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SYMPOSIUM INTRODUCTION

Modeling Organismal Responses to Changing Environments

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Synopsis Throughout their lives, organisms must integrate and maintain stability across complex developmental, morphological, and physiological systems, all while responding to changing internal and external environments. Determining the mechanisms underlying organismal responses to environmental change and development is a major challenge for biology. This is particularly important in the face of the rapidly changing global climate, increasing human populations, and habitat destruction. In January 2024, we organized a symposium to highlight some current efforts to use modeling to understand organismal responses to short- and long-term changes in their internal and external environments. Our goal was to facilitate collaboration and communication between modelers and organismal biologists, which is one of the major aims of the Organismal Systems-type Modeling Research Coordination Network, OSyM. Accompanying this introduction are a series of papers that are aimed to enhance research and education in linking organismal biology and modeling and contribute to building a new community of scientists to tackle important questions using this approach.

Introduction

Organisms are complex, living systems, constructed of multiple interconnected elements (modules; Csete and Doyle 2002), operating at multiple spatial and temporal scales. Understanding the mechanisms that underlie organismal function and development and their interactions is urgently needed because of the demand for scientists to accurately predict the response of organisms to short- and long-term environmental changes and to understand important links between genotypes and organismal phenotypes. However, obtaining this information remains a major obstacle for organismal biology. This information is not only needed for a basic understanding of biological systems, but also because around the world, animals, including those that humans depend on (e.g., for dietary protein, crop pollination, ecosystem services) face unprecedented pressures from expanding human populations, habitat destruction and fragmentation, ocean acidification, and climate change. But our ability to predict the features of complex integrated systems that make animals resilient or inflexible to changing environments is poorly developed.

One of the grand challenges in organismal biology that has been identified is how animals walk the tightrope between stability and change (Schwenk et al. 2009). A central paradox in biology is that to maintain function, organisms must maintain the integration of complex developmental, morphological, and physiological systems (stability) but simultaneously respond and adapt to continuously changing internal and external environments. This includes changes through development and ontogeny, as well as in cases of phenotypic plasticity, acclimation, or adaptation (Fig. 1). Understanding how organisms maintain the balance between integrated stability and adaptive flexibility (both short-term accommodation and long-term evolutionary adaptation) is of growing importance.

Systems-level approaches to studying function are already used in several fields of biology. Systems models have long been used in ecosystem and community ecology to understand the complexities of ecosystem function, nutrient cycling, and food webs (e.g., Carpenter et al. 1987; DeAngelis and Gross 1992) and to predict impacts of invaders on ecosystems and communi-

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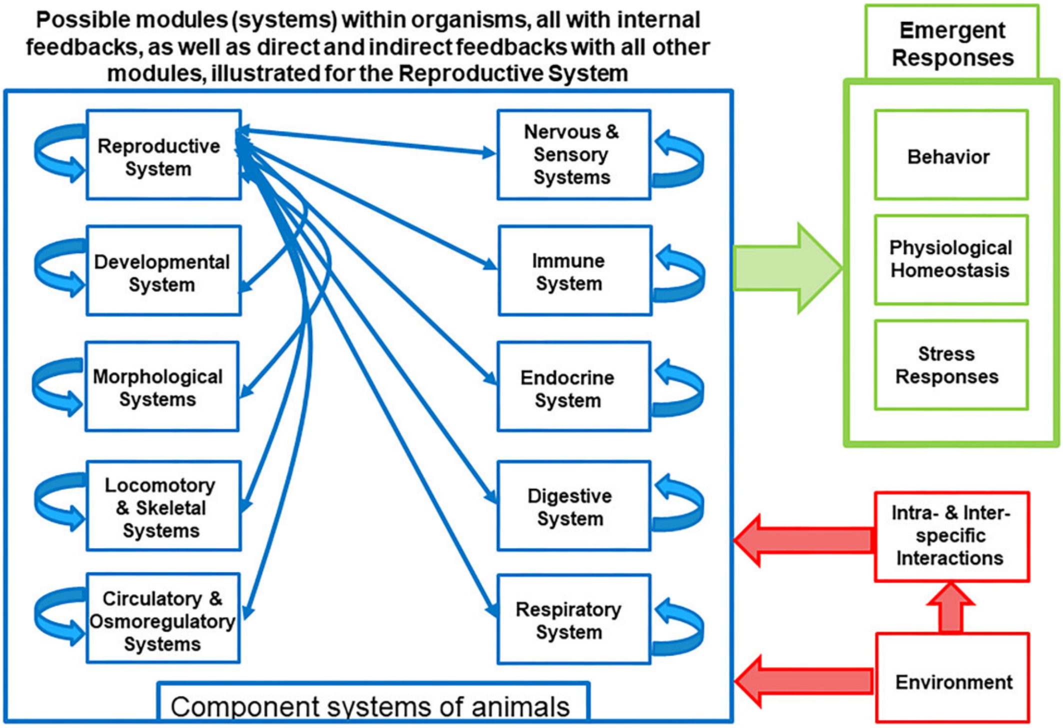

Fig. 1 The largest box on the left depicts the organism and the boxes within depict the component modules (systems) that are integrated to produce whole organism properties. Each module has internal dynamics and feedbacks. However, each module operates within the integrated whole, and thus has the potential to influence, and be influenced by, all other modules/systems within an organism. Such complexity is typically beyond individual research programs. The box on the top right depicts possible emergent responses of organisms that result from the complex dynamics among and within component modules that may affect evolutionary fitness. The two boxes on the bottom right depict biotic and abiotic factors external to the organism that impact the function and responses of internal modules that then affect whole organism responses. Systems-type models provide a means of dealing with internal module dynamics, while simultaneously allowing simplification of components and deal with the complexity of the entire system.

ties (Padilla et al. 1996). Molecular and cellular biologists use systems-level approaches to understand the complexity of functional systems at the sub-organismal level. "Systems biology" in this context encompasses engineering and modeling approaches used to understand emergent properties of systems focused on metabolic and cell signaling networks (Kitano 2002) or immunology (Cappuccio et al. 2015). The field of systems neuroscience uses systems-level approaches to understand how neural circuits generate coordinated motor outputs to produce complex and coherent behaviors in response to changing sensory inputs (Grant 2003; Sengupta and Samuel 2009). System models have also been used to answer questions about animal communication (Hebets et al. 2016). Less common, but sorely needed, is the application of systems-level modeling and engineering approaches in organismal animal systems that integrate information across biological scales to address questions of stability and change (Cowan et al. 2014; Padilla and Tsukimura 2014; Padilla et al. 2014). Through a series of workshops and collaborations, including an NSF-funded workshop focused on the grand challenge question of how animals walk the tightrope between stability and change (Padilla and Savado 2013; Padilla et al. 2014), scientists from a wide range of biological disciplines called for efforts to advance the field of organismal animal biology by using systems-level approaches (Padilla and Tsukimura 2014; Padilla et al. 2014). Similarly, scientists have articulated the need for integration and collaboration to tackle big questions in organismal animal biology (e.g., Denny and Helmuth 2009; Mykles et al. 2010; Tsukimura et al. 2010; Angiletta and Sears 2011; Stillman et al. 2011). This has included a call for greater interdisciplinary collaboration between biologists, applied mathematicians, and engineers to integrate new analytical and modeling approaches into studies of organismal animal biology (e.g., Csete and Doyle 2002; Cohen 2004; Cowan et al. 2014).

To answer these calls for interdisciplinary collaboration and address the grand challenge, we have developed a research coordination network, Organismal Systems-type Modeling, OSyM (organismal-systems.org), to move research forward and provide forums for biologists and modeling experts to develop necessary collaborations, as well as the training needed to pursue new and exciting ways to explore cutting-edge questions in this emerging, but vital area of research on how animals balance maintaining stability while accommodating change. The two goals of OSyM are to: (1) provide mechanisms to build and broaden the community of organismal biologists, mathematicians, modelers, computer scientists, and engineers using integrative, systems-level approaches to investigate stability and change in organismal animal systems, and (2) facilitate development of effective collaborations and the exchange of approaches, skills, and ideas among members of this community.

All areas of biology, including many aspects of organismal biology, are rapidly becoming more quantitative. Biologists must deal regularly with big data sets and be able to draw conclusions about complex systems functioning across multiple scales from single genes to whole genomes and from individual systems within organisms to the entirety of complex integrated organismal systems (e.g., the nervous system and the functioning of individual neurons to mapping the human brain). In this context, understanding whether and how organisms respond to short- and long-term environmental changes are pressing needs. To do this, we need better knowledge of the systems-level attributes of organisms that make them resilient or robust, or conversely sensitive or fragile, to internal and external environmental perturbations.

Throughout their lives, organisms must integrate and maintain stability across complex developmental, morphological, and physiological systems, all while responding to changing internal and external environments. Determining the mechanisms underlying organismal responses to environmental change and development is a major challenge for biology. This is particularly important in the face of the rapidly changing global climate, increasing human populations, and habitat destruction. The collection of papers from this symposium highlights recent efforts to using modeling to understand organismal responses to short- and long-term changes in their internal and external environments. Contributions to this symposium included work across a range of systems and organisms, and many of these contributions are by young scientists that represent new research at the front of this emerging area of scientific collaboration. Our goal is to illustrate how collaboration and communication between modelers and organismal biologists is being applied to answer questions in the biology of organisms in environments that change.

Symposium overview

Our symposium highlighted new cutting-edge research where modeling has been used to address questions about organisms and their responses to change. This research approach can be useful across a broad range of topics and sub-disciplines within organismal biology. Articles in this issue detail recent efforts that describe modeling efforts that include big data, how environmental variables acting across different temporal and spatial scales affect organisms, their populations, the importance of functional morphology and biomechanics, as well as teaching students to conduct such research.

Seasonal environmental factors can have large effects on species and are likely to impact organisms differently. As climates change, seasonal patterns in weather, and especially weather extremes, are likely to be felt by a wide range of organisms. Le Sage (2024) used modeling to explore seasonal responses of frogs to fungal pathogens (Le Sage 2024). The impacts of changes in environmental parameters can have population level impacts on organisms. These were illustrated by changes in population genetics by work by Wada et al. (2024). Wada et al. examined how the responses of zebra finch populations are affected as a function of temperature and food availability.

Layered on top of any seasonal changes, microclimates are of special interest for smaller organisms, and can be at the crux of understanding adaptations and responses of organisms that can take advantage of microclimate differences in a landscape. Wang et al. (2024) provide an example of using microclimate information to determine behavior and impacts of insects. Levy and Shahar (2024) offer an insight into how we can use big data and artificial intelligence (AI) approaches to enhance our understanding of microclimates and animal behaviors under changing climatic conditions. They also suggest that advanced data-driven approaches can inform and enhance conservation strategies.

For whole organism biomechanics, modeling across body size to determine how to maintain mechanical advantage can help us understand trade-offs and evolution of locomotor performance. Polet and Labonte (2024) explore locomotion and how gearing in musculoskeletal systems maintains function across size, including in large vertebrates. At a smaller size scale, O'Neil et al. (2024) used ablation experiments to understand control of locomotion in water striders, and the ability to modify behavior to accommodate limb loss and maintain and recover locomotor ability.

Moving to very small spatial scales, especially in viscous fluids like seawater, Chan and Ko (2024) took on the challenge of modeling fertilization kinetics in a marine invertebrate under different environmental conditions associated with climate change. Beyond fertilization, early development is a time when energetic investments can be especially important for buffering organisms that are particularly vulnerable to environmental stressors and change. Hunt von Herbing (2024) address this by using a model system, zebrafish (*Danio rerio*) to investigate the energetics of early development and responses to environmental stressors, especially those associated with climate change.

In addition to the new challenges posed by Levy and Shahar (2024) regarding fully using big data and the prospects of developing AI to help incorporate microclimate modeling into understanding and predicting organismal responses to changing environments, Milligan and Rohde (2024) address the big question of why biologists must embrace quantitative modeling head on. They illustrate the value of increased incorporation of modeling and increased quantified mechanistic relationships in all aspects of organismal biology. Finally, Padilla and Grünbaum (2024) address the challenges of preparing the next generation of organismal biologists given this new lens of increased importance of quantitative models. Given the ever-increasing quantitative nature of our science, students need to be able to use and conceptually understand different modeling approaches, use models to construct and test quantitative hypotheses about important mechanisms, and construct meaningful and informative scientific studies using models. Students need to learn how to communicate effectively about quantitative logic and results. The authors lay out one possible approach that will, hopefully, help students get there.

Challenges and outlook

To successfully apply systems-type models to organismal biology, cross-disciplinary interactions are required among organismal biologists, engineers, applied mathematicians, and modelers, who are all interested in addressing similar systems-level questions. One challenge of working across fields is that jargon, terms, and definitions are often field-specific. Communication can be difficult with cross-disciplinary interactions and even interactions across disparate fields within animal biology, because jargon, terms, and definitions are often field-specific. Engineers, organismal biologists, mathematicians, and modelers often use different words to describe the same processes or use the same words to mean very different things, hindering our ability to effectively communicate and collaborate (Padilla et al. 2014). To foster these cross-disciplinary interactions, we need additional forums, like this SICB symposium, for developing and integrating knowledge across systems, for learning to apply mathematical and engineering approaches to solve similar problems, and for training the next generation of scientists to be adept at these new approaches for organismal animal studies.

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Conflict of interest

The authors have no conflicts to declare.

Data availability

No data were collected for this paper.

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