Chapter 2
Ecological Novelty: Towards an Interdisciplinary Understanding of Ecological Change in the Anthropocene

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Abstract This chapter presents a broad view of an ecological science in search of new paradigms for tackling the ecological challenges of the Anthropocene. In a first part, I introduce the concept of 'ecological novelty' to characterise ongoing environmental change. The environmental change that brings about ecological novelty can be characterised by at least six attributes: it is (1) man-made, (2) large, (3) very fast, (4) multi-dimensional, (5) variable, unknown and unpredictable and (6) of global extent and even affecting remote wilderness areas. In the second and third parts, I focus on two fundamental challenges that ecological novelty poses for ecological research: (i) distinguishing between nature and culture as separate realms of scientific investigation becomes obsolete; and (ii) understanding how ecological systems change requires embracing the complexities of ecosystems under real-world conditions (as opposed to controlled experimental settings) resulting from open system boundaries, contingencies and historicity. Ecology has long explored the transition zone between the natural and social sciences, and can significantly contribute to an interdisciplinary understanding of societal adaptation, whether to climate or more generally to environmental change.

2.1 Introduction

Humans are transforming the abiotic and biotic conditions on Earth so profoundly that many scientists claim our planet is entering a new geological epoch, dubbed the Anthropocene (Crutzen and Stoermer 2000). While climate change is one aspect of ongoing anthropogenic environmental change, other factors are equally important; for instance, biogeochemical cycles are being changed, biodiversity is vanishing, and the last remnants of wild land are being transformed through human

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land use (Turner and Clark 1990; Steffen et al. 2004; Millennium Ecosystem Assessment 2005).

In this chapter, I am interested in how ecological research addresses environmental change in the Anthropocene as a first-order construct, namely how it studies physical facts as opposed to social constructions and representations of these physical facts (‘second-order construct’) (cf. Greschke and Tischler, Chap. 1, this volume). Put differently, I discuss how ecologists study cause and effect relationships among physical, biological and social factors as a basis for explaining and predicting (socio)ecological patterns and processes in the Anthropocene. However, as will become apparent in several instances in the text, separating ecological facts from the social constructions and representations of this empirical knowledge can be problematic when dealing with environmental change, given that several issues blur the distinction between the production of facts and their representation, interpretation and use. Much ecological knowledge is uncertain and incomplete (‘unknown unknowns’) and several alternative interpretations of empirical information may be valid (e.g. Larson et al. 2013). Furthermore, knowledge production and use are often entangled (e.g. Kueffer and Hirsch Hadorn 2008), rendering it difficult for ecologists to navigate their dual role as scientists and advocates of social change and interventions in nature (e.g. Lach et al. 2003). In such cases, the researcher loses his or her status as an objective observer and becomes embedded within networks of social interpretation and acting (e.g. Taylor 2005). Finally, as environmental systems are increasingly shaped by social as well as biological processes, ecology is being transformed into a science of hybrid social and ecological systems.

This chapter comprises three parts that together present a broad view of an ecological science in search of new paradigms for tackling the challenges of the Anthropocene. The first part sets the stage, whereby I introduce a conceptual framing of environmental change in the Anthropocene, which I call ‘ecological novelty’ (Kueffer et al. 2011a). For an ecologist, ‘ecological novelty’ better captures the emerging dynamics than notions of ‘climate change’ or ‘global change.’ Changes happen at different spatial scales, and patterns and processes at local scales are particularly difficult to understand and manage. Novel ecosystems usually arise, not due to changes in isolated factors such as rising temperatures, but through the interactions of many entangled physical, chemical, biological and social factors. Moreover, it is not change *per se*, but rather the magnitude, rapidity, unfamiliarity and uncertainties of these changes—the novelty—that challenge traditional science and human-nature relationships.

In the second and third parts, I focus on two fundamental challenges that ecological novelty poses for research: (i) distinguishing between nature and culture as separate realms of scientific investigation becomes obsolete; and (ii) understanding how ecological systems change requires embracing the complexities of ecosystems under real-world conditions (as opposed to controlled experimental settings) resulting from open system boundaries, contingencies and historicity.

Ecology has long explored the transition zone between the natural and social sciences, which makes ecology an interesting partner for the social sciences in understanding societal adaptation to both climate change and environmental change more generally. My aim here is to show that ecology not only increasingly shares the same study object with environmental social sciences and humanities—namely, adaptation to rapidly changing socio-ecological systems—but also that the epistemological and methodological challenges converge. I hope that this chapter helps to build bridges between environmental research in ecology and the human sciences and enriches the vision of a locally-grounded and interdisciplinary science of societal adaptation to environmental change.

2.2 What Is Ecological Novelty?

Humans are fundamentally transforming the abiotic and biotic conditions on Earth (Turner and Clark 1990; Steffen et al. 2004; Millennium Ecosystem Assessment 2005). These changes affect all levels of biological organisation—genomes, populations, communities, ecosystems, landscapes—and result in patterns and processes with which we are not familiar at local, regional, and global scales (Kueffer et al. 2011a). Thus, future ecological systems will be very different from those we know from the past or present. Current environmental change, and thus also ecological novelty, has six important characteristics: it is (1) man-made, (2) large, (3) fast, (4) multi-dimensional, (5) variable, unknown and unpredictable and (6) of global extent and even affecting remote wilderness areas. In the following, I explain and illustrate each of these six characteristics and consider how they affect ecological novelty.

2.2.1 A Man-Made Planet

A first characteristic of ecological novelty is that it is man-made (Vitousek et al. 1997; Turner and Clark 1990). Seventy-five percent of Earth's ice-free land has been altered as a result of human settlements and land use (Ellis et al. 2010), with most remaining wild land found in unproductive places such as at high latitudes and in deserts. Within the next few decades, humans might consume the total global annual terrestrial biomass production (net primary production) that is accessible to them (Running 2012). Climate change primarily results from human activities (IPCC 2007), most biogeochemical cycles (e.g. water, CO_2, nitrogen, phosphorus) have been fundamentally transformed by humans (Vitousek et al. 1997; Steffen et al. 2004), and humans are also the main cause of species extinctions and reshuffle biotas by transporting thousands of species to new places where they were not naturally present (Millennium Ecosystem Assessment 2005). Chemicals (e.g. DDT, endocrine disruptors), engineered organisms (genetically modified organisms, synthetic biology), and other artefacts (e.g. nanotechnology products) are increasingly released into the environment. Accordingly, there are few places on Earth—and few physical, chemical and biological processes—that have not been substantially influenced by humans.

One consequence of the dominant and pervasive role of humans in nature is that feedbacks between ecological change and societal responses have become ever tighter (e.g. Warren 2011). Sometimes, societal adaptation to environmental change results in more fundamental effects on ecological processes than the initial environmental change. For instance, in response to climate change, agriculture might expand into areas that were previously unsuitable, introduce new types of crops or produce biofuels as a new energy source, with ecological consequences for the agricultural land and surrounding landscapes (Sutherland et al. 2012; Warren 2011). People will migrate and land use patterns will shift (Warren 2011). Moreover, geoengineering techniques ranging from reforestation to ocean fertilisation with iron to the release of aerosols to the atmosphere would also have profound consequences for the Earth's ecology if applied on a large scale to moderate global warming (Royal Society 2009).

Such feedbacks between environmental change and human responses might be modulated or accelerated through changing human perceptions of ecological systems due to the loss of experience about past conditions ('shifting cognitive baseline syndrome') (Papworth et al. 2009). For instance, Turvey et al. (2010) recorded how fishing communities along the Yangtze river within decades lost their traditional knowledge about culturally and economically important species such as the extinct Yangtze River dolphin or the possibly extinct Chinese paddlefish. Some conservationists are concerned that ecological research contributes to shifting cognitive baselines by emphasising pervasive human-caused change of ecosystems, thereby characterising the conservation of undisturbed nature as an illusion and acting as "an impetus for accelerated changes in land use" (Caro et al. 2012).

2.2.2 Magnitude of Change

A second characteristic of ecological novelty is the magnitude of current environmental change (Vitousek et al. 1997; Steffen et al. 2004; Fischlin et al. 2007; Millennium Ecosystem Assessment 2005). The anthropogenic component of many biogeochemical cycles (e.g. water, nitrogen, phosphorus) is as large as or larger than all natural fluxes combined. Pools of many chemical substances (e.g. CO_2, methane, nitrous oxide) have at least doubled in the atmosphere, oceans and/or terrestrial ecosystems since pre-industrial times, or will soon do so. The current species extinction rate is estimated to be 100–1,000 times higher than natural. Furthermore, an increase of the global mean temperature (GMT) of at least 2 °C and more likely 3–4 °C (or more) above pre-industrial times is expected before the end of the twenty-first century (New et al. 2011). With an increase of 2–3 °C GMT, the chapter of the 2007 *IPCC* report on the impacts on ecosystems (Fischlin et al. 2007) predicts major losses of some biomes (e.g. coral reefs, Amazonian rainforest, Arctic tundra) and globally one-quarter or more of all species are expected to be committed to extinction. With an increase of 4 °C or more, the report predicts catastrophic ecological impacts, with widespread extinctions around the globe (Fischlin et al. 2007).

In short, most places on Earth will experience physical, chemical and biological conditions in the near future that are very different from those that characterised them in the past.

2.2.3 Rates of Change

The magnitude of changes in itself represents a huge challenge for the adaptation of ecosystems and societies to environmental change. However, it is the speed of these changes that will make adaptation excessively difficult or impossible in many situations. At a local scale, humans have been changing ecosystems for thousands of years, although the dramatic ecological change that characterises the Anthropocene is very recent (Steffen et al. 2004; Millennium Ecosystem Assessment 2005). In some parts of the world, this phase of rapid change began around 250 years ago with the industrial revolution, whereas it is only now beginning in other regions. However, most changes are now very fast and even accelerating, with little evidence that these trends will change in the near future (Steffen et al. 2004; Millennium Ecosystem Assessment 2005). As an example of the rate of change, consider how c. fifty percent of the global Earth surface was still largely wild 300 years ago, while only c. five percent was used intensively (Ellis et al. 2010). Today, less than 25 % of land is in a wild condition, while over 50 % is intensively used, with much of this change occurring in the last few decades. At present, over ten million hectares of forest are converted to agricultural land annually (Koh and Gardner 2010). With a predicted increase in the global mean temperature of 3–4 °C compared to pre-industrial times in the next 50–100 years (New et al. 2011), few ecosystems will be able to adapt to the new climate conditions (Fischlin et al. 2007).

In a few decades to centuries, environmental conditions on Earth will change fundamentally. For geophysical, ecological and evolutionary processes that unfold over thousands to millions of years, this period is extremely short; indeed, so much so that some ecological adjustments will only gradually become evident. Such time lag effects are omnipresent and pose a special challenge for environmental research and management. For instance, even if all anthropogenic CO_2 emission was abruptly stopped, the climate system would still not cool for millennia (Solomon et al. 2009). Time lags also distort observations of biodiversity loss: many rare species are still present in the wild in low numbers despite being doomed to extinction ('extinction debt') (Kuussaari et al. 2009).

The rapidity of changes represents a huge challenge for ecological and societal adaptations to ecological novelty. Paleoecological data from past periods of rapid climate change in the Earth's history indicate that species and ecosystems need time to adapt to new environmental conditions (Warren et al. 2011). Similarly, societies and land use systems only adjust gradually to changing conditions. Indeed, a well-functioning adaptation to a current ecosystem state (or current environmental change) can turn into a dysfunctional adaptation in just a few decades. This problem is further accentuated by the uncertainties and vagaries of the future; for instance, the adaptation that needs to be in place in a few decades can be very different depending on whether the planet will warm by 2 or 4 °C. Furthermore, trajectories of change might fluctuate; for instance, a place may first get wetter for some decades and thereafter become prone to droughts.

2.2.4 *Many Changes Happen at Once*

Another characteristic of ecological novelty is that many different physical, chemical, biological and social factors change in parallel. For example, there will not only be changes in temperature and precipitation patterns, but also in biogeochemical cycles, the distribution of biodiversity—through both species extinctions and the invasions of non-native species—and land use. These parallel changes interact and lead through synergies among multiple factors to new patterns and processes. It is often very difficult to understand which changes are responsible for a certain ecological effect, and generally only a combination of different changes can explain emerging ecological realities. Due to these interactions, a given change can result in different or even opposing ecological effects in different places (e.g. Kueffer et al. 2013a). For instance, pollinating insects such as the honeybee are in decline in many areas. The reasons are not well understood, but may include habitat fragmentation, pesticides, pathogens, invasive species, climate change, the small remaining size of pollinator populations, as well as interactions between several of these factors (Potts et al. 2010).

2.2.5 *Surprises Become the Normality*

While humans are increasingly altering their environment, they do not understand or cannot predict many of the consequences of their actions. Many consequences of anthropogenic environmental change are not foreseeable and perhaps not even detectable until much later. A classic example is the hole in the ozone layer. It was not expected that chlorofluorocarbons (CFC) reaching the stratosphere would react with ozone. Although relevant ecological knowledge concerning a relatively stable ecosystem will accumulate over time, and historical records can elucidate system behaviours under different conditions, neither accumulated experiences nor information from the past might be relevant for understanding fundamentally novel systems.

Ecological systems often respond in a non-linear way to environmental change, with the consequence that abrupt and irreversible change occurs once a threshold has been crossed. Such non-linear responses further add to the difficulty of predicting ecological consequences. Furthermore, in the case of certain environmental variables, not only the mean value changes but also the variability around the mean. For instance, while the average summer temperature of individual years in northern

Switzerland between 1961 and 1990 varied by 4 °C around the mean of 16 °C, with climate change the annual summer temperature of a 30-year period could vary between 17.5 and 24.5 °C (variability of 7 °C) in the future (Schaer et al. 2004). One consequence of such increased variability is that species and ecosystems must be able to adapt not only to a mean summer warming of 4.5 °C, but also to an increase of the temperature of the hottest summers by 6 °C to 24.5 °C, while still experiencing summer temperatures of only 17.5 °C in other years. Besides such changes of inter-annual variability, seasonality will also change, with climate change predicted to unequally affect summer and winter temperature and precipitation patterns in many regions.

2.2.6 Global Extent and Pervasiveness of Changes

The global extent of many environmental changes also has implications for ecological novelty and how we should respond to it. First, there remains little leeway for prevention and reversibility; once a problem has been recognised in one area, it is likely to also be present in many other areas. Second, causes and effects can be interlinked across very large distances; for instance, CO_2 emission in an industrialised country can reflect a cause for a drought in Africa. Finally, much environmental change is difficult to contain, given that climate change, air pollution or invasive species do not stop at the boundaries of protected areas. The implications of this include even remote wilderness areas being increasingly characterised by anthropogenic impacts, establishing protected areas not being sufficient to preserve vulnerable biodiversity, and reference systems of non-anthropogenic nature becoming lost.

2.3 Towards an Ecological Science of Man-Made Nature

In the future, ecological science will deal almost exclusively with ecological systems that are shaped by humans. In ecology, the social sciences and humanities, there is a long history of trying to conceptualise hybrid natural/social systems (e.g. Lorimer 2012; Haila 2000; Latour 1993; Scoones 1999; Davidson-Hunt and Berkes 2002; Turner and Robbins 2008; Taylor 2005, *and citations therein*). However, such ideas have mostly remained at the fringes of mainstream ecology and social sciences. Over the past five decades, a number of subfields have also emerged from ecology that address the impacts of man on nature from different angles. These fields are more tightly linked to mainstream ecology and include conservation biology (Soulé and Wilcox 1980; Sodhi and Ehrlich 2011), invasion biology (Elton 1958; Richardson 2011), restoration ecology (Jordan et al. 1987; SER 2004), ecosystem resilience and adaptive management (Holling 1978, 1973; Chapin et al. 2009) and urban ecology (Sukopp et al. 1990; Pickett et al. 2001, 2011). My intention in this paragraph is not to review these diverse approaches for dealing with 'socio-nature'; rather, I will highlight three fundamental research problems related to hybrid natural/social systems that require conceptual innovation, and in particular the closer integration of ecology with human sciences.

First, ecological theory generally treats humans as *causal factors* in physical systems, in analogy to any other animal. However, humans are psychological, social and cultural *actors*, and an integration of ecology with human sciences is needed to adequately describe human behaviours in ecological systems. Indeed, mainstream ecology typically addresses hybrids of nature and culture as socio-ecological *systems* by focusing on the distribution and change of biodiversity and energy and material flows, thereby expanding ecological theory developed for wild nature to man-made ecosystems without explicitly conceptualising human agency. Research fields that emerged from the human sciences to address environmental issues such as political, human or social ecology or land-change science (e.g. Latour 1993; Scoones 1999; Davidson-Hunt and Berkes 2002; Turner and Robbins 2008, *and citations therein*) build on theories of human agency, although these ideas have not yet reached the mainstream in ecology.

Second, ecology is a science of wild nature. However, if nature untouched by humans is organised through different ecological laws than anthropogenic nature, ecological theory must be adapted. The constitutive assumption of theory in biology, including ecology, is that the fundamental organising principles governing nature can be understood as a result of long-term processes in the past that were not influenced by humans: natural evolution and the assembly and self-organisation of biological communities and ecosystems. A famous quote by evolutionary biologist Theodosius Dobzhansky states: "nothing in biology makes sense except in the light of evolution" (Dobzhansky 1973). Consequently, ecological research is mostly focused on those ecosystems that are least affected by humans. It is assumed that in 'pure' nature, general ecological laws can be uncovered that will also apply to anthropogenic ecosystems. However, strongly human-influenced ecosystems may function in ways that are fundamentally different from wild nature. For instance, many regions lost all large animals, including large herbivores, frugivores, and top predators such as tigers, sharks or wolves, following the arrival of humans, with profound implications for the functioning of their ecosystems (Hansen and Galetti 2009; Jackson 2001; Estes et al. 2011). Furthermore, humans also substantially change the magnitude of species movement between ecosystems, both by enhancing and restricting it, thereby influencing fundamental ecological processes such as gene flow or community assembly processes. In addition, man-made ecosystems are often characterised by novel disturbance regimes that differ from historic ecosystems in terms of the frequency, type and intensity of disturbances. Therefore, it is not evident whether the functioning of anthropogenic ecosystems can be understood based on the empirical generalisations and theoretical principles derived from wild ecosystems. The functional similarity or dissimilarity between pre-human and human-shaped ecosystems should be explicitly investigated, because in the Anthropocene nothing in nature makes sense except in the light of human action.

Third, prediction is an important goal of ecology, although in human-dominated ecosystems this requires anticipating both biological and social changes. For instance, predicting future species invasions depends upon anticipating the way in which humans move species, manage the land and value nature and non-native species (Kueffer 2010). In urban ecology, a consideration of future urban development is necessary to understand the effects of urbanisation on biodiversity and ecosystem functioning in rapidly urbanising landscapes (Ramalho and Hobbs 2012). The rapid expansion of biofuel plantations, especially oil palms, has fundamentally changed the opportunities for nature conservation in the tropics (Koh et al. 2009). Climate change science has a weak ability to account for feedbacks between climate change and societal adaptation to a changing climate (Warren 2011). All of these examples show that a predictive science of ecological novelty will have to be able to address feedbacks between ecological and social change.

2.4 Understanding Rapidly Changing and Novel Ecological Systems

The rapid and fundamental changes typical of ecological novelty imply that ecological knowledge gained in the past might not be relevant in the future. This requires the generation of continuously new ecological knowledge about the functioning of emerging novel ecosystems. Some ecologists believe that addressing these new demands requires a shift in the boundaries between the experimental/nomothetic and observational/ideographic research approaches (e.g. Sagarin and Pauchard 2012). This relates to alternative views of ecology, as either an experimental and nomothetic science focused on universal laws or an observational and ideographic science focused on rich understandings of particular real-world cases, which have fluctuated in importance throughout the history of ecology (Kohler 2002; Brown 2011; Pickett et al. 2007; McIntosh 1987). For some, ecology is, or should be, a ‘hard’ science such as physics, which aims at identifying universal laws through experimental testing of hypotheses. By contrast, for others, it is, or should be, a ‘soft’ science such as most environmental or social sciences, which embraces the openness, multi-scale nature, historicity and contingencies of real-world systems and aims to reconstruct and interpret the past and present of particular real-world systems through the integration of heterogeneous—and mostly observational—data. If observational/ideographic research approaches gain new prominence in ecological research in the near future, reciprocal learning between ecology and (some forms of) research in the social sciences and humanities that face similar methodological and epistemological challenges could help both scientific cultures to work towards a common scientific methodology for understanding man-made real-world systems.

While recent debates concerning the relevance of observational/ideographic research approaches (e.g. Sagarin and Pauchard 2012) resemble older ones (e.g. McIntosh 1987; Kohler 2002; Shrader-Frechette and McCoy 1993), the rise of a data-intensive ecological science places these debates in a new context. Indeed, ecology is rapidly becoming a globally interconnected and collaborative science with the computer power necessary for sharing and analysing huge amounts of data (e.g. Sagarin and Pauchard 2012; Coleman 2010). In this paragraph, I will review the rise of a data-intensive ecology, discussing how these developments touch upon fundamental questions about the production and use of ecological information, such as: who are the producers of relevant ecological data and who interprets the data? Inputs from research in the social sciences and humanities interested in how sciences work will help ecology to better design the ways in which knowledge is produced, interpreted and shared.

2.4.1 The Emergence of a Data-Intense Ecological Science

The amount and diversity of data available for ecological analysis is rapidly growing (Sagarin and Pauchard 2012). One reason is that new data sources are emerging, especially through developments in remote sensing. Satellites collect data, resulting in global maps of land cover or ecosystem properties such as biomass production at a spatial resolution that is often sufficiently fine for ecological analysis (Aplin 2005), while airborne surveys produce very high resolution information on three-dimensional vegetation structure, the distribution of species and their traits, or the chemical composition of plant canopies (Schimel et al. 2013). A second reason is that long-term ecological research programmes that compile all data collected in their study areas in centralised databases are increasingly being established (e.g. http://www.lternet.edu/). Moreover, monitoring programmes are also run for applied purposes (e.g. forestry inventories, biodiversity monitoring schemes, global Earth observatories). A third reason is that major efforts are invested in collecting, compiling and sharing existing data for secondary analysis (e.g. Kueffer et al. 2011b). It is increasingly expected that data from observational or experimental research is publicly shared after publication, and inaccessible data—for instance, from historic documents, or records in museums and herbaria—is made accessible in electronic form. Finally, holders of local and traditional knowledge are recognised as valuable data providers, with practitioners and citizens encouraged to document and share their observations (Sagarin and Pauchard 2012; Silvertown 2009; Dickinson et al. 2010; Berkes et al. 2000).

As a consequence, huge amounts of ecological data are freely available on the internet. For instance, such datasets cover: climate variables (http://www.worldclim.org/), land cover maps (http://nsidc.org/data/modis/), historic photographs (http://mountainlegacy.ca), vegetation surveys (Dengler et al. 2012), species distributions (http://www.gbif.org/), species traits (http://www.try-db.org/TryWeb/Home.php) or DNA[1] sequences (http://www.ncbi.nlm.nih.gov/genbank/). The growth in

[1] Deoxyribonucleic acid, a molecule containing genetic information.

data availability is paralleled by new possibilities to analyse large datasets. The increasing computing power of desktop computers supports ever more complex calculations, while new statistical and computing technics are being developed and shared through open-source software such as R (http://cran.r-project.org/).

2.4.2 Data-Driven Pattern Recognition Versus Theory-Based Understanding

Secondary analysis of large datasets that were originally collected for other purposes opens new possibilities for scientific inquiry. In a data-intensive science, there is more leeway for defining the relationship between data and theory in the process of identifying and testing explanations. At one extreme, data-driven algorithms search large datasets for interesting patterns or make ecological predictions without little or any input of prior knowledge. For instance, *BIOMOD* (Thuiller et al. 2009) is an ensemble forecasting modelling platform that allows aggregating spatial predictions of species distributions derived through different statistical/artificial intelligence techniques and parameterisations. In principle, such techniques require no input of prior knowledge (except for the initial selection of variables and data) and provide no explanation (except for a quantification of the range of 'reasonable' relationships between variables or 'likely' forecasts). At the other extreme, expert systems elucidate and aggregate qualitative and tacit expert knowledge in a systematic way (Perera et al. 2012). Between these extremes lie approaches such as Bayesian statistics, model selection or meta-analysis, which infer explanation from data with some input of expert knowledge and by weighing the evidence in support of alternative explanations (Ellison 2004; Burnham and Anderson 2002; Hobbs and Hilborn 2006).

Thus, the relationships between data-driven pattern recognition and theory- or expert-based understanding are becoming increasingly diverse, which relates to the topic of the next section. Specialised data analysts should not produce final data interpretation but rather help data providers and users to become involved in the procedures of the data analysis.

2.4.3 Who Are the Producers of Relevant Ecological Data and Who Interprets the Data?

Traditionally in ecology, the person who collects the data is also the person who analyses and interprets it. However, the emergence of a data-intensive ecology changes this arrangement in two important ways. First, the diversity of data collectors is increasing, with some ecological data no longer collected by academic ecologists. This diversification of data sources results in an increasingly wide range of people being linked to ecological research, including people with contrasting expertise, stakes, social networks and personal relations with nature and environmental problems. Second, the data collectors and data analysts are often no longer the same people. While an academic ecologist still generally prepares a scientific publication with data that he/she collected, theoretical biologists, physicists, mathematicians, statisticians or computer scientists are increasingly specialising in analysing and interpreting ecological data that was collected by others. At the same time, the growing availability of free ecological data and easy-to-use analysis tools through the internet potentially leads to a democratisation of ecological analysis, whereby everyone can conduct ecological analysis at his/her desktop computer with data that was collected by others.

How data interpretation is shared among data collectors, specialised data analysts and data users has important implications for environmental decision-making. Given that data and knowledge about complex and rapidly changing ecological systems are necessarily highly uncertain and incomplete, there is much leeway for alternative interpretation (e.g. Larson et al. 2013). At present, there is a tendency for data interpretation to be fully handed over to specialised academic data analysts. While such specialised analysis certainly reflects a useful way of analysing ecological data—just like climate models are a useful tool for devising climate adaptation strategies—arrangements of data interpretation that more strongly involve diverse data collectors and users might be fairer and more likely lead to broadly legitimated decisions about human interventions in nature (cf. Kueffer et al. 2012).

2.4.4 Experimental Research in the Real-World

Many ecological processes occur at spatial and temporal scales that are not amenable to experimental manipulation. Nevertheless, scientists have innovated different strategies to extend the spirit of experimentation into the real-world. Natural experiments, gradient analyses and chronosequence studies interpret observed patterns as the result of experiments that took place in nature. Natural experiments are observational studies that exploit differences between sites (or other observational units) in nature as experimental treatments (Diamond 1983; Kueffer et al. 2013a). The trick is to observe how a dependent variable varies between sites that differ in one major factor ("the experimental treatment") yet not others. It is also occasionally possible to compare observations before and after an event at the same site, e.g. before and after a volcanic eruption (Dale et al. 2005). Gradient and chronosequence studies represent a special form of natural experiments. In gradient studies, the variation of a dependent variable is observed along continuous gradients, e.g. an elevational or latitudinal temperature gradient (e.g. Kueffer et al. 2013b). Chronosequence studies compare observation at sites that have experienced a certain ecological process for different time periods and use these observations to reconstruct how an ecological system develops with time, e.g. with ecosystem age (Wardle et al. 2004) or after being invaded by an invasive species (Lankau et al. 2009). Such observation-based "experiments" allow studying long-term effects of "experimental treatments" that cannot be implemented through a research project for practical reasons, and data can sometimes be gathered from many replicates. The main weakness is that researchers are not in control of experimental manipulation.

Ecologists also perform 'true' experiments in the field, sometimes at a large spatial scale of a whole watershed or lake. Large-scale field experiments correspond to a traditional understanding of experiments insofar as the experimental treatment is manipulated by the researcher, although they have other important weaknesses; namely, they only run for a short time (compared to natural experiments), only some variables can be controlled by the experimenter (compared to laboratory or microcosm experiments) and replication is often low (Diamond 1983; Carpenter et al. 1998). For these reasons, Carpenter et al. (1998) argued that large-scale field experiments should not be used to test hypotheses, but rather to "compare diverse alternative explanations." They advise against replication, at least in certain situations, suggesting that multiple experimental ecosystems should each be manipulated in a different way to explore alternative ecosystem behaviours. Thus, there appears to be an inversion of the roles of experiments and observations in field research. Traditionally considered the exploratory mode of ecological research, observational studies are increasingly used to test hypotheses (e.g. through natural experiments) (Sagarin and Pauchard 2012; Fraser et al. 2013), while experiments—traditional used for hypothesis-testing—are considered exploratory research.

The discussion of different types of experimental approaches in field research gains another important dimension when considering that such research is increasingly undertaken in human-influenced settings, e.g. by comparing ecological parameters along land use gradients, between sites that have been impacted by humans in different ways or at different times, or before and after a management intervention. This means that ecological research is increasingly embedded in real-time in ongoing deliberate (e.g. a management project) or unwanted experiments of human-induced change (e.g. Felson and Pickett 2005; Gross 2010), and, through their daily actions, citizens are not only becoming data collectors for ecology (see above) but also experimental manipulators.

2.4.5 Problems of Scale: Local In-Depth Case Studies Versus Global Comparative Studies

Thanks to an increasingly globally interconnected and collaborative science, coordinated research that conducts the same observational or experimental studies across many sites is becoming increasingly common (Fraser et al. 2013; Kueffer et al. 2013a; Kueffer 2012; Hobbie et al. 2003). This opens new possibilities for performing experiments (Fraser et al. 2013) or in-depth case studies (Kueffer 2012; Hobbie et al. 2003; Kueffer et al. 2013b). Such comparative research across multiple sites helps to circumvent an important trade-off in ecology, between collecting data from a broad range of different locations, species and ecosystems

(Pyšek et al. 2008; Kueffer et al. 2011b) and studying the ecology of particular places in-depth (Billick and Price 2011). Indeed, networking local case studies globally (Kueffer 2012; Kueffer et al. 2013b) represents an alternative bottom-up research approach to global change, compared to the top-down vision of a planetary science of global change (Mooney et al. 2013) that has set the global change research agenda since the 1980s (Kwa 2005).

2.5 Conclusions

The objective of this chapter was to present a broad view of an ecological science in search of new approaches for tackling the scientific challenges of societal adaptation to ecological novelty (rapid and fundamental ecological change in the Anthropocene). I have emphasised the multifaceted nature of ecological novelty, whereby each aspect confronts science and society with difficult problems. For an ecologist, 'ecological novelty' better captures emerging dynamics than the notions of 'climate change' or 'global change.' Changes occur at different spatial scales, and patterns and processes at local scales are particularly difficult to understand and manage. Ecological novelty does not arise through changes in isolated factors such as temperature, but rather from the interactions of many entangled physical, chemical, biological and social factors. Moreover, it is not change *per se*, but rather the magnitude, rapidity, unfamiliarity and uncertainties of these changes—the novelty—that challenge traditional science and human-nature relationships.

Human influences on nature are rapidly and irreversibly expanding. The new challenges for environmental sciences are: (i) to theoretically grasp the essence of 'socio-nature' that is governed by coupled natural and social processes; (ii) to anticipate environmental change that is driven by rapid ecological *and* social change; and (iii) to mediate between an ecological understanding of humans as *causal* forces and a human sciences perspective on humans as self-conscious and cultural *actors*.

Ecological change in the Anthropocene is rapid and fundamental. Consequently, environmental management must be continuously adapted and thereby should particularly consider alternative scenarios of future changes and feedbacks between environmental change and societal adaptations to such change. Ecological science is innovating new ways for embracing the scientific complexities of such rapidly changing real-world systems in order to support societal decision-making, although scientific uncertainty and ignorance remain important and are often irreducible. As a result, separating the study of ecological facts from the social constructions and representations of this empirical knowledge can be problematic when dealing with ecology novelty. The emergence of a data-intensive and collaborative ecological science holds potential for redefining the relationships between collectors, analysts and users of ecological information, and such opportunities should not be missed to account for the unruly relationships between the production, interpretation and use of uncertain and incomplete ecological knowledge. Particularly due to increased global connectivity and collaboration in ecological research, networking multiple local in-depth case studies is emerging as an alternative bottom-up approach to global change research compared to the top-down vision of a planetary science of global change.

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