# Learning to roll with the punches: adaptive experimentation in human-dominated systems

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**The interdisciplinary study of human–environment interactions is becoming increasingly important around the world. Long-term experimental manipulations that combine approaches from both the ecological and social sciences could play an important role in the study of human–environment feedbacks in cities. The inclusion of in situ human subjects in this research is vital, as it facilitates more accurate scientific models and might produce social benefits such as increasing public trust in scientists. Within a landscape experiment, human subjects may alter experimental conditions to suit their needs, imitating the rapidly changing environmental conditions in cities. In response, researchers adjust explanatory models in a process which could be called "adaptive experimentation". These ideas are illustrated by a description of a proposed experiment in the Phoenix metropolitan area, where residential landscaping will be manipulated and the feedbacks between ecological processes and the activities of resident humans studied.**

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As reciprocal influences between humans and the climate, biota, and ecological functions of the world have become both stronger and more widely recognized (Vitousek *et al.* 1997; Bennett *et al.* 2003; Palmer *et al.* 2004; Steffen *et al.* 2004), there has been a growing need for research on ecological processes in human-dominated ecosystems (McDonnell and Pickett 1993; Collins *et al.* 2000; Grimm *et al.* 2000; Alberti *et al.* 2003). In some ecosystems, structure and function are now determined primarily by human social interactions, perceptions, and behaviors (eg Naveh 1998; Hope *et al.* 2003). Urban areas in particular require a variety of vital ecosystem services (Luck *et al.* 2001; Kinzig *et al.* unpublished). They also serve as potential habitat for flora and fauna (Miller and Hobbs 2002; Figure 1). One pressing challenge in ecological research is to understand the complex feedback mechanisms between human and non-human components of ecosystems (Berkes *et al.* 2003; Palmer *et al.* 2004). Pursuit of this goal is complex and unpredictable, requiring new and innovative research methods.

### In a nutshell:

- The study of interactions between humans and the environment is critical in understanding how humans create and respond to environmental change
- Adaptive experimentation is a mechanism for ethically applying manipulative experiments in studies of human-dominated ecosystems
- Combining approaches from both environmental and social sciences is essential to fully understand human–environment interactions in urban areas
- This integration may provide social benefits, including a better public perception of science and scientists
- Where it is safe and ethical, the explicit inclusion of people living and working in a study area in urban social–ecological studies can promote scientific realism and reveal non-intuitive causal relationships

A wide variety of approaches have been successfully used to study the feedbacks between humans and their biophysical environment (Table 1). Historical ecology and social surveys specifically address human responses to their environment, opportunistic use of natural experiments allows simultaneous study of different stages of human–environment feedback loops, and simulations and modeling allow prediction of future events. Each technique is associated with a set of advantages and disadvantages. Here we focus on the experimental approaches and contend that, while observational studies can be quite powerful, an experimental approach is also important in predicting interactions and feedbacks between humans and the environment.

Manipulative experiments are rarely used in studies of human–environment interactions, despite the key role that experimentation usually plays in science. There are both ethical and logistical reasons for this lack of inclusion of in situ human subjects. Combining approaches from both the biophysical and social sciences can yield fundamental new insights into coupled human–environmental systems. However, because the social dynamics of subjects may change unpredictably in response to experimental intervention, the conceptual models and the experiments that they motivate should be capable of

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**Table 1. A brief review of experimental approaches that investigate at least one direction of human–biophysical feedback**
*Examples of each major conceptual category are shown with their key advantages and disadvantages. Each approach represents different trade-offs among experimenter control and replication, spatial scale considered, resources necessary to conduct the study, and the realistic consideration of human activities and perceptions.*

| *Approach* | *Advantages* | *Disadvantages* | *Examples* |
|---|---|---|---|
| Small-plot experiments | Allows extensive replication, strict controls, and factorial treatments involving several predictor variables. | Small spatial size excludes consideration of many processes. Human element cannot be simulated easily. | N-deposition (Wedin and Tilman 1996) |
| Large-plot/landscape experiments | Controls and some replication possible. Allows consideration of processes operating at scales greater than a few meters. | Extensive replication much more difficult. Human element usually simulated. | Clear cut effects on water and nutrient flow (Hornbeck *et al.* 1993). Fire and livestock grazing (Collins *et al.* 1998; Knapp *et al.* 1998) |
| The watershed approach | Allows study of whole ecosystem functioning. Before–after comparisons and untreated "reference" watersheds useful. | Replication often not possible. Strict controls difficult. Manipulations may be impractical or unethical. | Urban systems (Groffman *et al.* in press). Natural systems (Likens and Bormann 1995) |
| Chronosequences and natural experiments | Opportunism. Observation of different stages of sequence at once. Active manipulation can be avoided. Good for social–anthropological studies. | Controls generally lacking. Confounding factors. Key events may have occurred in past and critical information missing. | Land-use effects on communities and function (Mitchell *et al.* 2002; Currie and Nadelhoffer 2003) |
| Historical ecology | Allows consideration of many factors and large spatial and temporal scales. Human and non-human feedbacks clearly elucidated. | Post hoc explanations with limited prediction ability. Limited replicability. | Human sociohistorical relationships with habitat structure (Balée 1999) |
| Simulations and modelling | Allows consideration of many factors and large spatial scales. Can require limited field-based infrastructure. | May not include key factors. Possible lack of "realism". Human behavior is difficult to predict. | Global change (Ollinger *et al.* 2002; Svirejeva-Hopkins *et al.* 2004) |
| Social surveys | High replicability and comparability. Can include large spatial and temporal scales. High correlation potential. | Low potential to identify causality. Generally lacks non-human feedbacks. | Environmental values (Dunlap *et al.* 2000) |
| Adaptive management | Embraces uncertainty and human/non-human feedbacks. Policy and management benefits. | Mostly limited to resource management questions and intervention by institutions. Difficult to generalize findings | (Walters and Hollings 1990; Gunderson 1999; Armitage 2003) |
| Adaptive experimentation | Embraces uncertainty and human/non-human feedbacks. Controlled experimentation elucidates causality and allows for replicability. Social, policy, and management benefits | Requires a priori correlational analysis or modeling. Spatial scale limited by logistic constraints. Ethical considerations. | Controlled habitat experiments with in situ humans (see Panel 1) |

***Figure 1.*** *It will be an increasing challenge for rapidly expanding urban areas to provide essential ecosystem services ranging from recreational opportunities to habitat for flora and fauna. Urban planning and conflict resolution benefit from the integrated study of human and non-human system dynamics. This is especially true in arid cities, where the introduction of water radically alters landscapes.*

adapting to these shifts. Rapidly changing environmental and social conditions are commonplace in cities (Collins *et al.* 2000; Grimm *et al.* 2000). This pragmatic approach to research, which we call "adaptive experimentation", is therefore of particular relevance in urban ecosystems.

Here we discuss the advantages, challenges, and opportunities that result from the inclusion of humans as an integral component in manipulative experiments and discuss the potential contribution of such work to the understanding of social and biophysical functioning. The challenges and opportunities of conducting such research are illustrated using a unique case study (Panel 1), built around a residential landscaping experiment being developed at the Central Arizona – Phoenix Long Term Ecological Research program (CAP LTER).

 

## Adaptive experimentation

Adaptive experimentation in human-dominated systems is a research approach that balances traditional reductionist experimental design (ie replication, controls, and independence of study subjects) with the incorporation of realistic system complexity and consideration of the ethical concerns that arise when studying humans. Teams composed of natural and social scientists collaborate to develop conceptual, mathematical, or simulation models which highlight key operations within the study system, and predict potential causal relationships among components. Correlations between large-scale biophysical data (eg satellite imagery, vegetation cover, and biological diversity) and social data (eg census data or structured survey responses) are used to help develop testable hypotheses and place the experimental work in a suitable context. Adaptive experiments involve in situ human subjects, whose feedback is used to formulate and revise research design and predictive models. These experiments are devised with the expectation that hypotheses, as well as the experimental treatments themselves, may be modified in mid-course (more than once if necessary) due to the unpredictable behavior of the human subjects and our growing understanding of the complexity of the system (Figure 2). Adaptive experimentation, by definition, is carried out on systems with humans as an integral, dominant component; otherwise, existing conventional experimentation can be used.

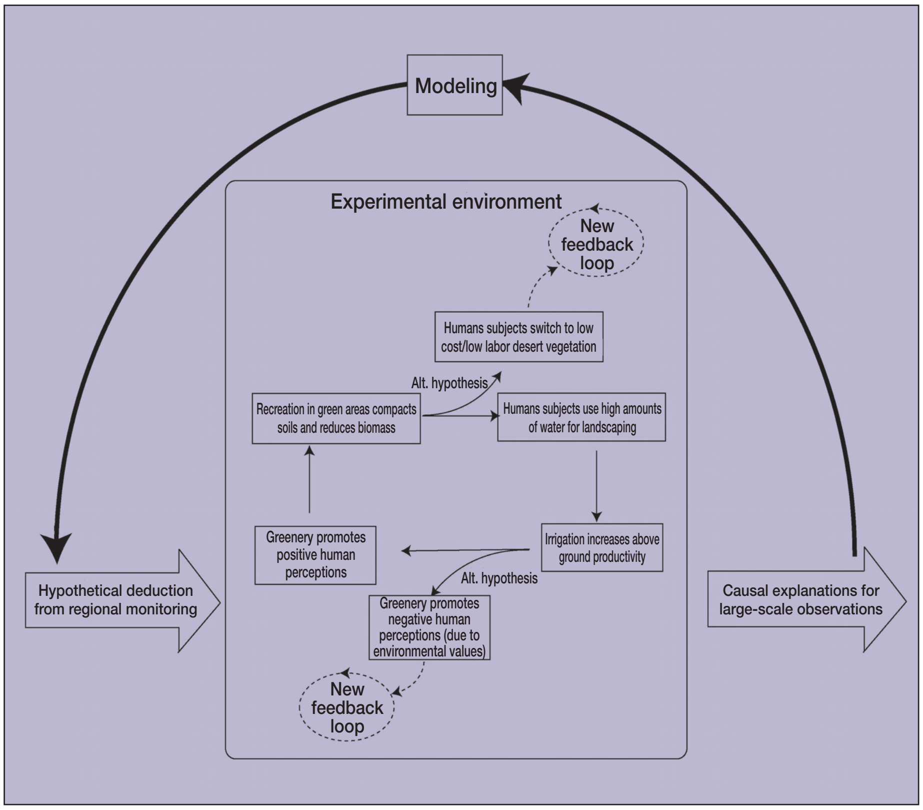


***Figure 2.*** *Research protocol and a potential feedback loop involving human–environment interactions at CAP LTER's residential landscape experiment site, including hypotheses to be tested in the experiment. Note that alternate hypotheses exist, each of which could send the experiment into alternate loops.*

Adaptive experimentation has some aspects in common with traditional adaptive management (Walters 1986; Gunderson 1999), but there are two key differences. First, adaptive management, as used by natural resource managers, is generally aimed at developing management practices for a system, and mid-course changes are made to achieve a politically negotiated, predetermined outcome. Statistically rigorous, controlled experimentation almost never occurs in adaptive management, because of competing institutional interests, fear that results may threaten the status quo, and other political processes (Walters 1997). In contrast, adaptive experimentation is an academic endeavor, intended to build basic knowledge through replicable experimental design. Social, policy, or managerial benefits are treated as desirable but secondary outcomes. Secondly, adaptive experimentation incorporates most of the formal aspects of classic experimental design, including independence of study units, use of replicates, and controls (Panel 1). Hypotheses, as well as the experimental treatments themselves, may be modified during the experiment, more than once if necessary. While the adaptive experimentation approach may be slower to influence policy because it generates knowledge outside management institutions, this knowledge is useful to managers in the longer term. Additional differences between adaptive management and experimentation are that the latter might typically be applied at smaller scales and may be less reliant on the use of models than adaptive management scenarios.

The landscaping experiment being developed at CAP LTER (Panel 1) asks: "How does residential landscape type affect a number of key ecosystem processes in a residential urban environment?" The adaptive experimentation approach could also be applied to address a question such as: "What role do domestic and feral cats play in the trophic structure of the urban ecosystem?" In this case, the experiment might involve selecting similar homes and yards with and without domestic cats, and using different types of fencing to exclude birds (and perhaps feral cats) from yards in a randomized treatment design. The adaptive part of the experiment might be to allow residents to "ban" their cats from outdoor access, if preliminary data showing increased bird predation

**Panel 1. The CAP LTER residential landscaping experiment**

The structure and productivity of residential vegetation across the arid Central Arizona–Phoenix LTER study region relies heavily on irrigation to supplement normal rainfall and is determined by human preferences (Martin *et al.* 2003). In the process, residents increase residential landscape water use and lower vegetation water-use efficiency (Martin and Stabler 2002). This continues despite the emerging popularity of desert landscaping in Phoenix, which is predominantly a top-down phenomenon directed by public and private interest groups (Martin 2001). The aim of this experiment is to manipulate residential landscapes at 24 of about 152 homes, which form the North Desert Village at Arizona State University's East campus. The houses (all virtually identical, since they were formerly housing for the Williams Air Force Base) are rental units for student family housing (Figure 3).

*Figure 3. One of the areas to be re-landscaped using one of four popular landscaping styles.*

Four experimental treatments will be installed, designed to recreate the prevailing residential yard styles and coincident methods of water delivery found throughout the Phoenix area (Martin 2001; Martin *et al.* 2003). These are:

a) mesic – exotic, high-water-use vegetation and turf grass
b) oasis – a mixture of drip-irrigated, high- and low-water-use plants (including palms, desert shrubs, and succulents) and sprinkler-irrigated turf grass
c) xeric – consisting of low-water-use, desert-like (non-native) plants, with drip irrigation and set in decomposing granite to create an idealized desert look typical of many modern yards in the southwestern US
d) native desert – a combination of native trees, shrubs, and cacti, with no supplemental irrigation

Each landscape type will be replicated at six homes, arranged in mini-neighborhoods around an adjacent common area (Figure 4), which will be landscaped using the same design and plant species. An additional mini-neighborhood of six homes and a common area will be monitored as a control. Residents will be allowed to modify the landscape in the yard immediately around their own home, but not in the common areas. Plant diversity in the six yards will be the same as in the common area, but diversity from yard to yard will contain a random subset of the total planting list for that design, due to space limitations (558 $m^2$ per yard).

Pre-treatment and long-term, post-treatment data will be gathered for soil trace gas flux, net primary production, soil microflora and arthropod communities, bird and small mammal diversity and behavior, and microclimate. Social variables include human behavior (ie direct measures of water use, recreation, and landscaping behavior), ecological knowledge, social network structure, overall environmental values, and perceptions of landscapes. The hypothesized causal relationships between these biophysical and social variables (Figure 2) derive from CAP LTER's large-scale regional monitoring of biophysical and social patterns and processes. Due to the difficulties involved in predicting human behavior, this experiment included public participation in design and the ongoing potential to adapt to emergent hypotheses.

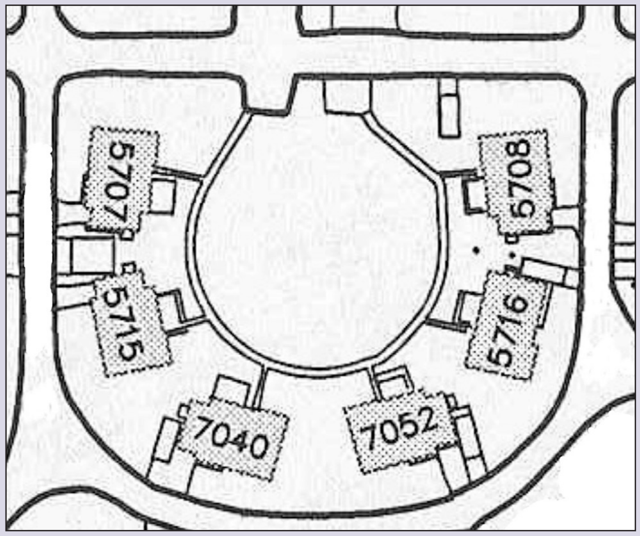


*Figure 4. Example of a mini-neighborhood with six houses and a common area. Each of four mini-neighborhoods will receive a different landscaping treatment.*

moved cat owners to make such a change. Another example of applying this approach could be to ask: "Does banning the use of pesticides and herbicides in suburban yard maintenance make a real or perceived difference to plant and human health?" Here, an experimental design of similarly landscaped yards might receive full, partial, zero, or "placebo" chemical treatments (the latter would involve treating yards with "chemicals" that actually consisted of plain water). One might allow residents to selectively ban or reintroduce certain chemicals from parts of their yards if a substantial landscaping problem developed (eg imminent death of a beloved tree or bush due to insect attack).

In the following sections we discuss the benefits and the costs of using adaptive experimentation in human-dominated landscapes.

## Advantages of adaptive experimentation

### *Statistical considerations and detection of causality*

Manipulative experiments with replication and controls that include human subjects are well-suited for isolating the influence of individual variables on human–environment interactions. Controlled experiments improve the reproducibility of results and, with sufficient replication, reduce statistical error (Eberhardt and Thomas 1991). Consistent treatment effects can therefore often be more confidently attributed to the causative mechanism. This may be particularly relevant in human-dominated systems, where many factors co-vary. While less reductionist methods (eg comparing watersheds, gradient analyses) can be powerful tools for detecting long-term changes and generating questions about internal mechanisms, identifying causal relationships without experimentation can be difficult. For example, use of the urban–rural gradient concept to investigate potential human-induced changes to soil chemical and physical properties (eg McDonnell *et al.* 1997) can be confounded by concomitant changes in soil types along the gradient. Social variables such as income and ethnicity also often co-vary with behaviors such as environmental activism (Mohai 1985).

### *Experimental realism*

To date, manipulative studies of human-induced effects on ecological processes (eg nutrient cycling) have involved treatments that imitate or exaggerate human activities (Bowden *et al.* 1992; Wedin and Tilman 1996). However, the responses of in situ humans to changes in biophysical conditions are motivated by economic and social forces and depend on highly variable behavioral and social contexts (Berkes *et al.* 2003). Explicit inclusion of people in an experiment allows the complete human–environment feedback dynamic to develop within a realistic experimental scenario. This scenario includes the possibility that human subjects may spontaneously alter the parameters of a study in mid-course.

For instance, in the residential landscaping experiment described in Panel 1, residents may initiate plantings or apply water to a "desert" treatment. While such occurrences might be seen as disruptive to researchers conducting a fixed experiment, in the adaptive approach such possibilities are incorporated into the experimental design, further enhancing the study's realism. In the residential landscaping experiment, residents of some landscape types may want to modify planting designs to their own tastes. To allow this to occur while maintaining a controlled design, the experiment will allow residents to alter landscapes around individual houses, but not in the communal areas. This preserves an area in each treatment where the initial planting designs are maintained for comparative purposes, while providing residents with the freedom to garden and allowing researchers to study human behavioral responses to both types of landscape manipulation.

### *Fostering interdisciplinary collaboration*

Experience has shown that adaptive experimentation catalyzes interdisciplinary integration (Panel 1). Non-intuitive causal relationships are more likely to be discovered when environmental and social scientists are each encouraged to adapt their own disciplinary techniques to cross-cutting research questions (Grimm *et al.* 2000; Dove 2001). Biologists and physical scientists benefit from working with sociologists and anthropologists who have studied cities for centuries, while social scientists are able to benefit from an understanding of biophysical patterns and processes from researchers specializing in those fields.

### *Social benefits*

Potential subjects may initially be reluctant to participate in socioecological experiments due to a general distrust of scientists. When designed sensitively and with public input, however, human-inclusive experiments can potentially reconnect communities with non-human ecological processes, build public trust in science, and induce behavioral changes in public agencies (Whyte 1991). Incorporating human subjects into experimental designs also helps to remind researchers that their work requires the interest, permission, and support of the people living in the area under study.

Not only can public participation help to demystify scientific research, but participants may also develop a sense of ownership of the experiment, instead of perceiving it as an intervention imposed by others. This may also diminish the potential for later misinterpretation of research intentions and behavioral backlash (for instance, organized political opposition to the experiment, vandalism of experimental equipment, or jealousy within a control population over perceived benefits of a treatment which it is not receiving). Participants should also be more likely to participate willingly over the long term, and to apply experimental conclusions if they are included in a dialogue with researchers.

## ■ Drawbacks and challenges of adaptive experimentation

### *Ethical and social limitations*

Any experiment involving humans must rigorously address ethical considerations. Practically, this is achieved by requiring that all human research conducted at institutions receiving federal funding is approved by a human subjects review board. Proposed projects cannot discriminate based on ethnicity, income, or gender, and any disproportionate distribution of anticipated negative effects must be rigorously justified (Bryant and Callewaert 2003). For example, the habitat manipulations that are part of an experimental treatment (Panel 1) must result in improvements that are fairly distributed among the human subjects involved. Precautions must be taken to reduce potential harm from experimental treatments (in fact, researchers bear legal liability). Experiments must be described to subjects in sufficient

**Panel 2. The spiny cactus problem**

Potential problems associated with including humans in the CAP LTER residential landscaping experiment led researchers to include participants in experimental design. Researchers particularly wanted to study ecological function and human reaction to desert plants, and preliminary research indicated the aesthetic appeal of landscapes with desert plants like the saguaro (*Carnegiea gigantea*; Figure 5). At public meetings and in interviews, however, some human subjects expressed concern about the safety of including spiny native desert plants close to houses and areas where their children play (eg Figure 6). This led to the hypothesis that recreational activity is lower in yards with desert landscapes, so that fewer negative effects on plants and wildlife (Figure 2) might be expected. Researchers responded to residents' concerns by including more non-spiny plants that serve similar ecological functions, and by carefully positioning and caging the remaining spiny plants to minimize the risks to children while not interfering with wildlife. Thus, flexibility on the part of the researchers led to a situation in which human subjects received what they wanted, while researchers gained new insights into landscaping decisions.

**Figure 5.** *Saguaros are very popular due to their aesthetic appeal. Indeed, high prices paid for these cacti suggest their emerging role as status symbols in landscaping.*

**Figure 6.** *Residents expressed concerns about installing xeric landscapes with native spiny plants because of the danger to children and pets.*

detail for them to choose whether to participate, and thus give their informed consent. This increases the logistical burden in experimental design and may cause subjects to alter their behavior in response to information from researchers.

Yet from both a practical and an ethical standpoint, we have found such communication not only necessary, but beneficial. Feedback from people living on our site during the experimental design phase highlighted the potential (and perceived) hazards of spiny desert plants associated with recreational behavior and previously not considered by researchers. As a result we have been able to modify our experimental treatments to both increase public safety and explore the perceived dangers of certain desert plants (Panels 1 and 2).

### Disciplinary barriers to integration

Cultural, financial, and, in particular, disciplinary barriers may exist in many collaborative research projects (Anonymous 2003). Defining research questions can be difficult in integrated studies, because individual disciplines have their own discrete methodology and bodies of knowledge, often with scant theory or data in common with other disciplines. A willingness to collaborate and to be open to creative input from colleagues, modelers, statisticians, and human subjects is essential for researchers wishing to undertake adaptive experimentation in human-dominated systems. Finding shared questions that are relevant to all participants is also vital, as is specifying assumptions, research domains, and theoretical components (Pickett *et al*. 1994). Such adaptability may be seen as too compromising for individualistic researchers trained in the classic mode. However, an ability to switch one's focus away from the narrow confines of what one might have pursued individually is vital in collaborative work.

### Budget constraints

Adaptive experiments can be far more expensive to run than traditional disciplinary projects. The need to include a diversity of researchers, extra resources to cope with changing conditions during the experiment, and additional administrative oversight all require managerial time commitment and additional resources. Budget flexibility must also be built into any adaptive experimental framework.

### *Wider applicability of results*

Findings from experiments are to some extent confined to the setting in which they are carried out. However, those that are most successfully extrapolated have an experimental design that reflects a wider geographic context, reaching beyond the treatment boundaries across scales of time and space (Hobbs and Yates 2003). For experiments involving humans in situ this can be achieved by integrating biological monitoring, social surveys, simulation modeling, and comparative work at larger scales (Likens *et al.* 1996; Driscoll *et al.* 2001; Likens *et al.* 2001).

Obtaining a human experimental group representative of the wider population is more difficult than in traditional ecological studies – plant or animal populations typically do not have a choice about participation. Humans willing to participate in ecological experiments may represent subpopulations who have stronger environmental values, are more open about private activities, or have different political affiliations than those who decline to take part.. The selection of a diverse subject pool is also constrained by the geographic limits of an experiment. Researchers therefore need to understand as much as possible about behavioral motivations within structured study populations, so as to better place experimental results within a larger context. For instance, hypotheses about changes in human behavior resulting from habitat manipulation can be derived from large-scale questionnaire surveys about perceptions and goals (Panel 1).

### *Scale constraints*

As with all experiments, the adaptive approach is best suited to questions that can be addressed at scales that are practical for experimental manipulation (Table 1; Panel 1). Addressing a question such as "How do changes in human watershed management practices affect salmon recovery in the Pacific Northwest?" is more suited to an adaptive management approach (Walters 1986), because of the difficulty of performing replicated manipulations with controls at such large scales.

## ■ Conclusions

Controlled experimental manipulations that include *in situ* human subjects can and should be an integral component of ecological research in human-dominated ecosystems. This research context adds complexity and uncertainty to the experimental process, which necessitates an adaptive approach. Indeed, most traditional ecological experiments are implicitly adaptive. Idealized designs in research proposals are often modified during implementation as investigators deal with the realities of complex systems. Adaptive experimentation ensures that adaptation and modification are explicit components of the research plan.

Despite the proposed benefits of adaptive experimentation, experimental or interdisciplinary methods are not the only valid approaches for this type of research. Other approaches (Table 1) remain useful, and sometimes preferable, under many circumstances. It may sometimes not be logistically or ethically feasible to apply adaptive experimentation, for instance in cases where control subjects would be denied a critical and beneficial treatment. It might be possible for researchers to combine other experimental approaches with opportunistic study of economically, socially, and governmentally driven (but ethically acceptable) changes, such as human migration (Atran *et al.* 2002; Casagrande in press) and ecological restoration projects (Hartig *et al.* 1994). Overall, however, a participatory, interdisciplinary, and adaptive experimental approach that includes in situ humans will prove illuminating for the understanding of human-dominated ecosystems.

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