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EDITORIAL

Carrying out experiments in landscape ecology

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The Oxford dictionary defines experiments as "a scientific procedure undertaken to make a discovery, test a hypothesis, or demonstrate a known fact". Although there are branches of science (e.g., paleontology, astronomy) which do not have an experimental focus, ecology broadly has historically tried to leverage experimentation into its approaches to research. Experiments in ecology are often through observational/natural experiments, where an existing phenomenon in nature (e.g., island size, an abiotic gradient) or a natural disturbance (e.g., wildfire) is the treatment, and measurements are made in the field. As well, ecologists also use manipulative experiments, whether in the field (e.g., via structures such as exclosures or warming chambers) or in the lab or lab-like setting (e.g., mesocsoms) (Kohler 2002; McGarigal and Cushman 2002). The hallmarks of good experimental design are the presence of a control, randomization of samples/treatments, and replication of sample units and treatments. Designing a good experiment is difficult. In particular, landscape ecologists working at large spatial scales can find it challenging to carry out rigorous experimentation, especially for manipulative experiments. One obvious barrier when making investigations at kilometres-extents is that the researcher cannot apply treatments across replicate landscapes. Without replicate units of a particular treatment, robust inference form an experiment is not possible. The other dimensions of good experimental design may also be difficult to apply when working at landscape-scales. To avoid committing Type I error, researchers should be sampling randomly. However, the spatial structure of landscape patterns (e.g., underlying gradients, naturally occurring patches) may mean that random sampling is confounded by underlying patterns. Similarly, it may be difficult to establish a true control for a treatment landscape that is many hectares or square kilometres in extent.

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When looking at the breadth of research in landscape ecology over the past few decades, it would seem that much of our work is more akin to research in astronomy, paleontology, and paleolimnology where an *n* of 1 is acceptable, and where inferences are derived from repeated observations in different places, and hypotheses are developed inductively more than deductively (Fig. 1a). The other approach that is quite dominant in our field is the use of modelling, and here, we might overlap more with fields like theoretical biology and theoretical physics. There is nothing wrong with these approaches to science, but I believe there is more room for explicitly experimental work in landscape ecology.

Others have written about the benefits and drawbacks of large-scale experiments (McGarigal and Cushman 2002; Barley and Meeuwig 2017). In 2012, Jenerette and Shen (2012) provided readers of this journal with the first in-depth profile of

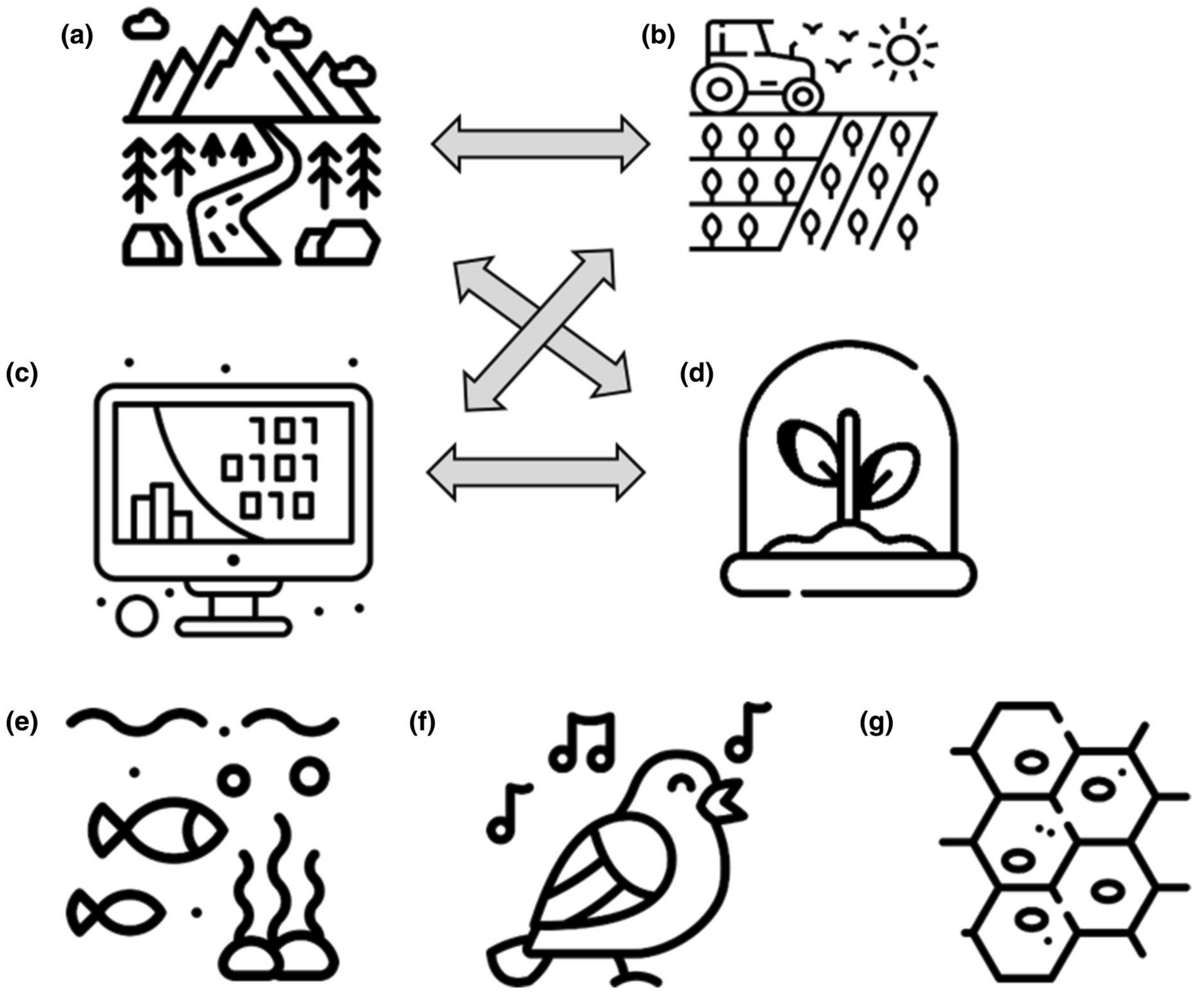

Fig. 1 Schematic illustrating the various ways in which we can conduct experiments in landscape ecology. We typically think of landscape ecology studies as being observational studies/natural experiments in kilometres-extent landscapes (**a**). However, successful experiments have carried out experimental mowing or tilling on the scale of hectare in agricultural settings (**b**). As well, landscape ecologists can harness technologies such as computer models (**c**) and mesocosms (**d**) to run experiments. Finally, exploring research in novel landscapes, such as seascapes (**e**), soundscapes (**f**) and the landscapes of cells and tissues (**g**) may offer up new opportunities. Integrative research that combines approaches (illustrated by the arrows, may realize even more possibilities. This figure was designed using resources from Flaticon.com, specifically from Smashicons, Freepik and Smalllikeart

experimentation in landscape ecology. Their perspectives article provided a taxonomy of experiment types in landscape ecology, organized around four groups, with different goals: (I) identification of landscape structure; (II) identification of process variation within landscapes; (III) identification of process sensitivity to landscape structure; (IV) identification of landscape pattern formation factors. Jenerette and Shen (2012) also reminded us that experiments serve to test hypotheses or used to discover new knowledge. Experiments in the lab trade off a high degree of control over confounding factors for the realism that field experiments offer. At the same time, drawing inferences beyond the scale of the experiment to larger landscapes is a further challenge for experimentation in our discipline (Jenerette and Shen 2012).

While Jenerette and Shen (2012) described the different types of experiments in terms of *what* they are trying to elucidate, their essay did not describe in detail *how* we carry out experiments in landscape ecology. They provided general description of several types of experiments, including large extent ones, which are costly and logistically challenging. These are often the types of experimental manipulations that come to mind for landscapes and can include experimental harvest blocks in forests (such as at the Savannah River Experiment; Haddad et al. 2003). At slightly smaller extents of a few hectares, we have examples of experimentally planted patches of vegetation to manipulate habitat loss and fragmentation (Fig. 1b), such as the Bowling Green experiment (With and Pavuk 2011). These experiments are highly realistic, given that they occur in forests and agricultural fields. At the same time, they may have minimal replication of treatment units, usually between one and eight. Treatments usually manipulate one or more of patch size, shape, inter-patch distance or connection to other patches/the matrix, and thus are ideally suited for Jenerette and Shen's (2012) Group III experiment types. Although experiments such as these have provided useful insights into how different organisms respond to habitat loss and fragmentation, they are not the only way to do experiments in landscape ecology.

Landscape ecologists have always actively embraced the use of computers (Fig. 1c); indeed the very first issue of this journal contained two papers that used computer-based research (Gardner et al. 1987; Turner 1987). Current computing power is such that there are many tools and platforms available for in silico experimentation, including cellular automata models, agent-based models and mathematical and statistical models. In silico experiments that are more extensive even combine multiple model types into a single study. Researchers can harness computers to conduct many types of experiments in landscape ecology, from testing how landscape configuration affects movement of an organism, to seeing how policy decisions influence landscape change, and assess human preferences to these future landscapes.

Other branches of ecology, notably community and ecosystem ecology, have made extensive use of mesocosms and microcosms (Fig. 1d) to do manipulative experiments. Researchers could leverage these tools to address landscape ecology questions about patch quality, for example, or use them to test how patch quality and/or configuration affect movement of organisms between patches. Creating scaled-down landscapes ("landscapes from a beetle's perspective"; Wiens and Milne 1989) treats these container experiments as model systems for kilometres extent landscapes that can easily be used for manipulative experiments, and in turn may better inform cross-scale inferences.

When considering how to design experiments in landscape ecology to address particular questions, we should not neglect landscapes beyond the terrestrial realm. Seascapes (Fig. 1e), riverscapes and soundscapes (Fig. 1f) offer unique spatial and temporal dynamics that may make them highly amenable to certain experimental applications. Finally, recent work has suggested scaling down to the levels of cells and tissues (Fig. 1g) in our own bodies to consider how landscape perspectives can help address diseases like cancer (Lloyd et al. 2015). Harnessing tissue cultures as experimental model landscapes might be a further avenue for landscape ecology research; environments where a high degree of replication and control is quite feasible.

No matter what spatial extent (microns to kilometres) or medium (terrestrial, marine, aquatic, corporeal) we carry out our experiments, a common challenge in landscape ecology research is grappling with scale issues. Fortunately, there is a large and robust literature, both within the discipline of landscape ecology, and beyond, on scale and scaling (Gardner et al. 2001), that we can draw on to help with cross-scale inference, and incorporating aspects of scale into our experimental design. Explicit focus on scale and hierarchy concepts are at the core of landscape ecology, and with creativity, and a diversity of experimental approaches, we can conduct experiments across multiple scales of interest.

To do experiments well in landscape ecology, we need to talk more about what makes a good experiment and how we can improve on the experiments we have already done. Until now (Wiersma 2022), students and researchers have not had a comprehensive text to guide them on how to do experiments in landscape ecology. A "how to" book on landscape ecology experiments can never be fully comprehensive, nor capture the wide range of landscapes and questions that our interdisciplinary discipline grapples with. Nonetheless, it may provide a useful starting point for conversations.

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