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Ecological laws: what would they be and why would they matter?

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There remains considerable debate over the existence of ecological laws. However, this debate has not made use of an adequate account of what a relationship would have to be like in order for it to qualify as an ecological law. As a result, confusions have persisted not only over how to show that ecological laws do (or do not) exist, but also regarding why their existence would matter – other than to whether ecology looks like physics. I argue that ecological laws would have to possess collectively a distinctive kind of invariance under counterfactual perturbations. I call this invariance "stability." A law of physics, such as the law that all bodies travel no faster than the speed of light, is not only true, but also necessary in a physically significant sense. (A body *must* travel no faster than light; it *couldn't* do otherwise, even if it were subjected to a greater force.) Likewise, the stability of ecological laws would render them necessary in an ecologically relevant sense. Furthermore, ecological laws would differ from fundamental laws of physics in the range of counterfactual perturbations under which they are invariant. Therefore, I argue, the existence of ecological laws would make ecological explanations irreducible to even the most complete possible physical explanations of the same phenomena. Ecological laws would make ecology genuinely autonomous from physics.

Recently, there has been considerable discussion of whether ecology seeks laws, whether it has already found some, and whether there are any ecological laws to be found (Murray 1992, 1999, 2000, Quenette and Gerard 1993, Lawton 1999, Turchin 2001, Berryman 2003, Colyvan and Ginzburg 2003, Ginzburg and Colyvan 2004). In many of these discussions, the authors defend their favorite candidates for ecological lawhood. Among the popular candidates have been the Malthusian "law" of exponential population growth (Ginzburg 1986, Turchin 2001, Berryman 2003), the allometries of macroecology (Colyvan and Ginzburg 2003, Ginzburg and Colyvan 2004), the rules of stoichiometry and the fact that organisms interact with their environment (Lawton 1999, p. 178), the generalization that ecological succession will occur if an open site becomes available and species have differential availability or performance at that site (Pickett et al. 1994, p. 68), the competitive exclusion principle (Vandermeer 1972, p. 10, Murray 1979, p. 164), the impossibility of a population's increasing without bound (Murray 1986, p. 156, Loehle 1988, p. 101), and the principle that a population with constant age-specific rates of survival will eventually reach and maintain a steady state (Murray 2000, p. 406). Other authors argue that ecological phenomena are too complex and locally variable, temporally and spatially, to be covered by general ecological laws (McIntosh 1987, Peters 1991, Abrams 2001, Hansson 2003), and that consequently, ecology is "more a science of case studies and statistical regularities than a science of exceptionless, general laws" (Schrader-Frechette and McCoy 1993). Indeed, a tension between a theoretical pluralism that values historical case studies, on the one hand, and an aspiration to build general, unifying models, on the other hand, permeates the history of ecology (Kingsland 1995).

One striking feature of recent debates over the existence of ecological laws is the relative neglect of a logically prior question: what would an ecological relationship have to be like in order for it to qualify as an ecological law? Without an answer to this question it is difficult to ascertain whether a given ecological relationship constitutes an ecological law. Rather than address the empirical question of whether there are in fact any ecological laws, I shall offer a characterization of ecological law (and, for that matter, of physical law) that all parties to the dispute over ecological laws ought to be able to accept. This characterization will explain not only what an ecological law would have to be, but also why the existence of ecological laws would matter to ecological reasoning – apart from addressing any lingering "physics envy" that ecologists have sometimes been accused of feeling (Lawton 1999). Ecology's "autonomy" (Mayr 1996) – its having its own laws – would entail that an ecological explanation of some fact (such as a population's growth or a region's biodiversity) is irreducible to any conceivable explanation of the same fact that could (at least in principle) be given by physics. Whereas Berryman (2003, p. 700) contends that ecology "must be subject to . . . the more basic laws of physics and chemistry" and there is obviously a sense in which this is true, since ecological systems are also physical systems, I shall argue that there is also a sense in which ecological laws would be broader than the fundamental laws of physics, if ecology is truly autonomous. Laws of ecology – like the laws of thermodynamics – would be "substrate neutral" (Dennett 1995) and hence applicable even to certain hypothetical systems that violate the fundamental laws of physics.

Before working our way toward the concept of an ecological law, we must back up to explain the general concept of a law of nature.

Laws of nature: the standard picture

Traditionally, logic divides the facts into three broad categories. First, there are the logical, conceptual, mathematical, and metaphysical necessities: facts that absolutely could not have been otherwise, such as the fact that if p is true and p requires q, then q is true. The rest of the facts (the "contingent" facts) divide into two classes: the laws of nature (e.g. that all copper objects are electrically conductive) and the "accidents." Typical examples of accidents given in the philosophical literature are that all of the coins in my pocket today are silver-colored (Goodman 1983, p. 18) and that all solid gold cubes are smaller than a cubic mile (Reichenbach 1954, p.10, Hempel 1966, p. 55). Not every regularity is a law, since even an accident is a truth. Consequently, laws cannot be defined simply as general truths, the definition that Berryman (2003, p. 695) and Lawton (1999, pp. 177–178) give. What, then, distinguishes laws from accidents?

To begin with, an accident just happens to obtain. A gold cube larger than a cubic mile could have formed, but proper conditions happened never to arise. In contrast, it is no accident that a large cube of uranium-235 never formed, since the laws governing nuclear chain-reactions prohibit it. In short, things *must* conform to the laws of nature – the laws have a kind of *necessity* (weaker than logical, conceptual, mathematical, or metaphysical necessity) – whereas accidents are just coincidences.

That is to say, had Bill Gates wanted to build a large gold cube, then (I dare say) there would have been a gold cube exceeding a cubic mile. But even if Bill Gates had wanted to build a large cube of uranium-235, all U-235 cubes would still have been smaller than a cubic mile. In other words, the laws of nature govern not only what actually happens, but also what would have happened under various circumstances that did not actually happen. The laws underwrite "counterfactuals" (Goodman 1983, pp. 8–9), i.e. facts expressed by statements of the form "had p been the case, then q would have been the case". We often assert counterfactuals, as when we say "had I not gotten lost along the way, I would have arrived sooner". Science discovers which counterfactuals are true, as when Lavoisier discovered that a person who is standing up and moving about would have consumed less oxygen had she instead been sitting quietly at rest. To figure out which counterfactuals are true (e.g. which terrestrial conditions would have been different, were Earth's rate of rotation on its axis half as great), we investigate the laws of nature, because the laws would have been no different under various counterfactual circumstances (e.g. had Earth been rotating half as quickly on its axis). In contrast, some accidental facts would have been different under various counterfactual circumstances. The laws would have been no different, had p been the case, for any p that is "nomically possible" (i.e. logically consistent with all of the laws). But for each accident, there is some such p under which it would not still have held. In the next section, I shall return to this idea, labeling it "nomic preservation".

Counterfactuals are notoriously context-sensitive. In Quine's famous example (Quine 1960, p. 222), the counterfactual "had Caesar been in command in the Korean War, he would have used the atomic bomb" is correct in some contexts, whereas in others, ". . . he would have used catapults" is correct. What is preserved under a counterfactual supposition, and what is allowed to vary, depends to some extent upon our interests in entertaining the supposition. But (according to nomic preservation) in any context, the laws would still have held under any nomic possibility p.

There are other differences between laws and accidents. Because of their necessity, laws have an explanatory power that accidents lack (Hempel 1966, p. 56). For example, a certain powder burns with yellow flames, not another color, because the powder is a sodium salt and it is a law that all sodium salts, when ignited, burn with yellow flames. (This law, in turn, is explained by more fundamental laws). The powder *had* to burn with a yellow flame, considering that it was a sodium salt – and that "had-to-ness" expresses the laws' distinctive kind of necessity. In contrast, we cannot explain why my wife and I have two children by citing the regularity that all of the families on our block have two children – since this regularity is accidental. Were a childless family to try to move onto our block, they would not encounter an irresistible opposing force.

Since we believe that it would be merely coincidental if all of the coins in my pocket today turn out to be silver-colored, our discovery that the first coin I withdraw from my pocket is silver-colored fails to justify raising our confidence in the hypothesis that the next coin to be examined from my pocket will also turn out to be silver-colored. A candidate law is confirmed differently (Goodman 1983, p. 20): that one sample of a given chemical substance melts at 383 K (under standard conditions) confirms, for every unexamined sample of that substance, that its melting point is 383 K (in standard conditions).

That in science the very same claims play all of these special roles (in connection with necessity, counterfactuals, explanations, and inductive confirmations) suggests that scientific reasoning draws an important distinction here, which philosophy characterizes as the distinction between laws and accidents. (Obviously, this distinction is concerned with what laws *do* rather than with what truths happen to be called "laws"; Heisenberg's uncertainty "principle", the "axioms" of quantum mechanics, and Maxwell's "equations" are recognized laws of physics). However, it is notoriously difficult to capture the laws' "special roles" precisely. For example, suppose we try to distinguish laws from accidents on the grounds that laws support counterfactuals in a manner that accidents do not. That my car's maximum speed on a dry, flat road stands in a certain relation to the distance of my car's gas pedal from the floor is not a law (since it reflects the engine's accidental features). Yet this relationship supports counterfactuals regarding the car's maximum speed had we depressed the pedal to one-half inch from the floor. This relationship has "invariance with respect to certain hypothetical changes" (Haavelmo 1944), though not certain changes to the engine. Indeed, for nearly any accident, there are *some* hypothetical changes with respect to which it is invariant. All gold cubes would still have been smaller than a cubic mile even if today I had been wearing a differently colored shirt. Of course, the laws permit some conditions (e.g. had Bill Gates wanted to build a large gold cube) under which the gold-cube generalization would not still have held. But a devastating circularity threatens if we use the notion of consistency with the laws to delimit the range of counterfactual perturbations under which a fact must be invariant in order for it to qualify as a law. We would then be using the laws to pick out the range of counterfactual suppositions that, in turn, are used to pick out the laws. To understand what laws of nature are, we need a means of distinguishing the laws from the accidents that does not presuppose that this distinction has already somehow been drawn.

Laws of nature: a more adequate account

Some philosophers (van Fraassen 1989) would argue that the best way to avoid this problem is to avoid using the concept of a natural law in the first place, and accordingly to regard counterfactuals, inductive generalizations, and explanations as playing minimal roles in science. Other philosophers (Mitchell 2000, Woodward 2001), in contrast, insist that these elements are important in scientific reasoning, but that they are not best understood in terms of a sharp distinction between laws and accidents. Rather, different explanatory generalizations have different ranges of invariance under different sorts of counterfactual perturbations. Loosely speaking, a broader range of invariance enhances a regularity's explanatory power. I have defended a different view (Lange 2000, 2002): that there is indeed a sharp distinction between laws and accidents, and that laws collectively possess a distinctive, maximal invariance under counterfactual perturbations.

To see how the laws can be distinguished from the accidents without circularity, let's return to:

> nomic preservation (NP): g is a law if and only if in any context, g would still have held had p obtained, for every p that is logically consistent with every law.

For example, NP entails that "all gold cubes are smaller than a cubic mile" is not a law since it is not the case that the gold-cubes generalization would still have held under any conditions consistent with the laws (since it would not still have held had Bill Gates wanted to build a large gold cube). In contrast, "all sodium salts, when ignited, burn with yellow flames" is a law because any counterfactual supposition under which sodium salts would not still have burned with yellow flames (e.g. a supposition ascribing certain imaginary energy levels to the sodium atom) is a supposition that is flatly inconsistent with some law of nature. According to NP, the laws would all still have held under any counterfactual supposition that is logically consistent with the laws. No accident is always preserved under all of these suppositions. But (as mentioned at the end of the previous section) the circularity in NP's definition of "law" is evident. The range of counterfactual suppositions under consideration in NP has been designed expressly to suit the laws.

What if we extend the same courtesy to a set containing accidents, allowing it to pick out a range of counterfactual suppositions especially convenient to itself: those suppositions that are logically consistent with every member of that set? Take, for example, a "logically closed" set of truths (i.e. a set containing every logical consequence of its members) that includes the fact that all gold cubes are smaller than a cubic mile. The set's members would not all still have been true had Bill Gates wanted to build a large gold cube. So for the set's members all to be invariant under every counterfactual supposition that is logically consistent with each of them, the set must contain the fact that Bill Gates never wants to build a large gold cube; the counterfactual supposition that he wants to do so is then logically inconsistent with a member of the set. However, presumably had Mrs. Gates wanted a large gold cube, then Bill would have wanted one built. So having included the fact that Bill Gates never wants to build a large gold cube, the set must also include the fact that

Mrs. Gates never wants one, in order for all of the set's members still to have been true under any counterfactual supposition with which every member is logically consistent.

Such a set must be very inclusive. Suppose, for example, that the set omits the accident that all of the apples on my tree are ripe. Here is a counterfactual supposition that is logically consistent with every member of the set: had either some gold cube exceeded one cubic mile or some apple on my tree not been ripe. Under this counterfactual supposition, there is no reason why the generalization about gold cubes (which is in the set) takes priority in every conversational context over the apple generalization (which we have supposed not to be in the set). So it is not the case that the gold-cube generalization is preserved (in every conversational context) under this counterfactual supposition. Hence, the set must include the apple generalization if the set is to be invariant under every counterfactual supposition that is logically consistent with every one of its members. (Having included the apple generalization too, the set now has a member that is logically inconsistent with the counterfactual supposition that either some gold cube exceeds one cubic mile or some apple on my tree is not ripe). The upshot is that if a logically closed set of truths includes an accident, then it must include every accident if it is to be invariant under every counterfactual supposition that is logically consistent with every member of the set.

But according to NP, the set of laws possesses exactly this kind of invariance. We can now specify (without circularity) the laws' distinctive relation to counterfactuals. Take a logically closed set of truths that is neither the empty set nor the set of all truths. Call such a set stable exactly when every member g of the set would still have been true had p been the case, for every counterfactual supposition p that is logically consistent with every member of the set. We have arrived at

> nomic stability (NS): g is a law exactly when g belongs to a stable set.

On this view, the laws are distinguished by their collective stability: taken as a set, they are invariant under as broad a range of counterfactual suppositions as they could logically possibly be. Obviously, no truth can be preserved under a counterfactual perturbation that contradicts it. But within this constraint, the laws as a group are maximally invariant. That is, all of the laws would still have held under every counterfactual supposition under which they could (i.e. without contradiction) all still have held. No set containing an accident (except the set of all truths) can make that boast.

Because the set of laws is as invariant under counterfactual perturbations as it could be, there is a sense of necessity corresponding to it. Necessity involves being the case no matter what, in the broadest possible sense of "no matter what." That is, necessity involves possessing a maximal degree of invariance under counterfactual perturbations. No sense of necessity corresponds to an accident, even to one (such as my car's gas pedal–maximum speed function) that would still have held under many counterfactual suppositions.

In roughly this way, I have suggested (Lange 2000, 2002), the notion of "stability" allows us to draw a sharp distinction between laws and accidents. The laws' stability explains why the laws possess a kind of necessity; the laws' stability accounts for the fact that an event "must" obey the laws of nature. The laws' stability supplies a way out of the circle that results from defining the laws as the truths that would still have held under those counterfactual suppositions that are consistent with the laws. Fortified with this conception of a natural law, we can now turn to the question of what a law of ecology would have to be like.

What would a law of ecology be?

We must now consider what it would be for a set to be stable for the purposes of a given scientific field, where that field may equally well be physics or ecology. Such stability requires, to begin with, that the set's members all be reliable – that is, close enough to the truth for the field's purposes. John Stuart Mill (1961, pp. 552–553) nicely explains the point:

> It may happen that the greater causes, those on which the principal part of the phenomena depends, are within the reach of observation and measurement . . . But inasmuch as other, perhaps many other causes, separately insignificant in their effects, co-operate or conflict in many or in all cases with those greater causes, the effect, accordingly, presents more or less of aberration from what would be produced by the greater causes alone. . . . It is thus, for example, with the theory of the tides. No one doubts that Tidology . . . is really a science. As much of the phenomena as depends on the attraction of the sun and moon . . . may be foretold with certainty; and the far greater part of the phenomena depends on these causes. But circumstances of a local or casual nature, such as the configuration of the bottom of the ocean, the degree of confinement from shores, the direction of the wind, &c., influence in many or in all places the height and time of the tide . . . General laws may be laid down respecting the tides; predictions may be founded on those laws, and the result will in the main . . . correspond to the predictions. And this is, or ought to be meant by those who speak of sciences which are not *exact* sciences.

A reliable g must reflect all of the "greater causes". But it may neglect a host of petty influences – what Lawton (1999: 146) refers to as "fine tuning," as distinct from "*the* processes (which is what we write in grant proposals)". For example, classical physics might suffice for the purposes of human physiology or marketing; relativistic corrections are negligible. Biological controversies often concern the "relative significance" of various factors (Beatty 1995), and these disputes may be understood as concerning which are the "greater causes" that must figure in biological laws (Sober 1997, p. S461). Since the laws of an inexact science omit the negligible influences, they are only approximately true, as Colyvan and Ginzburg (2003) note.

One way to argue that there are no laws of ecology is to argue that where ecological phenomena are concerned, there is no distinction to be drawn between the "greater causes" and a host of petty, local, idiosyncratic influences that must be ascertained on a case-by-case basis. Unlike the tides, the argument would go, there is no clear distinction between the signal and the noise – in the analogy employed by Rosenzweig and Sandlin (1997) – or between the biological equivalents of inertia and friction – in the analogy employed by Murray (1992).

What range of invariance under counterfactual perturbations distinguishes the laws of a given field from its accidents? Since the field's range of concerns is limited, certain facts and counterfactual suppositions lie outside of the field's interests, and the field is irrelevant in certain conversational contexts. With this in mind, we can call upon "nomic stability" (from the previous section) to help us distinguish the laws of a given field from its accidents. Roughly speaking, for a set of reliable claims to be stable for a given field's purposes, the set's members must all be invariant under every counterfactual supposition that is relevant to the field and consistent with every member of the set. A set that is stable for ecological purposes, then, will possess as much "resilience" under ecologically relevant counterfactual perturbations as that set could possibly possess – and hence will consist of ecological laws. More fully: a logically closed set is stable for the purposes of a given science, and hence its members are laws of that field, if and only if its members not only are all of interest to the field and reliable for the field's purposes, but also would all still have been reliable, for the field's purposes, under every counterfactual supposition of interest to the field and consistent with the set (and in every conversational context relevant to the field).

To unpack this idea, let's apply it to an ecological example. A recent article in Nature (Pounds and Puschendorf 2004) refers to the species–area relationship as "one of ecology's few ironclad laws" (a phrase that echoes Schoener 1976, p. 629). The most commonly discussed form of the species-area relationship is this "area law": that the number S of species of a given taxonomic group on an "island" (as far as creatures of that group are concerned) in a given "archipelago" increases, ceteris paribus, with the island's area A in accordance with a power function ($S = cA^z$). My immediate concern is not with whether this "area law" is indeed a law of ecology. It is to explain what it would take for the "area law" to be a genuine ecological law and what difference its lawhood would make.

Notice that the "area law" contains a "ceteris paribus" (typically translated as "all other things being equal" or "in the absence of disturbing factors") proviso. This proviso means roughly that the law concerns only one of the relevant "greater causes" (in Mill's phrase). For example, in economics, it is a law that the rate of wages varies inversely, ceteris paribus, with the supply of labour (Marshall 1961, p. 825). The other "greater causes," such as inflation, must be held fixed. (Some of these other "greater causes" may never receive explicit mention in economics textbooks. We all understand implicitly that the "law" is not intended to apply if a rumor suddenly spreads that illness is brought on by contact with the currency in which the wages are paid). The proviso also signals that even when all of the other greater causes are absent (or held constant), the "law" is inexact. It leaves out a host of minor disturbing influences that, although real, are small or rare enough to be negligible for the relevant purposes. The "law" is reliable for the relevant purposes, despite neglecting these minor disturbing influences, because often enough it is close enough to the truth. As Diamond and May (1981, p. 231) say with regard to the "area law": "Such relations are admittedly crude and neglectful of detail, but they provide an informed first guess at the relation between the area of a reserve and the number of species which are eventually likely to be preserved in it". For a case to satisfy the ceteris-paribus proviso, it is not necessary for all of the other causally relevant factors to be absent. Only the other factors understood to be too important (for the relevant purposes) to neglect must be absent.

What are the other "greater causes" in the case of the "area law"? For the sake of argument, suppose that as MacArthur and Wilson (1963, 1967) maintain, area is one of the "greater causes" of island biodiversity because a larger island tends to have larger available habitats for its species, so it can support larger populations of them, making chance extinctions less likely. Let's suppose as well that larger islands also present larger targets for stray creatures (Lomolino 1990). Therefore, larger islands have larger immigration rates and lower extinction rates, and so tend (ceteris paribus) to equilibrate at higher biodiversity. Nevertheless, a smaller island much nearer the "mainland" may have greater biodiversity than a larger island much farther away. Distance from the mainland is one of the "greater causes" covered by the ceteris paribus qualifier to the "area law." Likewise, a smaller island with much greater habitat heterogeneity may support greater biodiversity than a larger, much more homogeneous island. Habitat heterogeneithy is another of the factors covered by "ceteris paribus." And there are others.

But (for the reasons I just explained) to discover the "area law," ecologists do not need to identify every petty influence that may cause deviations from $S = cA^z$, only the "greater causes" that must be taken into account in order for the area law to yield predictions that often enough are good enough for the intended sorts of applications. Some of these applications are practical, such as the design of nature reserves. Others are theoretical, such as serving as a common starting-point for building more accurate ecological models in a case-by-case fashion, each model incorporating the idiosyncratic features of the particular case for which it is intended. In this role, the area law functions like Hooke's law for springs, for example, to which non-linear terms may be added case-by-case when greater accuracy is required.

For the sake of argument, I shall suppose that the "area law" with this ceteris-paribus proviso is indeed reliable. But this may not be so. Some other relationship between biodiversity and area, such as an exponential (or semi-log) model, may be superior to a power (or double-log) function (Connor and McCoy 1979, McGuinness 1984). Perhaps the law extends only to a qualitative relationship: species richness on islands increases with area monotonically, yet to a gradually lessening degree. Perhaps species richness is influenced not by area per se, but only by area insofar as it is associated with another factor, such as habitat diversity (Connor and McCoy 1979, Rosenzweig 1995). Another possibility is that the MacArthur-Wilson equilibrium theory partly misidentifies the major confounding factors, so the "area law" is reliable only with an amended ceteris-paribus proviso. Perhaps the processes underlying the same species-area equation differ in different systems and at different scales (Rosenzweig 1995), and so different ceteris-paribus provisos are required. More drastically, perhaps there is no small set of "greater causes", but instead in each case there is a myriad of idiosyncratic, non-negligible, local factors (such as interspecific interactions), so that only a case-by-case approach makes approximately accurate predictions regarding island biodiversity. In supposing that the "area law" is reliable, I am not trying to prejudge any of these issues, merely to understand what ecological laws would have to be like and whether the "area law" is a promising candidate.

What would the "area law"'s range of invariance under counterfactual perturbations have to be like for it to qualify as an ecological law – for it to be necessary in an ecologically relevant sense? Here we can turn to nomic stability and ask whether the "area law" belongs to a set that is stable for ecological purposes. It seems likely to do so, but let's look at some challenges that this view apparently faces.

There are counterfactual suppositions under which the laws of physics would still have held, but under which the "area law" would not still have held. For example, had Earth always lacked a magnetic field, cosmic rays would have bombarded all latitudes, which might well have prevented life from arising, in which case S would have been zero irrespective of A. Here is another counterfactual supposition: Had evolutionary history proceeded differently so that many species developed the sorts of flight, orientation, and navigation capacities possessed by actual airplanes. (This supposition, albeit rather outlandish, is nevertheless logically consistent with the laws of physics since airplanes actually exist!). It is not the case that under this supposition, the "area law" would still have held, since an island's size as a target for stray creatures might then have made little difference to its immigration rate. (Creatures without the elaborate organs for flight and navigation could have hitched rides on those so equipped). Does the fact that the "area law" fails to be preserved under these counterfactual perturbations show that a set containing the area law is unstable for ecological purposes?

No. The first supposition (concerning Earth's magnetic field) falls outside ecology's interests. It twiddles with a parameter that ecology does not take as a variable. Biogeographers are interested in how species would have been distributed had (say) Gondwanaland not broken up, and in how Montserrat's biodiversity would have been affected had the island been (say) half as large. On the other hand, biogeography is not responsible for determining how species would have been distributed had (say) Earth failed to have had the Moon knocked out of it by an early cataclysm. (Earth's rotation rate would then have been greater, its tides would have been less, and the CO_2 level in its atmosphere would have been greater.) Biogeography is not geophysics.

The second counterfactual supposition I mentioned (positing many species capable of covering long distances over unfamiliar terrain nearly as safely as short distances over familiar territory) is logically inconsistent with other generalizations that would join the "area law" in forming a set that is stable for ecological purposes. For example, the "distance law" says that ceteris paribus, islands farther from the mainland equilibrate at lower biodiversity. Underlying both the area and distance laws are various constraints – e.g. that creatures travel along continuous paths, that the difficulty of crossing a gap in the creature's habitat increases smoothly with the gap's size (ceteris paribus). These "continuity principles" (MacArthur 1972, pp. 59–60) must join the area and distance laws in a set that is stable for ecology.

The area law might not still have held, had these continuity principles been violated. Yet according to nomic stability, the area law's range of invariance under counterfactual suppositions may nevertheless suffice for it to qualify as an ecological law because other laws of ecology state these constraints. Here is a parallel case from physics. Take the Lorentz force law: in magnetic field B, a point body with electric charge q and velocity v (compared to the speed of light c) feels a magnetic force $F = q\ (v/c) \times B$. Presumably, this law would not still have held, had charged bodies been accelerated beyond c. But this law requires no proviso limiting its application to cases where bodies fail to be accelerated beyond c. The proviso is unnecessary because other laws of physics expressly rule out superluminal accelerations. Hence, the Lorentz force law can exhibit the range of invariance demanded of a law of physics (according to nomic stability) without having to be preserved under counterfactual suppositions positing superluminal accelerations.

Thus, the "area law"'s failure to be preserved under the two counterfactual suppositions that I have just examined does not preclude the "area law" from belonging to a set that is stable for ecological purposes – i.e. a set that consists of ecological laws. Is there in fact such a set containing the "area law"? If so, then what are the set's other members? These are matters for empirical research. But another attractive candidate for ecological lawhood is the venerable latitudinal gradient of species diversity: that plots of a given area at lower latitude contain more species, ceteris paribus, than plots with that area at higher latitude. When, for example, Brown and Lomolino (1998, p. 459) assert that the latitudinal gradient would still hold, were each location on Earth to experience over the next 100 million years exactly the same environmental conditions as it did in 1998, Brown and Lomolino appear to be regarding the latitudinal gradient as possessing the sort of resilience under counterfactual suppositions that is characteristic of natural laws.

My account of ecological laws as forming a set that is stable for ecological purposes may perhaps seem not only somewhat elaborate, but also rather remote from actual science. However, I think it usefully highlights the way that lawhood is not something that a fact attains in isolation. Rather, lawhood is achieved only as a member of an integrated set of laws – integrated in that each member helps to limit the range of invariance that every other member has to possess in order for it to be a law. (Likewise in physics, as we just saw, the law prohibiting acceleration of a particle beyond the speed of light helps to delimit the range of counterfactual perturbations under which the Lorentz force law must be preserved in order for it to be a law.) Research into the mechanisms responsible for various large-scale ecological patterns might fruitfully be guided by the expectation that any laws will have to interlock in this way rather than be utterly independent. Consider the area law and the latitudinal gradient. Several proposals have been offered for ways in which they might interlock. For instance, one possible partial explanation for the latitudinal gradient is that the tropics receive greater (and less seasonally varying) solar energy, and to this extent can support more individuals, and hence more species by virtue of a relation governing how individuals are distributed, ceteris paribus, among species. The species-abundance curve may also be partly responsible for the area law (Preston 1962, May 1975, McGuinness 1984). If these views are correct, then an ecologically stable set that includes the latitudinal gradient would also have to include the area law, since the latitudinal gradient might not still have held had the area law been violated (because the species-abundance relation might not then still have have held). The same interconnection also follows from a different suggestion, made by Rosenzweig (1995, pp. 289–296), according to which the latitudinal gradient is explained partly by the fact that because of the Earth's shape, the tropics have greater surface area than the temperate zones (and the tropics are continuous, whereas the temperate zones are separate regions). Therefore, ceteris paribus, the tropics can support larger populations, making chance extinctions less likely. That the larger populations allowed by greater area inhibit extinctions also contributes to the area law, according to the MacArthur-Wilson equilibrium theory. So if these views are correct, then once again, a set that is stable for ecological purposes could be constructed around the latitudinal gradient only by also including the area law. The laws of a given inexact science would be expected to form this sort of unified structure if they are members of a set that is stable for the relevant purposes.

There is a closely related methodological lesson afforded by this conception of how ecological laws would have to function collectively. According to nomic stability, p is an ecological law only if p would still have been reliable under any counterfactual circumstance that is logically consistent with p together with the (other) ecological laws. This idea helps to capture the sense in which an ecological law must be "general." Suppose we now consider various ecologically relevant counterfactual circumstances q under which, we believe, p would not still have held. We might thereby be led to discover further ecological laws, since in order for p to be a law, q must be logically inconsistent with some other ecological law, perhaps one as yet undiscovered. The account of laws as forming a stable set directs our attention to pertinent questions to ask about the limits of a generalization's domain of application.

What difference would the existence of ecological laws make?

I have just mentioned several ways in which it might be fruitful in ecology to investigate whether or not a given principle rises to the level of an ecological law (as I understand what an ecological law would be). But there are other reasons why the existence of ecological laws would matter.

A set that is stable for ecology can omit some of the laws of physics. The gross features of the physical laws that are captured by "continuity principles" like those I have mentioned may suffice – without the fundamental laws of physics – to delimit the range of counterfactual suppositions under which an ecological fact must be invariant in order for it to qualify as an ecological law. If the "area law" is a genuine ecological law and the relevant "greater causes" are as I have supposed them to be, then the "area law" would still have held even if some of the fundamental laws of physics had been violated – for instance, even if all material bodies had consisted of some sort of continuous, space-filling, rigid substance rather than particles separated by empty space. The factors affecting species dispersal would then have been unchanged: for example, smaller islands would still have presented smaller targets to off-course birds and so accumulated fewer strays, ceteris paribus. Thus, the range of stability of ecological laws would inevitably be broader in some respects than the range of stability of the fundamental laws of physics. Ecological laws would not be sensitive to every detail of the fundamental physical laws.

This is a crucial point. The necessity of ecological laws corresponds to their range of stability. But that range includes some counterfactual suppositions violating the fundamental laws of physics. Consequently, the kind of necessity that would be characteristic of ecological laws could not be possessed by the fundamental laws of physics.

Of course, the approximate truth of ecological laws might well follow from the fundamental laws of physics and certain initial conditions that are accidents of physics. The ecological laws would then be reducible (in an important sense) to physics. Nevertheless, the lawhood of ecological laws – their stability for ecological purposes – cannot follow from the fundamental laws of physics and initial conditions, since their stability depends on their remaining reliable under certain counterfactual suppositions that violate fundamental physical laws (such as the law that all bodies are or are composed of certain sorts of particles). The fundamental laws of physics obviously cannot be responsible for the area law's remaining reliable under those counterfactual suppositions.

Hence, if there are in fact ecological laws, then ecology would have an important kind of autonomy. An ecological explanation of some fact would be irreducible to any conceivable explanation of the same fact that could (at least in principle) be given at a "lower" level. Of course, there are many senses of "reducibility" (discussed by Rosenberg 1985, Sober 2000). As I indicated above, I am not contending that ecological laws would be irreducible in every important sense of the word. Nor am I suggesting that the only way for ecological understanding to be interestingly irreducible to the explanations supplied by fundamental physics would be for ecological laws to exist. However, if ecological laws would have to form a set that is stable for ecological purposes, then the existence of ecological laws would suffice to make ecological explanations irreducible (in an important sense) to explanations of the same facts that could (at least in principle) be given in terms of fundamental physics. That is because an ecological explanation would show the explained ecological fact to be independent (in a sense that I have tried to make precise) of the fundamental physical processes that gave rise to it.

For example, there would be many different, correct explanations of why n species of land bird currently inhabit Mauritius. An ecological explanation would appeal to ecological laws and Mauritius's area, distance from the mainland, and so forth, to explain why there are n species rather than many more or far fewer. A second explanation would proceed at a "lower level": by explaining the fates, one by one, of each of the various individual creatures who might have migrated to Mauritius and left descendants. The second explanation could in principle even proceed by using the fundamental laws of physics to explain the behavior of each of the elementary particles involved. (That we could never in practice discover all of these details does not alter the fact that they explain Mauritius's biodiversity, just as a mathematical proof too long or complex for human beings ever to discover still constitutes a proof). The second, "lower-level" account explains not merely what the ecological account explains (why Mauritius is currently inhabited by n species rather than many more or far fewer), but also why Mauritius is currently inhabited by n species rather than one more or fewer – and, indeed, why Mauritius is inhabited by those particular n species rather than a different combination. However, it does not follow that the ecological account is merely a rough sketch of or promissory note for the second account. On the contrary, the ecological account includes explanatorily relevant information omitted from the "lower-level" account, despite its rich detail. For example, the "lower-level" account does not say that Mauritius's biodiversity would have been nearly the same even if, say, the stock of potential migrants (the mainland species of birds) had been very different – indeed, even if some of those species had been made of continuous rigid substance instead of particles. The ecological laws would then still have applied. So the ecological laws reveal that Mauritius, given its area, would have exhibited roughly the same biodiversity no matter what – in a sense of "no matter what" that is not limited by every detail of the fundamental laws of physics.

As I mentioned earlier, some alternative philosophical views of natural law say that different explanatory generalizations have different ranges of invariance under counterfactual perturbations, but that no sharp distinction can be drawn between laws and accidents. These philosophical views agree with my conclusion that an explanation of Mauritius's biodiversity using the "area law" is irreducible to an explanation of the same fact using the fundamental "laws" of physics. Nevertheless, I think that these alternative philosophical approaches fail to account adequately for the way that the "area law" deems Mauritius's biodiversity to be inevitable (ceteris paribus), given Mauritius's area, and for the way that the area law's role in ecology is analogous to (for example) the Lorentz force law's role in physics. (Each belongs to a set that is stable for the purposes of its field). However, these issues remain the subject of lively philosophical debate.

On my view, the fact that there are no creatures made of continuous rigid substance is (as far as ecology is concerned) merely an accident of the actual world – like the occurrence of the long-ago storm that deflected a given bird to Mauritius. Broadly speaking, Mauritius's biodiversity is insensitive to this accident. The ecological explanation of Mauritius's biodiversity uniquely supplies this information, if ecology turns out to have laws of its own.

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