Preface

Birdwatching brought me to mitonuclear ecology. As a pre-teen, I was introduced to birding by a high school biology teacher, and I quickly became obsessed with seeing all the birds in my *Golden Field Guide to the Birds of North America*. I certainly didn't appreciate it at the time, but a field guide to the birds of a region, through beautiful color illustrations, presents some of the most significant unexplained patterns in the natural world. All birds are neatly binned into species; the field guide suggests no ambiguity. Each species has a discrete range. Some birds thrive exclusively in warm climates. Other birds that seem identical in size, shape, and life history thrive in cold climates. Some birds are colorful; some are not. Like people, all birds come in two sexes. In some birds, the sexes look alike; in others, they do not. Explaining these patterns so starkly revealed in the pages of a field guide became the academic passion of my life. But a decade into the new millennium, despite 30 years of effort, I felt that I had made frustratingly little progress toward answering any of the basic questions that continued to confront me each time I opened a field guide. Then, I read *Power, Sex, Suicide: Mitochondria and the Meaning of Life* by Nick Lane, and for the first time I started to think about the major patterns of bird diversity from the perspective of the evolution of eukaryotes and the coevolution and coadaptation of mitochondrial (mt) and nuclear (N) genomes. It was as if I had turned on a light in a dark room.

In this book, I summarize emerging new theory and empirical observations that reinterpret key features of eukaryotic life in light of the necessity of coadapation of co-functioning mt and N genes. I call this emerging line of research mitonuclear ecology. It is the integration of studies of the coevolution and coadaptation of mt and N gene products into investigations of the evolution and ecology of whole organisms in natural environments. My purpose in creating this book is to present the new ideas and empirical observations that underlie mitonuclear ecology as an important new research focus. I propose that evolutionary ecology is poised to make a substantial leap forward in understanding fundamental features of complex organisms as evolutionary ecologists fully consider the implications of coadaptation and coevolution of mt and N genes to enable core life processes.

The origins of mitonuclear ecology lay in the biochemistry and cell biology laboratories that, in the mid-twentieth century, were in a different universe than lab groups focused on the evolution of whole organisms. In 1961, Peter Mitchell made one of the great intellectual leaps in the history of science when he proposed that chemiosmosis was the mechanism for oxidative phosphorylation and aerobic respiration in the mitochondria of eukaryotes (Mitchell, 1961) (Box 1.1). Mitchell's brilliant discovery was made at about the same time as the discovery that the mitochondrion carried its own genome (Nass and Nass, 1963; Schatz et al., 1964). Within a few years following these breakthroughs, cell biologists deduced that some components of the electron transport system were encoded by mt genes, while other components were encoded by N genes (Borst and Grivell, 1973). These were monumental discoveries by reductionistic biologists, but they went essentially unnoticed by organismal biologists focused on understanding evolution of plants and animals in natural environments. As a graduate student in the evolutionary biology program at the University of Michigan in the 1980s, I was taught nothing about oxidative phosphorylation, chemiosmosis, Peter Mitchell, or the function of mt genes. I was informed that mt genes were housekeeping genes, that variation in mt genotype was functionally neutral, and that the only reason to pay attention to mt DNA was for phylogenetic reconstructions. In retrospect, it was the biggest failure of my education in biology.

In the spring of 2012, I saw a reference to the book *Power, Sex, Suicide: Mitochondria and the Meaning of Life* by Nick Lane (2005) and on a whim I ordered a copy. I had never heard of Lane, and the topic of the book—mitochondria and the origins of complex life—was far from my focal interests as a behavioral ecologist studying plumage coloration in birds (Hill, 2002). By the end of the first chapter, I was captivated. It is not an exaggeration to say that Lane's book fundamentally changed my academic life and the direction of my career as a biologist. What I found in Lane's book was a narrative that shook the foundation of my view of biology—at once showing me the relevance of subcellular biology and forcing me to rethink fundamental aspects of evolutionary theory. I shared the book with my colleague, Jim Johnson, who is a biochemist well acquainted with mitochondrial processes, and Jim too was captivated. Jim was reading ahead of me and he sent me a note suggesting that I should page ahead to the section on the genes that code for the electron transport system. Jim wrote to me: "Lane makes the argument that the *compatibility* between the *DNA in the mitochondria... and the nucleus* is critical for overall respiratory efficiency." Jim's note was my first introduction to the concept of mitonuclear compatibility. Jim and I were already thinking and writing about the role of mitochondrial function in the production of ornamental red pigments in birds (Hill and Johnson, 2012; see also Chapter 7). After reading Lane's book we began to contemplate the role of mitonuclear interaction in condition-dependent sexual signaling. Soon thereafter, we set to work on outlining a theory of sexual selection whereby ornaments signal mitonuclear compatibility (Hill and Johnson, 2013).

Conceptualizing how mates could be sorted for mitonuclear compatibility by assessment of ornaments was one of the greatest intellectual challenges of my career, and, in considering how mate choice might maintain mitonuclear coadaptation, I came to realize that mitonuclear interactions lie at the heart of not only sexual selection but also the process of speciation and the nature of species. The role of mitonuclear coevolution in the process of adaptation fell into place and soon I was viewing essentially all of the major features of complex life through mitonuclear lenses. This book is an attempt to organize new thinking (emerging in my own head as well as within the subdiscipline of evolutionary ecology) about how mitonuclear interactions shape complex life.

The theme of this book is *mito*nuclear coadaptation and coevolution and explicitly not broader *cyto*nulear interactions. I scarcely mention plastid genomes in these chapters. I think there can be merit to making theoretical arguments as universal as possible (and hence I resisted my inclination to focus this book only on *animal* mitonuclear ecology), but there comes a point at which too broad of a focus is no focus at all. It will be challenging enough for field ecologists to wade through my opening chapters focused on genomic architecture, cell biology, and respiratory pathways. It would be counter-productive to follow these chapters with additional chapters on photosynthesis and a second set of genomic interactions between chloroplast and N genomes. Mitonuclear interactions are the common threads that bind all eukaryotes. There are, to be sure, many parallels in mitonuclear and chloronuclear genomic interactions, but I leave the development of plastid nuclear ecology for other evolutionary biologists.

I make no attempt to be balanced in my presentation of ideas and hypotheses. The purpose of this book is to succinctly outline the basic principles of mitonuclear ecology and to advocate for the importance of this approach to evolutionary questions. Topics such as the evolution of sex, the nature of species, and the process of sexual selection all have histories of investigations stretching back decades and a literature of hundreds if not thousands of papers. A balanced and comprehensive review of any of these topics would be a book-length project in itself, and such reviews are already available. I draw on previous literature primarily to set the stage for the new hypotheses emerging from consideration of the coadaptation of mt and N genomes.

My target audience is organismal biologists with limited training in cellular respiration and cell biology. With an audience of biologists, I don't take the space to explain basic concepts like transcription, translation, natural selection, genetic drift, and so forth, but I do try to be careful in what I take for granted regarding previous knowledge of biochemistry and cell biology. It is my hope that not only organismal biologist interested in cellular-level processes but also cell biologists interested in macro-evolution will find this book interesting. It is in the integration of genomics and biochemistry with ecology and organismal biology that the power of mitonuclear ecology lies. We need insights from both the top down and the bottom up. I would be exceedingly pleased if undergraduate and graduate students found the book to be a useful compass, pointing, at least in a general sense, in the direction that new research in evolutionary ecology might most fruitfully proceed.

Acknowledgments

Much of this book was written while I was on a sabbatical visit to Monash University in Melbourne, Australia, for the first part of 2018, hosted by my friend and colleague Damian Dowling. The Dowling lab has emerged as one of the most innovative research teams in the world, pushing forward the boundaries of understanding of mitonuclear ecology. Damian and his lab group could not have been more welcoming and encouraging as I struggled to write some of the most challenging chapters of the book. Damian and the Dowling lab read every chapter in early draft stages and

provided hugely valuable input. While in Australia, I also had extensive discussions and received critical feedback on my book from other colleagues, particularly Paul Sunnucks, Leo Joseph, and Chris Greening. Chris Greening is a brilliant biochemist with interests that range from the physical interaction of atoms to how climate might shape the ranges of Australian birds, and he did his best to coach me through the complexities of oxidative phosphorylation. Leo Joseph, curator of birds at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and an international expert on species boundaries in birds, critiqued the chapter on speciation. Paul Sunnucks showed me the potential impact that mitonuclear thinking can have on studies of phylogeography in the field as we trapped eastern yellow robins on his study sites. The faculty and students at Monash served as vital sounding boards for my ideas, and I am very grateful for the time and effort they invested in making my book better. In Australia I also went on a lecture tour, presenting my ideas at universities throughout Victoria, New South Wales, and the Capital District. The opportunity to vet my ideas in front of hundreds of biologists from diverse backgrounds helped me gauge how the ideas in my book were likely to be received. Thanks to all of my Australian colleagues who vetted my ideas. And finally, my most important first-draft readers were the students and postdocs in my own lab and in the lab of my wife and close colleague, Wendy Hood, at Auburn University. The Hill–Hood lab groups were key in helping organize and construct chapters, and Wendy was the great motivator for getting the project done. Other colleagues including Daniel Sloan, Justin Havird, Ron Burton, Ryan Weaver, Zhiyuan Ge, Nick Justyn, Matt Powers, Yufeng Zhang, Halie Taylor, Noel Park, Kyle Heine, Chloe Josefson, Kristjan Niitepold, Tori Andreasen, Rebecca Koch, Andrea Pozzi, Rebecca Vaught, Winston Yee, Vanessa Higham, Sean Layh, Magdalena Nystrand, Ilaria Venturelli, Ekta, Yoshana Fonseka, Venkatesh Radha, and Tara-Lyn Carter provided key feedback on various chapters. Sasha Pavlova and Hernan Morales provided unpublished data and figures.

The idea for writing this book emerged initially from a weekly reading/discussion group centered on Nick Lane's book *Power, Sex, Suicide: Mitochondria and the Meaning of Life* that I organized in the Department of Biological Sciences at Auburn University in the fall of 2012. That discussion group was formalized into a graduate class, "Mitonuclear Ecology," that I taught at Auburn in 2014 and 2016. Notes from my Mitonuclear Ecology class formed the foundation of this book. The students, postdocs, and faculty who participated in those classes played key roles in shaping my thinking about the coevolution and coadaptation of mt and N genes, and to the participants in those discussion groups I owe the impetus for creating this book.