Rethinking Evidence Practices for Environmental Decision-Making in the Anthropocene

Dealing with Dissent in Knowledge Societies

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4 Rethinking Evidence Practices for Environmental Decision-Making in the Anthropocene

What Can We Learn from Invasive Species Research and Policy?

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We live in a time of multiple, interacting and accelerating crises, including climate change, overexploitation of natural resources, pollution, growing inequalities and injustice, political and social instabilities, war, migration and weakened democratic and truthful deliberations.[1] Many of these crises are directly or indirectly linked to the degradation of ecosystems and biodiversity loss.[2] Since 1993, the nations of the world have committed themselves to the protection and restoration of the Earth's diversity of life through the *UN's Convention on Biological Diversity* (CBD).[3] The *UN Decade on Ecosystem Restoration* from 2021 to 2030 further emphasizes the urgent need to reverse the degradation of ecosystems worldwide within the coming years.[4]

Evidently, the current economic system is a major driver of ecological degradation,[5] and technological solutions will not suffice to avert catastrophic climate change and biodiversity loss.[6] The UN's "17 Sustainable Development Goals" of the *2030 Agenda for Sustainable Development* instead recognize the need for integrative sociocultural and ecological solutions.[7] This will require that the voices and ecological competencies of diverse cultural groups, many of them marginalized or oppressed, must be strengthened with the help of expertise from the humanities, social sciences and arts.[8] Following an era dominated by economics and engineering, the 21st century must become a century of cultural diversity and ecological sensibilities. Indeed, ecology is reaching the status of a guiding natural science of our time. Since 2012, the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)* has been coordinating experts around the world to assess ecological knowledge for policy-making.[9] While for most of the 20th century physics was seen as the paradigmatic model of scientific inquiry, in the 21st century, we must better appreciate the ontological, epistemological, methodological and pragmatic implications of an ecological view of nature and human-nature relationships.[10] Rich and thorough ecological expertise is essential for an urgently needed societal transformation toward a sustainable future.[11]

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Such an ecological turn will have important implications for how we see the role of scientific evidence in resolving conflicts and legitimizing decisions. Ecological expertise is confronted with particularly difficult challenges. Expertise about the open and non-equilibrium environmental systems of the Anthropocene is inevitably highly uncertain. Open environmental systems are characterized by features such as nonlinearity, emergent properties, non-equilibrium and causal chains that span vast spatial scales that make robust prediction and reliable advice on effective system manipulation difficult. This makes it also hard for experts to demonstrate that their evidence is reliable.[12] Moreover, the experimental testing of hypotheses and refinement of solutions through learning-by-doing in a controlled setting such as a laboratory is often not possible.[13]

To circumvent these problems, the modern natural sciences have often used the strategy of turning open-system problems into closed-system problems. Accordingly, innovations have been developed in laboratories and their risks assessed based on highly simplified model systems, while the potential consequences on the environment have often been neglected.[14] Intensive agriculture and plantations, for instance, have been designed so that they can easily be controlled and manipulated, while cities and technical artifacts are considered separate from nature. This has often led to unintended consequences stemming from new technologies and other innovations on the natural world. It has hitherto been possible to neglect these negative externalities because the planet that provided us with free ecosystem services and goods quietly absorbed our pollutants and waste and allowed us to conduct our dangerous experiments and destructive activities in remote areas where those affected, whether human or non-human, were powerless.[15]

Meanwhile, and especially since World War II, we have lost most of the refugia of nature,[16] and we now live in a full world,[17] with no cheap nature left.[18] A key characteristic of the Anthropocene is that even the rich and powerful among us can no longer escape the causal interconnections between the environment and human systems. Whether in a laboratory, in relation to technical infrastructures, in cities, in intensive agriculture or in the way we imagine our social and culture life, nature is talking back. We have to relearn how to listen to nature, while accepting that our knowledge about nature is inevitably incomplete and ignorance widespread.

A second challenge is that our thinking about nature and human-nature relationships is undergoing a paradigm shift. Fundamental ontological, epistemological, methodological and ethical assumptions underlying ecological research and our understandings of nature and human-nature relationships are open for debate in our pluralistic and globalized society. When such a phase of cognitive indeterminacy occurs in a field of expertise so closely intertwined with deliberations in society, the situation further complexifies. Silvio O. Funtowicz and Jerome R. Ravetz[19] have called this type of science-policy nexus *post-normal* in reference to Thomas Kuhn's description of scientific revolutions.[20] Fundamental assumptions about what counts as relevant and reliable expertise and evidence as well as about the ontology of the study subjects and the ethics and goals of interventions are being questioned from multiple and conflicting perspectives from within the sciences and society at large.[21] Because these various assumptions are mutually intertwined, it is difficult to separate political, cultural, ethical, epistemological and ontological aspects of a controversy.[22] And because conflicting perspectives are often incommensurable, there is no arbiter available to clarify debates.

This situation is further aggravated by the fact that our knowledge about nature is rarely based on direct observation accessible to a non-expert anymore; rather, nature increasingly speaks to us only indirectly through various specialized scientists and their diverse tools. Thus, scientific evidence about nature is increasingly more open to alternative and often conflicting interpretations.[23] When nature still speaks directly to us, many of us have lost the competencies to listen – we depend on interpreters to explain the ecological realities around us.

There is no easy way out of this bind. In particular, there is a growing recognition that reducing ambiguities by turning pluralistic and open-system problems into disciplinary and closed-system problems only worsens the situation.[24] Instead, we need to develop a new culture of evidence practices that embraces pluralism, ambiguity and ignorance. In some cases, previous strategies of evidence-based decision-making, such as the use of projections, risk assessments or cost-benefit analyses, still work.[25] In other cases, it might be more effective to design evidence-based decision-making processes and policy institutions that are more inclusive and transparent and facilitate continuous social learning.[26] In ecology, for instance, there is a long tradition of adaptive management processes that attempt to continuously improve interventions in nature through social learning-by-doing in the real-world settings of particular environmental problems.[27]

Often, however, it is not even clear what constitutes a scientific and societal problem, how it should be approached and who the relevant experts are. In such a situation, the formulation of the framing of the societal and scientific problem becomes in itself a critical step in the production of reliable and socially robust evidence.[28] Transdisciplinary and participatory research aims at clarifying contested problem structurings in pluralistic decision-making contexts.[29] Arguably, the situation is even more ambiguous in the case of ecological expertise in the Anthropocene because the epistemology and ontology of a whole research field – ecology – and even whole epistemes are exposed to heightened disagreement. It might therefore be necessary to embrace pluralism and disagreement as an opportunity for renegotiating the very fundament of our thinking.[30] The role of experts might become one of nurturing critical thinking, virtues and cultures of responsibility and empowerment and agency rather than of attempting to achieve a definite clarification of problem diagnosis, targets and solutions.[31]

In what follows, I present the example of invasive species research and policy as a model case of a scientific and societal issue that is characteristic of evidence-based deliberations in ecology and environmental decision-making in the 20th century. Biological invasions are the result of global environmental changes and globalization and are considered one of the main drivers of the biodiversity crisis. While there is a well-established expert community that addresses the issue through research rooted in a mainstream scientific discipline – ecology – the interpretation of the scientific evidence and the conclusions drawn for management action are increasingly contested from numerous angles; thus, biological invasions represent a case of post-normal science.[32]

Biological invasions were formally recognized as a specific scientific and societal issue after World War II. The framing of the problem is thus rooted in post-war ecological science and environmental decision-making. It was an era when ecological problems were framed as socially and epistemologically well-bounded issues amenable to clarification by academic and disciplinary ecologists alone and solved through policy-making that closely follows scientific assessments such as cost-benefit analyses or scenario analysis (mode 1 knowledge production *sensu* Helga Nowotny and colleagues).[33]

Ecology and the Science-Policy Nexus after World War II

The core of academic ecology after World War II contrasted strongly with early modern ecology in the 19th and early 20th centuries; thus, the expert culture of the post-war years was socially constructed in a specific way, and this shaped ecological thinking and decision-making related to the different environmental crises of the 20th century, including biodiversity loss and climate change.

Applied ecology was often institutionally isolated from basic ecology. It was widely distributed across diverse research institutions and departments of applied sciences such as natural resources management, fisheries, forestry or agriculture,[34] and scientists with an ecological expertise and research focus also worked at departments ranging from geography and anthropology to the environmental sciences. In contrast, basic ecology was increasingly separated from applied ecology and non-biological sciences, including geography and the social sciences, which in the 19th and early 20th centuries shared interests and regularly collaborated with ecology. A reflection of this separation was that humans were excluded from basic ecological theory as an agent integral to ecological systems. An interest in the ecology of human-made ecosystems such as cities, for instance, only re-emerged much later.[35] A gap opened between ecology and the social sciences and humanities. Partly this was a consequence of the episteme of modernity that assumed that nature and culture were separate realities, but it was also a result of more specific misunderstandings between natural and social scientists among others resulting from the heated sociobiology debates of the 1970s.[36]

Reductionist ontological frameworks increasingly shaped ecological theories.[37] The study of animal behavior came under the influence of behaviorism. Animals were interpreted as beings without consciousness and their behavior as purely mechanistic – following René Descartes' characterization of animals as machines. Animal behavior was studied in animals in captivity and often by harming them. The emergent properties of species communities were interpreted as the result of the interplay of autonomous individuals that compete for limited resources[38] – an ontological understanding of species coexistence that is interpreted by some historians of science as being rooted in an ideology of liberalism.[39] Ecosystem ecology that explained the overall workings of ecosystems as characterized by fluxes of energy, matter and information in analogy to physics solidified through major funding from the *US Atomic Energy Commission* with the goal of understanding the fate of radioactive isotopes in the environment.[40] It was further developed by building on the toolbox of systems science and cybernetics and with the help of computer simulation modeling.[41] Such systems ecology can be seen as technocratic,[42] and as an approach that characterizes ecosystems as a kind of a machine.[43]

After World War II, the ambition of basic ecologists was to advise on global-scale policies on biodiversity with context-independent and globally applicable knowledge intended to represent the consensus of a global scientific expert community, comparable to the advisory work of climate modelers in climate policy. However, it was not possible to make quantitative predictions as a basis for policy-making using computer simulations like those of climate scientists.[44] Instead, the hope was to deduce policy advice directly from ecological theory. For instance, mathematical models from population biology were used to determine minimal viable populations of threatened species;[45] species coexistence theory was used to show why local species diversity matters for ecosystem functioning;[46] biogeographic research on the correlation between the size of oceanic islands and the number of species present on these islands to advise on the design of nature protection areas;[47] and a combination of theoretical assumptions from biogeography, population ecology and evolutionary biology to argue that nonnative species – i.e. those introduced to a new geographic area by humans – pose high ecological risks (see below).

Deduction of expert advice and implicitly normative judgments from general scientific laws and thus underlying ontological and epistemological assumptions can be problematic, especially when implicit assumptions and how they shape sociopolitical discourses are not made transparent.[48] In particular, the assumption that non-anthropogenic, pristine ecological systems are characterized by a particularly high degree of biological organization implicitly influenced research and policy. In research, interpretations and generalizations of observational data were built on the assumption that ecological patterns represent well-designed adaptations. According to such a view, species traits represent optimized designs that help species to survive under particular environmental conditions, interactions of species are fine-tuned through coevolution, and the composition of species community is the result of ecological sorting so that coexisting species with complementary specializations (i.e. niches) fit together like pieces of a puzzle. This adaptionist interpretation has been criticized as empirically unjustified teleological thinking[49] and as based on an empirically unjustified assumption that there is some kind of harmonic balance in nature.[50] In policy, the view that pristine nature is particularly well-functioning thanks to long-term coevolution and ecological sorting led to the presumption that humans are by default a problematic disturbance factor in nature; and thus that protected natural areas are ecologically preferable to managed land and that species introduced by humans to an ecosystem – alien species – pose ecological risks. In the Anthropocene, these assumptions confront ecology with epistemological and pragmatic problems given non-equilibrium and anthropogenic ecological realities.[51] A second important implicit assumption was that ecological issues were framed as global rather than local policy issues. Ecology tried to fit into the emerging framework of climate change and global change science and policy.[52] The concept of biodiversity was meant to condense the overwhelming diversity of life across the multitudes of local places on Earth into one concise and highly generalized entity that could be used to talk to international decision makers. According to E.O. Wilson, the term was meant to become "the talisman of conservation, embracing every living creature".[53] This framing of ecological thinking and decision-making contributed to unequal und hegemonic globalized discourses about nature.[54]

In this context, biological invasions were conceived as a scientific problem and a societal issue. This background is important in understanding how invasion biologists were at first successful in framing a complex socioecological problem in such a way that a small and homogeneous group of scientists was accepted as the only legitimate experts and their expertise was largely undisputed, and how thereafter it developed into a highly contested post-normal issue characterized by incommensurable disagreements among experts and widespread contestation of evidence and policies by diverse stakeholders.[55]

Case Example: Invasive Species Research and Policy

As long as humans have migrated across the planet, they have carried other species to new places.[56] For instance, the successful expansion of indigenous people across the Pacific and the colonization of remote islands thousands of years ago depended on plants that they transported with them,[57] in Greek and Roman times, alien species were part of religious ceremonies,[58] and the redistribution of diseases, animals and plants played an important role in colonial expansion.[59] The transportation of species to new places was often deliberate because of their known usefulness, and thus they played an important subsistence role and were often perceived positively and integrated into daily life.[60] Alien species had manifold cultural and symbolic meanings, including as part of religious practices and as ornamentals.[61] These meanings often differed for different social groups.[62] Thus, throughout human history, alien species have been an integral part of livelihoods, and the perceptions of them have been pluralistic.

The Initial Framing of Invasive Species Research and Policy

When naturalists in the 18th century started to systematically document the diversity of the natural world, human-associated species were recognized as such but not seen as something fundamentally different from naturally occurring species.[63] Early 20th-century plant ecology further developed a differentiated conceptualization of different types of human-associated plant species, and they studied how humans shape local floras among others in urban areas.[64] Thus, these early naturalists addressed human-associated species as part of their broad interdisciplinary interests in the interplay of geographic, ecological and human factors in shaping the landscapes and biomes of the planet. It was only in the 1950s that introduced species began to be portrayed as a distinct scientific and societal problem. A book entitled *Ecology of Invasions by Animals and Plants* published in 1958 by the leading animal population ecologist at the time, Charles Elton, is generally seen as the birth of formalized research on invasive species.[65] The book initially triggered little interest in invasions as an environmental problem but was rather read as a contribution to basic ecology.[66] It was an international research program within the *Scientific Committee of Problems of the Environment (SCOPE)* framework[67] focused on biological invasions that triggered the rapid growth of a new research field specifically focused on biological invasions in the 1980s.[68] Elton's 1950s book and the subsequent international SCOPE research program in the 1980s are here treated together as the phase leading to the initial problem framing of formalized invasive species science and policy.

This initial framing of biological invasions as a scientific and societal problem has some interesting characteristics.[69] A diverse array of complex socioecological phenomena was subsumed under one unifying framework rooted in ecological theory. According to the broad scope of the postulated problem structuring, biological invasions encompass all alien organisms, ranging from animal and plant diseases to plants and mammals in all biomes of the world – from the Arctic to the tropics, both terrestrial and marine – that spread in all sorts of wild and man-made landscapes and are associated with diverse human activities. One achievement of Elton and subsequent invasion science was that insights from biogeography, population, community, ecosystem, landscape and evolutionary ecology were integrated to look at very diverse ecological phenomena through a single unifying lens, thereby contributing to theoretical synthesis in ecology. In contrast, there was little reciprocal conversation with applied research fields such as weed science, plant health, biological control or epidemiology that already had a long tradition of working on some of the issues that were now considered biological invasions. The new scientific framing thus redefined different applied ecological research questions as examples of the same kind of phenomenon, the essential workings of which should be clarified by basic ecology.

The underlying assumption that allowed for such a broad-brushed generalization of diverse real-world phenomena was that all natural ecosystems were considered to be uniformly characterized by the same ordering principles, and the modulating effects of the particular socio-ecological contexts were considered to be negligible in comparison to these universal ecological principles. In particular, humans were seen as an external disturbance to natural systems. Because alien species are by definition a human-induced change of the pre-human species composition of ecosystems, they were therefore by default considered a risk to the well-functioning of ecosystems. The (perceived) unusual population dynamics of invasive alien species, i.e. their rapid spread and tendency to reach high abundance, was attributed to their human-associated origin. Their nonnative origin was thus seen as the keystone of the causal interpretation of the dynamics of biological invasions – a view derived from particular ontological and epistemological assumptions about how nature works and should be studied. At the science-policy interface, these presumptions legitimated the normative claim that alien species are by default problematic and therefore should be prevented from entering new areas and where present should be controlled and if possible eradicated.

This normative prejudice gained special weight in decision-making because it was argued that, in line with the precautionary principle, the risk of biological invasions should be prevented proactively, i.e. newly arriving alien species should be controlled and if possible eradicated before an invasion could happen and therefore before any empirical data that demonstrated their negative impacts in a particular location became available. A normative principle of environmental policy – the precautionary principle – thus legitimized policy advice from ontological presumptions about nature without the need to refer to case-specific empirical data. The question of how to legitimize precautionary action has since been constantly renegotiated in invasive species research and management.

At first, however, invasion biologists were not forced to engage in deliberations about their implicit assumptions and were very successful in getting their perception of a new environmental risk integrated into policies at national and international levels. National and international legislation, science and policy networks and institutions and tools such as data inventories were quickly and widely established.[70] In 1993, the UN's *Convention on Biological Diversity* (CBD) came into force and included article 8(h) on invasive alien species, requiring parties to "prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species", and the *World Conservation Union (IUCN)* established an invasive species specialist group.[71]

A number of hypotheses can be formulated to explain why the need to proactively address the problem of biological invasions according to a framing proposed by a rather small group of invasion biologists was initially not contested and explains why these scientists were effective in influencing policies. First, the recognition of a new ecological risk resonated well with the emerging environmental awareness and the growing interest in problems attributable to global change. Invasions were seen as a paradigmatic example of the ecological consequences of environmental degradation and globalization. The SCOPE research program, which was a key driver for the formation of institutionalized invasive species research, was along with, for instance, the *International Biological Program* (IBP), aimed at addressing global environmental problems through coordinated international efforts. It further helped that invasions proved to be an interesting global natural experiment that could be studied particularly well through internationally coordinated multisite research, which increased its attractiveness for basic ecologists. Essentially, during colonial expansion, the same set of species was introduced to North America, South Africa, Australia, islands in the Pacific etc., and after 50–200 years, their fate in different biogeographic regions and habitats could be compared and analyzed based on observational data in, as it were, a long-term, outdoors multisite experiment (i.e. a natural experiment).[72]

Second, in contrast to other applied ecological research, invasion biology had close institutional affinities to basic ecology and could profit from the social status of leading ecologists. Charles Elton, for instance, was the leading animal population ecologist of his time and his book built on three lectures he gave on BBC radio to a large audience.[73] Equally, the SCOPE program involved some of the leading ecologists of the 1980s, and invasions were seen as a model system to test and further develop ecological theory, thereby raising the status of invasion-related research within basic ecology.[74] Third, with the emergence of international biodiversity policy institutions and legal frameworks such as the *Convention on Biological Diversity* in the 1990s, the scientific results of the SCOPE program about biological invasions came at the right moment to be integrated into international and then national legislation, and invasion biologists were well networked with decision makers in international biodiversity policy. Fourth, the proposed management actions fitted with established institutional frameworks and interests of stakeholders. Legislation and institutional mechanisms from plant health and animal and human epidemiology for the precautionary regulation of the transportation of problem species between nations already existed. Authorities at borders were prepared to control transboundary movement of listed species, and invasion biologists, for their part, were in a position to develop risk assessment tools that identified problem species as a basis for preventative screening. Also, the control and if possible eradication of problematic species – pests and weeds – was a well-established strategy that nourished a large and profitable industry and profited from broad social acceptance. And, lastly, the inherent narrative of invasion biology brought together cultural stereotypes from across the political spectrum: To prevent the unregulated "invasion" by "nonnative" species from outside a nation, to weed out and kill problem species and to protect pristine nature from negative human influence.

Thus, in summary, the case of invasive species research and policy rooted in the 1950s and developed throughout the 1980s and 1990s turned a broad range of complex socioecological phenomena into a socially and epistemologically well-bounded one, thereby containing contestation of evidence and its interpretation within the sciences as well as in society. A small and homogeneous group of scientists – trained in ecology and working at natural sciences departments – was privileged as the relevant experts. They advised on policy by using generalized rules about the workings of ecology instead of digging into the muddy details of real-world management cases. Of course, in the same period, many real-world invasions were managed locally, but this case-specific management and associated expertise were treated as applied science of lower status and therefore the institutional and epistemological core of the discipline of invasion biology was not affected by how applicable its theory was to local, real-world cases.

The example of invasive species science and policy illustrates how discipline-based policy advice – mode 1 knowledge production *sensu* Nowotny and colleagues[75] – is maintained through the social construction of a whole regime of codependent cultural, social, institutional and epistemological elements. To what extent this example of the social construction of proactive action in response to an environmental risk should be seen as a successful or problematic model for reducing scientific and social complexities to enable effective action against an emerging risk requires a differentiated assessment. Some of its accomplishments and weaknesses became evident when it started to break apart in the late 1990s. This is the next phase of the story of invasive species science and management.

Post-Normal Disturbances of the Expert Consensus

Toward the end of the 1990s, the science-policy regime of invasive species research and policy increasingly ran into problems and dissent was voiced more loudly within the sciences and in society.[76] The definitions of an alien and an invasive species were questioned by different experts and stakeholders,[77] and the whole problem framing as well as the science-policy regime were being challenged. What human-assisted extra-range dispersal meant was no longer quite so clear. From how far must a species come so that its dispersal counts as extra-range? For instance, does the planting of a species outside of its ecological habitat, but within the same geographic area – for instance plantations of conifers that naturally occur in mountainous areas but are often planted in lowlands – also count as a case of extra-range and thus nonnative occurrence? Furthermore, is there a time duration after which a long-established nonnative species is considered a native species? And, when should a dispersal event be considered a human-assisted one? For instance, do species that migrate due to anthropogenic climate change, but without being transported by humans also count as nonnative species? After all, why is human assistance even a relevant dimension of a definition of an ecologically novel species? Especially in the Anthropocene, does a definition that considers humans separate from nature still make sense (Figure 4.1), or how can ecological novelty be better defined in a time of massive anthropogenic ecological changes?[78] Such critique of the problem framing came from within invasion science and ecology – including new subfields such as global change ecology that had started to compete with invasion science for expert status on the same issues – as well as from diverse other disciplines, including geography, social and cultural sciences, and from practitioners, stakeholders and decision makers.[79] Thus, in line with Thomas Kuhn's model of scientific revolutions, conceptual questions that had been treated as a taboo by the prevailing paradigm suddenly became the focus of scientific debate. These questions had occasionally been discussed before in the scientific literature but did not receive much attention, while now they led to energetic scientific correspondence among the leaders in the field. In the case of a real-world and policy-oriented

Figure 4.1 The Bosco Verticale building in Milan (Italy) – a high-rise building planted with trees in an urbanized area. In the Anthropocene, human agency and man-made landscapes shape novel ecologies. Photograph by Christoph Kueffer.

science, however, the post-normal phase was not confined to discussions among a small circle of specialized experts, but triggered more wide-ranging debates about evidence-based decision-making on biological invasions.[80]

Indeed, the breakup of the paradigm opened space for more diverse expert perspectives.[81] In particular, critical voices called for case-specific evaluations of actual invasions and their management instead of assuming that all alien species should be treated equally as a problem independent of context.[82] As a result, a greater diversity of alternative policy options and expert advice became available, which made it more difficult to reach a consensus on management actions.[83] Furthermore, it was no longer possible to neglect the contingencies and context-dependencies of particular real-world invasions. Whether a particular mechanism is relevant in explaining a specific invasion depends on the ecological and anthropogenic context of the invasion.[84] Invasion science theory was not particularly well prepared to explain how confounding factors shape real-world invasion dynamics.[85] Thus, the scientific robustness of the available expert knowledge weakened. While broad expert consensus supported general theory about invasions, reliable predictions of the outcomes of specific invasions in particular contexts were more difficult to make. It also became more challenging to evaluate the impacts of particular invasions and the cost-benefits of their management.

One observation about the consequences of this post-normal disturbance of the biological invasion science-policy regime is that strong and incommensurable disagreements within an established scientific discipline led to division among experts from the same discipline and research field, who otherwise agreed on the validity of the underlying scientific theory and evidence.[86] In 2011, for instance, Mark Davis and other ecologists published a fundamental critique of invasion science in the scientific journal *Nature*,[87] which triggered strong responses from the community of invasion biologists.[88] In the same time period, Davis published a textbook about invasion ecology that represented the mainstream thinking in the field;[89] and his coauthors were equally well rooted in mainstream ecology. Thus, although they taught the same science to their students, their interpretations of evidence became incommensurable with mainstream thinking. Davis et al. stated that "nativeness is not a sign of evolutionary fitness or of a species having positive effects", thereby challenging the most fundamental pillar of the paradigm of invasion science.[90] They also argued that "the conclusion made [...] that invaders are the second-greatest threat to the survival of threatened or endangered species after habitat destruction" was based on no empirical data. This mounted a fundamental challenge to the claims of invasion biologists in their role as policy advisors. Daniel Simberloff and Montserrat Vilà, in their response entitled "141 scientists object", emphasized that they represented the expert consensus and responded to the critique that empirical data was lacking by emphasizing the need for proactive action in line with the precautionary principle: "severe impact of non-native species [...] may not manifest for decades" and "some species may have only a subtle immediate impact but affect entire ecosystems, for example through their effect on soils".[91] Thus, while these different experts agreed on the nuts and bolts of the underlying science, they were forced into separate camps at the level of overarching perspectives on the science and policy of invasions.

Indeed, perceptions of alien species and their management – whether by experts or those affected by an invasion – can be influenced by a wide range of factors, including the involved actors, the attitude toward the affected biodiversity and targeted invasive species, the social and cultural context of the invasion or terminologies.[92] For instance, state-led actions against an alien species on private land might be opposed due to personal stances about the role of the state in solving problems. Depending on the framing of the problem, fault lines between supporters and dissenting voices can shift radically. For instance, while there are many biological similarities between the ecological risks of invasive alien species and novel species engineered through biotechnology,[93] these two types of ecological risks are evaluated very differently by different experts. Some experts see a high risk stemming from alien species but not from genetically modified organisms, and vice versa. Overall, examples of dissent related to biological invasions show that the reasons for disagreement are not necessarily linked to any inherent aspect of biological invasions. Rather, who agrees or disagrees depends largely on how the problem is framed: Who is considered a relevant expert or actor, what the envisioned solutions are, who has a voice in the process of developing the problem understanding and solutions and how the problem is communicated and by whom.

This leads to another important observation. The great flexibility of forming alliances in support of an environmental cause is both an opportunity for and a threat to scientific experts. It highlights that transparent, inclusive and careful deliberations about the social, political, cultural, ethical and emotional dimensions of an environmental issue can be effectively employed to foster consensus. But it also leaves open the possibility that public support and perceptions will shift. Indeed, the perception of a particular alien species – for instance the tree genus Tamarix over the course of the 20th century in the United States – can change fundamentally.[94] Such shifts in problem understandings can trigger a need for the rearrangement of the whole science-policy regime that interlinks scientific expertise, policy responses and public perceptions. New legislation might have to be formulated, new institutional arrangements financed, the public engaged through different communication strategies and practitioners might have to learn new management approaches. Such knock-on effects might cascade through science-policy regimes with time delays leading to asynchrony between expert thinking and implemented solutions. In many places, policy-makers at local and national levels are currently implementing essentially the framing of invasive species management formulated in the 1980s and 1990s,[95] while some scientists have moved on and are now questioning whether these solutions are still effective. Furthermore, once one group of scientists loses its unquestioned status as the only relevant expert group on a particular issue, alternative science-policy regimes, all with their own temporal dynamics, can coexist with regard to the same policy issue. In the case of urban tree planting policies, for instance, there are two positions: The first calls for a native-species-preference policy (in line with invasive species science and policy),[96] while the second calls for an alien-species-preference policy (in line with horticulture and urban design and with the goal of adapting to climate change).[97] Which position is taken up by a particular city seems to be at least partly coincidental, although intermediate perspectives that bridge between the two positions have been formulated.[98]

A further observation is that sometimes the reframing of a problem understanding can open space for more stable and less contested and therefore more effective science and policy approaches. This is indeed what happened in the case of biological invasions in the 1990s. In 1996, an inter- and transdisciplinary multi-stakeholder program focused on biological invasions – the *Global Invasive Species Programme (GISP)*[99] – was initiated.[100] In the wake of the GISP, a new problem framing of biological invasions developed in complement to the existing one[101] – so-called pathway or vector science.[102] While the traditional framing of biological invasions aimed at understanding and managing the risks posed by particular alien species individually, pathway science aimed at understanding how different socioeconomic pathways led to the transportation of alien species across landscapes and continents. Thus, the focus of research shifted from understanding the biology of alien species to understanding the socioeconomics and practicalities of trade relationships. This new focus enabled the development of targeted concepts and tools for mitigating ecological risks associated with different transport pathways, for instance, the transportation of aquatic organisms in ballast water in international shipping,[103] or of plants in horticultural trade,[104] leading to different scientific questions and policy options depending on pathway (Figure 4.2). In the case of ballast water – i.e. marine water that is transported in ships that are not fully packed with cargo to stabilize them – an effective risk mitigation strategy is to sterilize the ballast water before releasing it back into the ocean at a port,[105] while in the case of horticulture, the responsible use of alien species in garden design can be fine-tuned through close collaboration with actors in the green industry.[106] This might mean that garden centers inform their clients about invasion risks, alien species are not planted in the vicinity of a nature reserve, or alien trees with known benefits for native pollinators are preferred in urban plantings over alien trees without biodiversity benefits. Developing such fine-tuned solutions with experts and stakeholders from practice increases their acceptance and effectiveness.

Figure 4.2 *Lupinus polyphyllus* is an ornamental plant that can form monospecific stands in cold environments as an alien species. Photograph by Christoph Kueffer.

Indeed, more generally, differentiating one overarching problem framing into multiple context-specific ones can help to lead to more pragmatic and less ideological solutions, which are more effective and can be better integrated into existing institutional frameworks. Thus, pathway science is not a replacement for species-focused risk assessments but a complement. Preventing some particularly problematic alien species through border control and species-specific strategies may still be necessary alongside diverse additional measures implemented for different pathways.

In summary, this phase of heightened evidence contestation in invasive species research and policy illustrates a fundamental dilemma of evidence-based environmental decision-making: When is generalized knowledge and expert consensus sufficient to legitimize action and when is it necessary to invest the time needed to collect case-specific evidence and allow for societal deliberation? Especially in cases when preventative and coordinated actions are needed, it is often not possible to gain sufficient case-specific evidence by the time a decision is required, and inclusive and open-ended deliberations might not lead to coordinated action across large geographic spaces (e.g. at international levels) and among diverse stakeholders. However, the alternative – defending the consensus of a narrow group of experts as the sole basis for legitimizing decisions – is also problematic. To maintain such narrowly focused consensus among experts, there is a strong incentive to accommodate critique of the existing paradigm and keep the conceptual core of the research field as stable as possible.[107] For instance, although it is increasingly evident that invasions are inherently driven by humans and can only be effectively addressed through approaches that integrate an ecological understanding with expertise on social and cultural dimensions,[108] the social sciences are still of only marginal importance in the published literature on biological invasions.[109] There is thus a risk that expertise is not adaptive enough to respond flexibly to dynamic, complex and ambiguous challenges. Secondly, the defense of narrowly framed expertise in a context of messy real-world realities and pluralism risks becoming ideological. Indeed, invasion biologists were increasingly confronted with such critiques. It was said that the concept of invasion "appeals to political and social values but has no scientific meaning",[110] invasion biology was denounced as a pseudoscience,[111] it was suggested that scientists were demonizing certain alien species,[112] and invasion biologists were criticized for promoting their views in rhetoric redolent of xenophobic nationalism.[113]

Invasion biologists have in recent years attempted to walk the line between defending their established problem framing and giving space to a greater diversity of voices. Franz Essl et al.[114] argue that "many conflicts in the valuation of the impacts of alien species are attributable to differences in the framing of the issue and implicit assumptions" and they propose principles to make valuation of alien species impacts more socially robust. They refer to Roger Pielke's model of the honest broker,[115] thereby accepting the need for participatory deliberation but maintaining that ultimately "science must play a central role in providing information and advice to policymakers". This reflects a more general development in the environmental sciences and policy toward more inclusive and reflective decision-making frameworks,[116] processes[117] and policy and academic institutions,[118] inter- and transdisciplinary research processes,[119] adaptive management and social learning processes,[120] and training environmental scientists in the skills necessary for participatory and integrative approaches.[121]

Rethinking Ecology and Environmental Decision-Making for the Anthropocene

The case study could end here. But the story has continued. In recent years, the awareness has grown that the reshuffling of species communities through anthropogenic interference leads to fundamentally novel ecologies of the Anthropocene, so-called ecological novelty.[122] Not only biological invasions and alien species contribute to it, but all sorts of other global change drivers: Land use changes, urbanization, climate change, extinctions, rapid evolutionary responses to an anthropogenic world and biotechnology. Positions among experts range widely from rigid preservationists' views that hope to reverse the trend toward ecological novelty[123] to pragmatic ones that call for a balanced approach[124] and optimistic ones that see a new biodiversity of the Anthropocene emerging.[125] Fault lines in the debates shift. Some conservationists don't judge alien species by default as problematic anymore but rather try to find ways to weigh their positive and negative sides depending on context. So-called novel ecosystems characterized by alien species are considered an integral part of and sometimes an opportunity for nature conservation.[126] Alien species are considered to play important roles in wild to anthropogenic ecosystems, including by supporting the ecoevolutionary adaptation of species communities to novel ecologies.[127] Conservationists promote the deliberate transportation of alien species to new biogeographic regions to replace the ecological functions of extinct species (re-wilding)[128] or to help species track climate change in space (assisted migration).[129] Collaborations between conservationists and biotechnologists look into possibilities to resurrect extinct species, adapt threatened species through gene-editing to a changing environment, control invasive species through biotechnology, or release synthetic organisms to clean up pollution.[130] There is almost a feeling of anything goes.

In this highly ambiguous and dynamic situation, the current strategy of environmental science and policy to enable consensus building through inclusive deliberation processes has limits. We might have to fundamentally rethink what robust evidence about complex and socially contested environmental problems entails, and what role it should play in legitimizing environmentally responsible coordinated action. Heterogeneous and context-specific ecological knowledge, which cannot easily be generalized, should become a more central pillar of evidence-based decision-making. Invasion scientists have for instance started to adopt strategies such as the identification of syndromes to generalize knowledge in a more context-sensitive way.[131] However, these strategies might not suffice to effectively use locally rooted evidence at national and international scales and in decision-making contexts where vested interests play a dominant role, i.e. in situations where evidence is exposed to the manufacturing of truth and communication campaigns of interest groups or more generally alternative facts and fake news. Rather than adhering to an unrealistic ideal of irrefutable facts that can be defended against vested interests as a necessary condition for environmental valuation and actions, the task of clarifying the evidence basis of environmental issues should emphasize a continuous process of nurturing critical thinking based on society-wide ecological competencies and rooted in a shared ecological ethic.[132] Such a reappraisal of situated ecological knowledge challenges the established hierarchy of knowledge within ecology that attributes higher status to universal than case-specific ecological knowledge. Supported by work in social studies of science and epistemology, we must move toward an expert culture of real-world ecological expertise that cherishes the full diversity of ecological knowledge, competence and sensibilities: Of field ecologists as much as of experimental ecologists and system modelers, and of practitioners, amateur naturalists and holders of traditional and indigenous knowledge as much as of academic ecologists. It has been shown that case-specific integration of diverse evidence can lead to more robust invasive species policies and management.[133]

Furthermore, given that in the Anthropocene ecological processes are interwoven with human activities, ecological expertise must become inherently inter- and transdisciplinary and especially build on close collaborations with the social and cultural sciences. Biological invasions are by definition human-associated ecological phenomena and they play out in man-made ecosystems and landscapes, and therefore biological invasions can only be understood robustly and addressed effectively based on interdisciplinary perspectives that integrate biology with landscape sciences and the social sciences and humanities.[134] One reason why ecological novelty seems so difficult to grasp is that current research does not address it as an inherently socioecological phenomenon.

Ultimately, improving only the evidence base for understanding a messy world will not suffice to deal with the novel ecological realities of the Anthropocene. Foremost we are faced with a lack of shared values

Figure 4.3 Caretaking for nature. In the Terra Nostra gardens in the Azores (Portugal), plants from around the world are combined to design novel ecosystems, while on oceanic islands, also many remaining fragments of "wild" habitat depend on continuous weeding and re-planting. Photograph by Christoph Kueffer.

and visions: What are good human-nature relationships and what are realistic goals for ecological regeneration in the Anthropocene? We have to address a deficiency in our culture to engage in rich social, cultural, emotional and cognitive ways with our ecological environment and to express our deep dependence on nature (Figure 4.3). Engaging with ecological novelty might thus require us to rethink how we can responsibly care for the degraded ecosystems of the Anthropocene and their manifold living beings, with the aim to regenerate their functioning, instead of using invasive species as scapegoats for the inevitable consequences of environmental destruction.

Conclusions

Through the prism of invasive species research and policy, a rich picture of ecological research practices and associated environmental decision-making in the 20th century emerges. It is evident that the disciplinary and mode 1 science-policy approach employed by ecologists after World War II has limits in a pluralistic world and on a planet characterized by a perfect storm of environmental crises. A disciplinary problem framing does not do justice to the socioecological phenomena of the Anthropocene, and the monopolization of expert power by an exclusive circle of academics trained at and employed by natural science departments of universities in the Global North lacks legitimization in a globalized, post-colonial world. Building policy advice on generalized ecological knowledge risks ineffective solutions and imposing normative positions and ontological assumptions held by a small social group on holders of diverse values, worldviews, ontologies and interests.

However, there are no easy solutions. General ecological knowledge and expert judgments about the well-functioning of ecosystems must play an important role in societal decision-making to enable proactive and coordinated environmental action. We cannot found decisions on case-specific empirical data and deliberations in every single management case. It is evident that some ecosystems have higher ecological qualities than others and that modern forms of land use destroy ecological qualities. It is also evident that certain academic and non-academic experts have a more in-depth understanding of ecology than the rest of society – especially in our era, when many citizens live a life isolated from nature. We must find new ways to interweave ecological knowledge with cultural and social practices, narratives, norms and our personal lives. In pre-modern times, ecological knowledge was embedded in mythologies and everyday life, and in the early days of the Enlightenment period, the boundaries between storytelling, the arts and the social and cultural sciences on the one hand and ecology on the other were still permeable. Thereafter, fears of biological determinism and naturalistic fallacies and of anthropomorphism and a loss of scientific objectivity were easy ways out of sometimes difficult inter- and transdisciplinary conversations between the natural and human sciences. We cannot afford to avoid such a dialogue anymore.

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