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COMMENTARY: REFLECTIONS ON 40 YEARS

Relevance *Versus* Reproducibility—Solving a Common Dilemma in Chemical Ecology

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Basic science aims at understanding nature. Because scientific 'understanding' is supposed to be free of the opinions and experiences of the individual investigator, the most important criterion for the quality of empirical studies is the independency of the results of the investigator, that is, their 'objectivity' or, more correctly, their 'inter-subjectivity'. Whether this goal has been achieved usually is measured in terms of reproducibility: ideally, a researcher B who repeats an experiment performed by researcher A should observe the same results and draw the same conclusions. Surprisingly, the central goal of science and this quality criterion often result contradictory to each other, particularly in ecology. Ecological interactions are context-dependent, which enhances the variability in the data and seems to dramatically reduce their reproducibility. The common solution is to move from the field to the greenhouse or growth chamber and work with genetically homogeneous populations, to control abiotic and biotic factors and avoid noise that results from using different genotypes.

Unfortunately, by aiming at maximizing the reproducibility of our results we frequently lose their ecological and evolutionary relevance. Natural populations are genetically variable. This variation represents an important source of adaptive, evolutionary changes, because selection can act only on variable traits. Furthermore, organisms are phenotypically plastic, and the capacity to express different phenotypes when facing different environments represents a crucial fitness-enhancing trait. Thus, variation that we perceive as 'noise' in our data might rather indicate a vitally important plasticity of the organism, and studying an organism under one specific set of environmental conditions might reveal just one single out of thousands of possible phenotypes, and perhaps a phenotype that is unlikely to occur in nature at all. How can we get rid of the noise without losing ecological relevance?

Of course, the above-mentioned lack of reproducibility applies only as long as we do not understand all factors that influence our process of interest. As soon as we understand all factors of relevance, we will obtain reproducible data. Therefore, I argue that (i) a zig-zag course between field and laboratory is likely to provide us with relevant AND reproducible data for ecological research and that, (ii) 'noise' is not necessarily something we simply have to get rid of, but rather a putative indicator of interesting phenomena that we do not yet understand. Perhaps, the most famous scientific breakthrough that was initiated by a failure in controlling the experimental conditions is the discovery of antibiotics. If Alexander Fleming had nicely controlled his experimental conditions and avoided the unforeseen infection of his cultures of Staphylococci by an environmental *Penicillium*, he never would have discovered the antibiotics. Rather, Fleming worked under non-sterile conditions, made a mistake, carefully observed the derivation from the expected outcome of the experiment, profoundly thought about possible explanations, formulated a hypothesis aimed at explaining this phenomenon, tested the hypothesis, observed reproducible changes in bacterial growth rates and, thereby, discovered antibiotics!

Similarly, although admittedly of much lower importance and requiring way lower levels of creativity, the discovery that extrafloral nectar (EFN) secretion by *Macaranga tanarius* represents a jasmonic-acid (JA) –mediated induced defense trait started from a noisy dataset. A field study aimed at quantifying the metabolic cost of EFN suffered from huge levels of variation. Even organizing the data by leaf age did not help much, although it became clear that leaf ontogeny affects EFN secretion. However, then I observed a positive correlation of EFN secretion rates with standing levels of leaf damage. Of course, correlations do not mean too much. In fact, a positive correlation of a plant trait with standing levels of damage can indicate two contrasting phenomena: induced resistance (when the damage comes first and then causes stronger expression of the trait, which consecutively hinders further damage) or induced susceptibility (when the stronger expression of the trait comes first and then enhances damage). Anyway, the multiple reports on JA-dependent induced resistance traits in other plants made it easy to formulate a hypothesis and test it in the field. Then, knowing that herbivory and mechanical damage indeed do induce EFN flow, it was time to go to the lab and work on the underlying mechanism (Heil et al. 2001) of a process that by this time was known to be of relevance for this plant in its natural habitat. Similarly, Rhoades in the 1980s first

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concluded VOC-mediated plant-plant signalling from patterns in field data, and this phenomeon then was confirmed under controled laboratory conditions.

Of course, every system requires its own approaches and there are many ways to success. For example, herbivore-induced volatile organic compounds (VOCs) that attract predators or parasitoids as 'plant bodyguards' were first discovered under laboratory conditions, using a strictly hypothesis-driven approach. "Models that tried to describe the observed extermination of spider mite populations by predatory mites in greenhouse crops gave bad results when based on the assumption of random predator behavior", states Marcel Dicke, and he continues "the predictions of the models (Sabelis and Van der Meer 1986) improved only when including a cue that is emitted locally from the infested leaves and retains the predators in the spider-mite patch. Based on these assumptions, experiments were designed that led to the discovery of spider mite-induced plant volatiles that attract and arrest predatory mites. This demonstrates that such herbivore-induced plant volatiles have ecological relevance". The story of success of these initial studies (Dicke and Sabelis 1988) and their followers is well-known among chemical ecologists.

In summary, of course we have to work under controlled conditions if we aim to understand the biochemical, molecular, and genetic mechanisms that underlie the phenotypes of interest. However, I think it is important to move back and forth between the lab and the field. The controlled laboratory conditions should reliably resemble conditions that the studied organism commonly faces in its natural environment, and we also should test our conclusions as drawn from laboratory studies for their relevance for the organism's behavior and fitness in the natural environment. Contemporary science suffers from being split into literally thousands of disciplines and sub-disciplines and from our tendency to let the available methods, models, and equipment define our research questions. 'Chemical Ecology' *per se* aims at being an interdisciplinary approach that uses chemical (and, recently, molecular) techniques to understand ecological phenomena. Therefore, as chemical ecologists we should seriously think about BOTH of these words when we design our experiments. Ideally, we would always aim at a combination of chemical and molecular work with field studies that test the obtained results for their ecological relevance in nature. Forty years of success of the Journal of Chemical Ecology demonstrate that scientists from different disciplines can join forces and overcome the communication problems that always arise when people from different disciplines interact. Let's hope that the next forty years will see even more efforts to build bridges among disciplines.

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