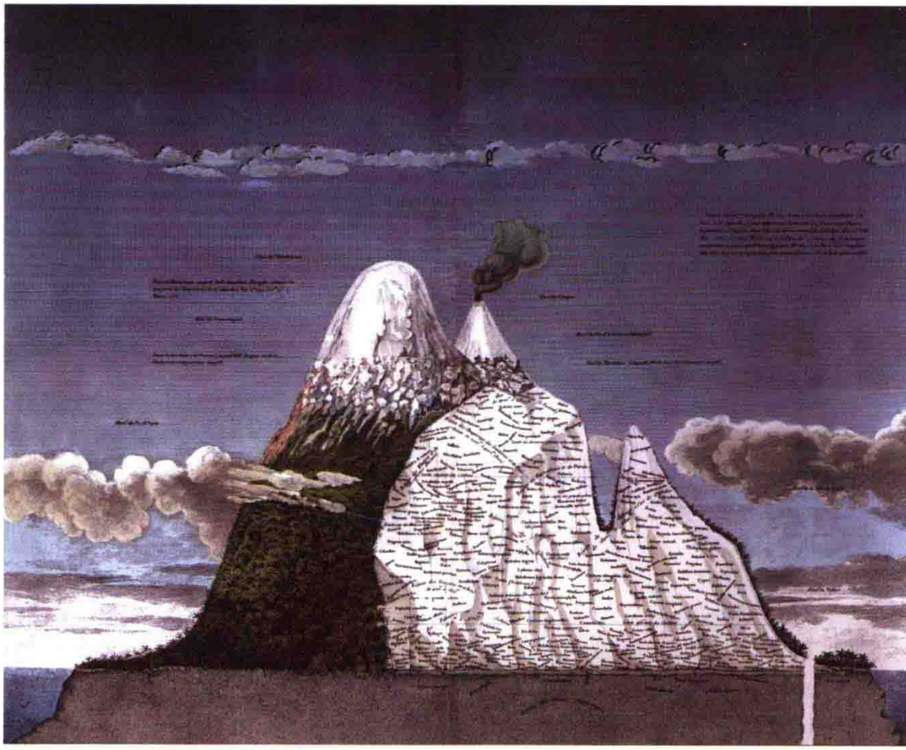

Figure 1.1 Part of Tableau des Régions équinoxiales from von Humboldt[86]. Shown is the centre of the Tableau, which is a schematic cross-section through the equatorial Andes. The plant species are listed according to the altitude at which Humboldt found them during his expedition. At the time of the current publication, an interactive version of this diagram in German, English and Spanish can be found at: http://www.avhumboldt.net/

Johann Wolfgang von Goethe, stated, 'One can truly say that he has no equal in information and lively knowledge', and Simón Bolívar, 'Alexander von Humboldt is the true discoverer of South America'. Ralph Waldo Emerson likened him to Aristotle and provided the excellent summary that, 'Humboldt was one of those wonders of the world ... who appear from time to time as if to show us the possibilities of the human mind, the force and range of the faculties, – a universal man.'

Von Humboldt saw his own accomplishments more modestly. As an octogenarian in 1854 in a letter to his publisher Georg von Cotta dated 31 October 1854[12], he listed his 'only' three accomplishments as: (i) observations concerning geomagnetism that resulted in the establishment of magnetic stations throughout the planet; (ii) the geography of plants,

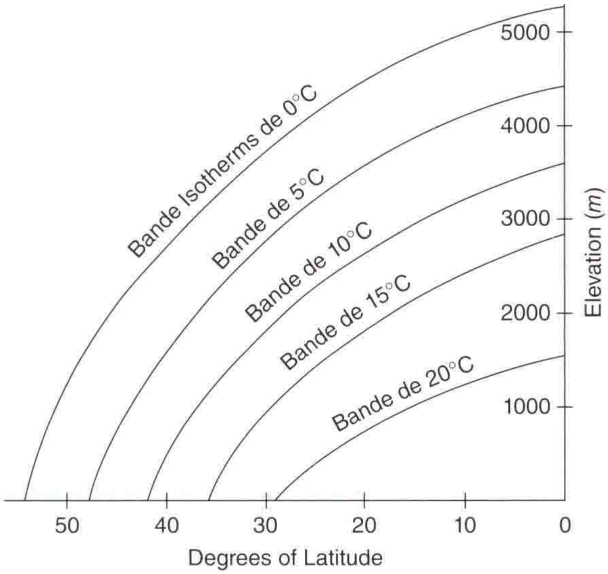

Figure 1.2 Isothermal lines from von Humboldt[87] as in the original with a relabelling of the axes. In this diagram, von Humboldt relates the isotherms for 0°C ('Bande de 0°'), 5°C, 10°C, 15°C and 20°C.

particularly of the tropical world; (iii) the theory of isothermal lines. The magnetic stations were the consequence of a direct appeal by Humboldt to the Royal Academy and to the British Society for the Advancement Science. The station observations eventually tied changes in the Earth's magnetic field with sunspot activity[13]. His work on the biogeography of plants and his vivid description of tropical ecosystems lead Darwin to sail to the tropics on *HMS Beagle* and was a principal influence on the development of Darwin's theory of natural selection[13]. The accomplishment that is most immediately germane to this chapter is the 'theory of isothermal lines' (Fig. 1.2).

Isothermal lines are those that connect locations with the same annual average temperature. As calculated by von Humboldt, this temperature is obtained by averaging of two daily observations, the temperature at sunrise and at 2 p.m., over a year[5]. Isothermal lines captured the regular variations in the height of snow on mountains (the higher in latitude the lower the line of permanent snow) and vegetation features (tree lines, transitions from evergreen to deciduous forests, etc.) as they changed with elevation and latitude (Fig. 1.2). Earlier discussion of Figure 1.1 listed the variety of measurements von Humboldt made with a diverse kit of instruments. He was a dedicated empiricist who collected measurements of the state of the environment all the time. From this myriad of observations on the state of the environment, he found isothermal lines provided a general summary of the global pattern of environment and vegetation. Von Humboldt probably would not have viewed isotherms as the 'limiting factor' for vegetation interacting with climate. Von Humboldt[14] saw the world as full of strong interconnections – '*Alles ist Wechselwirkung*' [Everything is interconnected]. Isotherms were measurements bringing along all of the interconnected physical, chemical and biological interactions.

Nevertheless, the perfection of how best to represent the environment and its interaction with the planet's vegetation was to occupy biogeographers for the next two centuries right up to the present day. There are two interdependent, fundamental issues that must be dealt with to evaluate the effect of climate change on natural systems.

1. How is the system resolved in time, space or complexity? To understand climate change effects on vegetation, must we understand leaf response, whole plant response, population response, etc., or somehow all of the above? This is the topic of this chapter and this will be revisited in Chapters 3 and 4. The development of increasingly more aggregated, more holistic representations of ecological systems is part of the historical development of the vegetation–climate challenge.
2. What in the environment dominates the response to ecological systems? What are the controlling factors? Most importantly, will the importance of these environmental factors change under novel conditions? In particular, will the importance of factors change with an increase in the CO_2 levels of the atmosphere – which has already happened to a degree from human actions and should continue to do so? Or, under novel climatic conditions will new factors control natural system response?

The importance of this understanding has been sharpened greatly by our concerns on the effects of climate change on the Earth's ecosystems. These two issues and the questions they imply derive from ecology's historical roots. They are brought into a fresh immediacy by our present-day concerns with global environmental change.

1.1 Early environmental biogeography: from mapping plant species distributions to mapping vegetation

The earliest mapping of vegetation over large areas touched upon the same issues that are in the current problem of evaluating the effects of climate change on vegetation. One of the issues involves identifying the factors in the environment that seem to control the vegetation. In past maps, environmental controlling factors in one region might not work so well in another region (the analogous current problem is that the rules that seem to work well in today's climate might not work in a future climate). Another important issue is the level of ecological organization that allow one to best understand patterns and changes in patterns. Von Humboldt in the discussion above focused on species as the unit of interest. Other units of organization might be fundamental processes such as photosynthesis or respiration and how they respond to climate. Alternatively, groupings of species into functional groups may better reveal climate–vegetation relationships. Perhaps amalgamating whole assemblages of species into recognizable plant communities is the key? These issues are topics of research in global change today and they are part of the deeper history of vegetation–climate relations.

European maps with indications of plants and vegetation date at least to the 15th century, when maps indicating forest vegetation with groups of small symbols of trees appeared. In the 16th century, as the importance of forests increased in designing military campaigns and the value of forests for timber and hunting in a deforested Europe became apparent, greater detail in the representation of forests and other vegetation on maps followed[15]. However, our focus here is not on the history of maps but on maps as formal expressions of relationships between climate and vegetation. To do so we will discuss a pair of important early maps.

First, von Humboldt's diagram (Fig. 1.1) is what is called a 'transverse view' map of vegetation[16]. It shows the elevational distribution of hundreds of plant genera and species as well as zones with some specific assemblages of plants (Zone of Palms; Region of Chaquiraga, the Gentinians and Frailexon from 2000 to 4100 m, etc.) on an idealized cross-section through Mount Chimborazo. It is not the oldest such map but it is certainly an important one. Twenty-three years earlier in 1784, Giraud-Soulavie[17] had made the first transverse vegetation map of the changes in Mediterranean flora with latitudinal climate gradients. These transverse-view maps idealize the manner that vegetation is arranged under the control of altitude – they are abstract models of climate–vegetation organization intended to be interpreted based on knowledge of the topography of a region.

Second, the Swiss botanist Augustin-Pyramus de Candolle and fellow naturalist Jean Baptiste Pierre Antoine de Monet, Chevalier de Lamarck printed the map shown as Fig. 1.3 in 1805[16]. Lamarck's remarkable contribution as a naturalist is historically eclipsed by his development of a now-rejected theory of the evolution of species, namely the idea that acquired traits in an individual's life time would be inherited by its offspring. Ironically, de Candolle's son (also a Swiss botanist), Alphonse Louis