during January to March, once in two days during April to June, usually rainfed with few sprinkles during July to September, and once in six days during October to December (Table 1). Since, the consumers pay more for the fresh leaves, staggered harvest is followed according to the DMLH model. The farmer will have a window of ten days for each type of plot in the month, which will enable him/her to supply fresh coriander leaves (growing period of the crop is less (25–40 days)). Every time the farmer harvests a crop and sows for the next crop cycle in the same plot, there is continuous crop growth in the meagre piece of land.

Figure 4. Standing crop of leafy coriander under micro-irrigation system in farmer's field.

With the DMLH model and staggered system of growing coriander, off-season crops can fetch a better price of their produce. The field study carried out in 2019–20 revealed that four types of coriander-farming situations prevail in Ranga Reddy district, namely off-season crop with or without protection and round-the-year crop with or without protection (Table 2). As the off-season crop is remunerative (Rs 89,500/acre in a season) with least investment (Rs 12,000) and B : C ratio of 7.46, majority of farmers have adopted this technology. In the region, the acceptance of the model can be visualized with its expansion to 50 acres of area in the Gadda Mallaiah Guda village, in 2 years (Figure 4). However, maximum profitability with minimum investment of time is possible with protected cultivation of leafy coriander as an off-season crop (Rs 115,300 acre in a season). Simultaneously, the farmers can obtain other benefits from different crops during the crop season, apart from this additional benefit. If the farmers cultivate leafy coriander for the whole year, they can reap the benefits of an average Rs 209,300/acre under protected conditions and Rs 144,300/acre under open-field conditions.

1. MoAFW, *Horticultural Statistics at a Glance*, Horticulture Statistics Division, Department of Agriculture, Cooperation and Farmers' Welfare. Ministry of Agriculture and Farmers' Welfare, Government of India, 2018.
2. Willet, W. C., *Science*, 1996, **254**, 532–553.
3. Guha, S., Sharangi, A. B. and Debnath, S., *Trends Hortic. Res.*, 2013, **3**, 27–32.
4. Sarada, C., Kalidasu, G., Reddy, Y. T. D. and Reddy, P. V., *J. Agrometeorol.*, 2011, **13**(1), 54–57.
5. Reddy, K. S., Ricart, S., Maruthi, V., Pankaj, P. K., Sai Krishna, T. and Reddy, A. A., *Irrig. Drain.*, 2020, **69**, 25–37.
6. Mehta, K. G., Patel, P. G., Ughereha, P. P. and Edison, S., *Ind. Cocoa, Arecanut and Spices J.*, 1996, **20**, 80–82.

V. Maruthi, K. S. Reddy, P. K. Pankaj, A. G. K. Reddy, G. Srikrishna and S. M. Vidya Sekhar are in the ICAR-Central Research Institute for Dryland Agriculture, Hyderabad 500 059, India.*
**e-mail: vegapareddy@gmail.com*

A tale of two biologies: distinctions in philosophy and practice between organismal and sub-organismal science

Kartik Shanker and Vishwesha Guttal

While the 21st century has been proclaimed as the age of biology, the disciplines of sub-organismal biology have received greater attention, often at a cost to organismal biology. However, the fields of organismal biology – ecology and evolution – are not only fundamental to biology, but are of societal importance in terms of their application in environmental conservation, sustainability and public health. We argue here that organismal and sub-organismal biology differ substantially in their philosophy and practice: while organismal biology focuses on systems and collectives, sub-organismal biology rests on reductionism. Further, we emphasize that these distinctions must be recognized in institutional and funding structures for organismal biology to fully realize its potential.

'Biology', a term coined by Lamarck in the early 1800s, is considered by many to be the science of the 21st century with its range of modern methods and applications. From molecular biology to microbiology, and cell and developmental biology, to genomics and proteomics, this range of disciplines receives both substantial attention and funding. Needless to say, with applications ranging from health (cancer biology, infectious diseases) to food security (transgenic crops to sustainable farming) to human well-being (biodiversity and ecosystems), the field appears to have as much to offer for the future of mankind as any other, if not more. The recent COVID-19 pandemic, which has brought the world to a grinding halt, more than even the World Wars of the last century, serves to hammer home this point, if somewhat painfully.

While this is without doubt an exciting time for biology, the bright facade hides a peculiar problem within the community. The modern adventure of biology appears to be composed of two different disciplines – let us refer to them as organismal and sub-organismal biology. These two obviously differ from each other in their subject matter (e.g. ecology or evolution versus cell or developmental biology) and their scale (population biology or ecosystem ecology at the scale of landscapes and beyond versus molecular biology at cellular or subcellular scales).

More fundamentally, however, we argue that organismal and sub-organismal biology represent two approaches that differ in their philosophy and practice: while organismal biology focuses on systems and collectives, sub-organismal biology rests on reductionism. This assertion may seem odd in an era where there is a strong narrative of integration within the biological sciences. Indeed, although well-understood by some, this problem is not widely acknowledged within the biology community in general. In this note, we not only highlight the underlying fundamental differences between the domains, but also stress that a lack of attention to these issues does have consequences – often negative – for the field of organismal biology (note 1).

To make the contrast, we shall compare organismal biology (encompassing ecology, behaviour and evolution) with the sub-organismal (cell and developmental biology, molecular biology) subdisciplines in biology. Of course, there may be many scientists in branches that are sub-organismal who follow the principles and practices of the former, and many fields that are technically organismal (particularly microbiology) that follow the methods of the latter.

As we discuss the chasm between organismal and sub-organismal biology, we draw interesting parallels to fundamental differences between sub-disciplines of physics (note 2). The focus on systems and collectives in organismal biology maps onto statistical physics (the study of the collection of particles); likewise, the reductionism of sub-organismal biology to particle physics (the study of elementary constituents of matter) (note 3).

The philosophy and practice of reductionism drives much of research in sub-organismal biology, where finding the detailed molecular mechanisms of biological phenomena is an end unto itself. Particle physics represents an epitome of reductionism among all sciences, trying to identify the smallest and most 'fundamental' constituents (and interactions) of matter. This is in contrast to studies in organismal biology where, much like statistical physics, the focus is on the collective or 'the whole system'. Various interacting elements at smaller scales (particles or living beings) can create novel collective phenomena at larger scales (properties of materials or biodiversity of forests).

By the presumed superiority of reductionist methods, because they yield the 'most fundamental' laws, research at larger scales is often dismissed as being 'derivative science'. Such assertions of reductionists, however, are based on a fundamental misunderstanding of both science and philosophy of science. Knowledge of the so-called fundamental laws at certain fine-scales does not guarantee that we can construct laws at higher scales. In other words, as the famous condensed matter physicist and Nobel laureate (late) Phil Anderson[1] said, reductionist rules are not necessarily 'constructionist'.

For example, no amount of 'fundamental' understanding of particle physics is able to predict which material may exhibit high-T_c superconductivity. Likewise, the detailed knowledge of molecular pathways of photosynthesis cannot explain patterns of species richness or biodiversity–ecosystem relationships. Evolutionary biologists have long argued that this is because there are new laws of nature at higher scales of biological organization, and that laws at higher scales of natural systems cannot be merely reduced to a 'sum of the laws' at the lower scales[1,2]. Put simply, it is neither trivial, easy nor obvious to deduce the laws at higher levels of organization. Therefore, the laws at higher scales are as fundamental and cannot be dismissed as mere derivates of principles/laws at lower scales.

In that sense, organismal biology is very much like statistical physics and astronomy[3]. In these scientific disciplines, stochasticity and interaction between individuals (or particles or larger physical bodies) result in new fundamental properties at higher levels of organization. Reductionist approaches are simply inadequate to understand these phenomena because the new properties (like species richness or conductivity of materials) simply do not exist at lower levels. Again, quoting Anderson[1], 'More is different', fundamentally so.

The principle of emergence as fundamental to understanding of nature is now well accepted in many disciplines. To some degree, this view has gained traction in sub-organismal biology in what is known as systems biology. However, the approach to thinking about and studying biological systems remains largely reductionist. In other words, more of the same.

Ecological systems exhibit variability, much to the distaste of reductionists as well as 'determinists'. Variability is often seen as needing to be minimized via reducing measurement errors and increasing the number of experimental replicates. However, in ecological systems, variability might be selected by evolutionary forces and thus be of interest. Therefore, the instinct of ecologists is to look for ecological and evolutionary explanations for the observed variability rather than assuming that it came from measurement error alone. Of course, there is also a tendency to assume that everything has an evolutionary explanation, when some of it may derive from measurement or estimation error.

To complicate matters, as the spatial scale increases, there are no replicates. Ecosystems cannot be replicated. This is analogous to astronomy or geology. We have one universe, one solar system and one planet earth. Often, a single data point. Yet, we make meaningful inferences about the natural world, both in physics and large-scale ecological systems. There are very few parallels to this approach in sub-organismal biological systems. Thus, understanding how we make these inferences is critical.

Deductive inference goes from the general premise to a specific conclusion; if the premise is true, the conclusion must necessarily follow. For example, take the statements 'Spiders have eight legs' and 'Boris is a spider' as the premises: then, by deduction, Boris must have eight legs.

In contrast, inductive inference goes from the specific case to a generalization. If every spider that one has seen so far has eight legs, one can make the generalization that all spiders have eight legs. Whether that is a reasonable generalization or not (weak or strong induction) depends on the quality of the data and the degree of generality inferred.

In general, deductive methods are often considered to be more rigorous, and somewhat revered in reductionist sciences. This is because inference in deduction is 'indisputable', while induction is probabilistic. Due to the nature of inferential logic, Karl Popper privileged deductive inference, and established the hypothetico-deductive method which suggests that one must set up theories (or models) and then test them using data which provide evidence for or against those theories. In many fields (including ecology), the predominance of deductive inference was formalized through the development of frequentist statistics which is strongly based on hypothesis testing.

But, induction is used in all branches of science, including generalizations from specific experiments. More often than not, the premises in deductive inference must themselves be arrived at by induction; e.g. how do we know spiders always have eight legs? More importantly, much inference across science is based on inference by best explanation (IBE), also called abduction, i.e. the 'most likely' of candidate hypotheses given certain evidence.

While generalizations are always inductive, the underlying mechanisms in sub-organismal fields are typically explored through a series of experiments using a deductive approach. However, when experiments cannot provide unequivocal evidence, for example, in studies of past time (in biology, geology or space) or at scales that cannot be manipulated (ecosystems, solar systems), even mechanisms must be inferred through induction or IBE. On the surface, this makes organismal biology seem weaker, but this is a misunderstanding of inference.

This is due to the limitation of the hypothetico-deductive framework and frequentist statistics itself; these frameworks are better suited for rejecting wrong models, but not for finding the best model itself. In organismal biology, as well as in a number of other fields today, there is a Bayesian revolution. In simple terms, while frequentist statistical methods infer the likelihood of the data given the model, Bayesian statistics emphasizes the likelihood of the model given the data, which is really what one wants to know.

One might think of Bayesian inference as going from observation to generalization, and therefore (to a degree) inductive. Therefore, technically, the Bayesian method allows inference even with a single replicate (or even a single data point). These modes of inference are intrinsic to organismal biology (even if one does not formally use Bayesian statistics for a given data analysis) and therefore critical to understanding how the discipline works. In summary, an approach that emphasizes the whole system rather than reducing it to parts, and a method of inference that inherently employs IBE and Bayesian thinking sets organismal biology apart from the fields of sub-organismal biology.

We argue that these fundamental differences in philosophy and practice lead to conflict and tension, sometimes merely of the irritant variety (e.g. who is doing superior science?), but often enough to be of consequence to science, public perception of science (e.g. which topics in biology are important?) and careers, that this must be acknowledged and addressed.

To place this in a historical context, from the early days of the growth of modern science, a great deal of emphasis has been placed on empiricism. From Copernicus to Galileo to Bacon, the emphasis of science was on observable phenomena and mechanistic explanations. Only a century later with the growth of natural history was final or ultimate causation reaccorded a place in science (since Aristotle), which eventually led to the emergence of evolutionary biology. In 1973, Theodosius Dobzhansky[4] wrote a famous essay titled 'Nothing in biology makes sense except in the light of evolution'. And more recently, Grant and Grant[5] argued that 'nothing in evolutionary biology makes sense except in light of ecology'. Yet, the role of these fields is rarely acknowledged in most fields of sub-organismal biology.

Despite this deep divide in both practice and philosophy among these subdisciplines, biology is treated as a single broad discipline in higher education and research. Consequently, the composition of the many expert committees that determine funding is often only represented by the numerically dominant disciplines of sub-organismal cellular and molecular biology. The alternate disciplines (relatively younger/newer perhaps) such as ecology and neurosciences which focus on the biology of systems are often poorly represented, thus putting applicants in these fields at a disadvantage. In general, it is inconceivable that any expert committee can actually review the broad concepts, details of methods, their feasibility and novelty (often within a short time), even in a given sub-discipline of biology, let alone for the broad breadth of biology that the two streams cover. This problem is aggravated when the fundamental approaches of the disciplines are so different.

When biologists from the two arenas share departmental space, it can create a host of other challenges from admitting students into Master's or Ph.D. programmes, or hiring faculty. In our own experience, even the process of evaluating candidates differs between organismal and sub-organismal biology, with organismal biologists placing substantial emphasis on concepts and quantitative skills rather than knowledge of facts[6]. Despite many efforts to integrate all of biological sciences into a single department, departments of ecology and evolution (or organismal biology) have remained separate from other departments of life sciences in universities across the world. With good reason it would seem.

In the call for a new integrative biology, there seems to be a push – at least in India – to bring these fields together. However, a true integration can only happen if there is a significant overlap in the practice and philosophies of science, and not just the object of interest. Our understanding is that organismal biology across the world has flourished when functioning autonomously from sub-organismal biological disciplines.

A challenge in understanding organismal biology is that it sits at the intersection of a wide variety of fields of investigation. Naturally, with a focus on understanding biological phenomena, a great deal of collaboration and integration does exist with many sub-organismal branches of biology. Historically, however, organismal biology is more broadly aligned with physical (including earth) sciences. From their origins, evolution and geology have been tied at the umbilicus. Finally, applied ecologists collaborate with a range of social sciences for the field of conservation science, a particular challenge of the 21st century. For each of these, it interacts with disciplines that do not frequent the domain of sub-organismal biology.

We therefore make a call to recognize these two branches as independent and requiring separate institutional structures (divisions in universities, funding programmes, committees, etc.), as was argued by many stalwarts in the 1960s in USA during the rise of molecular biology[2]. This may already be true to some degree in select institutions and initiatives in India, but needs to be more broadly acknowledged and institutionalized. We do seek greater collaboration with sub-organismal biology, but also stronger ties with a range of other disciplines. There is need for a wide range of interdisciplinarity within organismal biology, with fields ranging from molecular biology to genomics, geology to history to social sciences, and epidemiology to public health. Therefore, institutions, universities and funding agencies must recognize this to provide sufficient flexibility to the departmental, institutional and funding structures. We argue that such autonomy will lead to the fulfilment of the both the basic and applied potential of this discipline.

Notes

1. As if to drive home this point, we note with dismay that organismal biology, in particular ecology and evolution, constitute much of what was deleted by CBSE from biology in response to the delays caused by COVID-19.
2. We note that there are many similarities between the social sciences and ecology in terms of complexity, variability and non-repeatability, but in this note, we focus on the similarities and differences within the natural sciences).
3. The difference between classical and quantum physics as analogous to sub-organismal and organismal biology in terms of properties such as intrinsic stochasticity and uncertainty is also of interest, but we focus on the comparison of 'particles' and 'collectives' here.

1. Anderson, P. W., *Science*, 1972, **177**, 393–396.
2. Beatty, J., *Biol. Philos*., 1990, **5**, 197–210.
3. Guttal, V., *Resonance*, 2014, **19**(4), 368–375.
4. Dobzhansky, T., *Am. Biol. Teach.*, 1973, **35**(3), 125–129.
5. Grant, P. R. and Grant, B. R., *How and Why Species Multiply: The Radiation of Darwin's Finches*, Princeton University Press, Princeton, USA, 2007.
6. Shanker, K., *Curr. Sci*., 2014, **106**, 139–140.

ACKNOWLEDGEMENTS. We thank Nicholas Gotelli, Mark Burgman, Hari Sridhar and Sundar Sarukkai for their comments on earlier versions of this manuscript.

Kartik Shanker and Vishwesha Guttal* are in the Centre for Ecological Sciences, Indian Institute of Science, Bengaluru 560 012, India.*
**e-mail: kshanker@iisc.ac.in; guttal@iisc.ac.in*