



Scale, causality, and the new organism–environment interaction

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ABSTRACT

The fallout from environmental determinism of the early 20th century steered geography away from biological and evolutionary thought. Yet it also set in motion the diversification of how geographers conceive environment, how these environments shape and are shaped by humans, and how scaling negotiates the interpretation of this causality. I illustrate how this plurality of scalar perspectives and practices in geography is embedded in the organism–environment interaction recently articulated in the life sciences. I describe the new fields of epigenetics and niche construction to communicate how ideas about scale from human and physical geography come together in the life sciences. I argue that the two interdisciplinary modes or ‘moments’ of scalar thinking in geography are compatible, even necessary, through their embodiment in organisms. To procure predictability, organisms practice an epistemological scaling to rework the mental and material boundaries and scales in their environment. Yet organisms are also embedded in ontological flux. Boundaries and scales do not remain static because of the agency of other organisms to shape their own predictability. I formally define biological scaling as arising from the interplay of epistemological and ontological moments of scale. This third moment of scale creates local assemblages or topologies with a propensity for persistence. These ‘lumpy’ material outcomes of the new organism–environment interaction have analogues in posthuman and new materialist geographies. They also give formerly discredited Lamarckian modes of inheritance a renewed, but revised acceptance. This article argues for a biological view of scale and causality in geography.

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1. Introduction

“Knowledge is the agreement of the organism and the environment from which it emerges. Without knowledge, without the identity of the organism, and without this agreement, life could not be imagined.” Bataille (2001, p. 221) cited in Yusoff (2009, p. 1025).

From the environmental determinism of the early 20th century (Semple, 1911; Huntington, 1915; Taylor, 1937) to recent conversations about *Guns, Germs, and Steel* (Blaut, 1999; Merrett, 2003; Robbins, 2003; Radcliffe et al., 2009), geographic scholarship has often contested the nature of causality mediated through the environment. Following the publication of Diamond’s (1997) book, human and physical geographers alike weighed in their opinions on environmental determinism. Since then, discussions of environmental causality often gravitate back to *Guns, Germs, and Steel*. Yet this book represents only one of several interpretations of human–environment causality. Indeed, a defining feature of geography is its historic breadth on how environment is conceived, how these environments shape and are shaped by *humans*, and how scaling negotiates the perception of these causal dynamics.

But geography is not the only discipline with the goal of understanding how environment and life influence one another. The life sciences have long sought to detail the *organism–environment* interaction. For biologists, 2009 was a year of celebratory events and essays marking the 150th anniversary of the publication of Darwin’s *On the Origin of Species*. Geographers were more subdued in their recognition (Castree, 2009a,b; Summerfield, 2010). This reticence could be surprising, as evolution helped North American academic geography unify in its formative years around the study of human–environment interactions (Stoddart, 1966, 1986). Geographers reworked these evolutionary outlooks to construct their academic niche, but backed away from them when their incompleteness, their social implications, and their blatant falseness became visible. But how has biology changed over the intervening century, particularly in the last two decades? How does geography’s recent theorization of scale apply to non-human organisms? In what ways are recent life science ideas about the organism–environment interaction of relevance for conceptualizing causality in geography?

This article reconsiders geography’s connection to dialogues in biology about the organism–environment interaction. I take the position that the accelerating nature of innovation and insight in genetics and evolution are opportunities for geography to consider the content of the life sciences to balance critical perspectives of its social context (Latour, 2004; Boyd, 2006; Collins, 2009). Already,

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posthumanists and materialist geographers are drawing closer to biology. Articulating how facets of scale theory apply to organisms broadly defined might also enhance geography's engagement with the human–environment interaction.

In the first section of this article, I review how the environmental determinists of the early 20th century derived their notions about causality from the life sciences. Many geographers of this time selectively rejuvenated Lamarckian mechanisms of evolution and used them to justify their idiosyncratic and at times pernicious interpretations of the human–environment interaction. I posit that geography's subsequent self-imposed exile from biology and evolutionary thought set in motion geography's ongoing pluralization of ideas about how environment, scale, and causality are intertwined. Following Judkins et al. (2008), I describe how geographers have recycled or 'remediated' the original intent of environmental determinism – to explain causality from a spatial perspective – into a diversity of explanatory frameworks focused almost exclusively on humans and their humanized environments.

In the second section, I summarize the 'scalar causal logics' of geographers. These are the ways scale has been employed to characterize environmental causality. Based on the terminology of Sayre (2005), the scalar causal logics of geographers can be classified as one of two 'moments' of scale. The term 'moment' in this usage denotes a way or practice of use, not a period in time. By analogy, statistical 'moments' denote the interrelated practices for describing distributional properties such as mean, standard deviation, and skewness. I present the argument that both moments of scale in geography are compatible through organisms. Biological corporeality enacts their coexistence. I contend that this embodiment defines a third moment of scalar practice, biological scaling.

Of late, biology's exponential accumulation of knowledge offers perspectives on the organism–environment interaction unforeseeable a few decades ago. In the third section, I examine recent life science scholarship that illustrates biological scaling and the new organism–environment interaction. Using epigenetics and niche construction as examples, I describe how their dynamics remediate the formerly discredited notion of Lamarckian inheritance adopted by early environmental determinists. Epigenetics and niche construction exemplify a potential 'stickiness', a spatiotemporal persistence or inheritance originating from the scalar interactions among organisms and environment. I close with a summary of the precepts for a scalar, biological remaking of environmental causality, and discuss their overlap with geographic thought.

2. Environmental determinism and the remediation of environmental causality

"Conceptual innovation is a representational problem—how to represent the known information so as to enable satisfactory inferences that go beyond the target information at hand..." (Nersessian, 2008, p. xii).

Evolutionary biology had a strong influence on the origins of academic geography (Livingstone, 1993). Part of this was timing. *On the Origin of Species* was published in 1859 and evolutionary precepts were still reworking the intellectual enterprise when geography began to assert itself in the academies of North America in the late 1890s. To differentiate geography from geology, William Morris Davis advocated incorporating the organic elements of the landscape, including the human dimension. Ontography, the scientific relationship between cause and effect, would give geography identity amid the clamor for recognizable divisions of academic labor (Davis, 1915). This strategy was the first attempt at generalization by geographers of the modern period (Johnston, 1991).

However, the human place in evolution was subject to wide interpretation. Evolutionary thought at this time was as much a dangerous temptation for idiosyncratic translation as it was a fertile intellectual opportunity to forge geography's identity around the human–environment interaction. It offered geography promise and peril in the marketplace of ideas.

The presence of evolution in geography was in part a disregard for some of Darwin's ideas and the acceptance of others. Geographers selectively rejuvenated the evolutionary writings of Jean-Baptiste Lamarck (Campbell and Livingstone, 1983; Livingstone, 1984, 1985; Peet, 1985; Inkpen and Collier, 2007). Lamarck's influential *Philosophie Zoologique* began circulating in 1809, the year of Darwin's birth, and a full 50 years before the publication of Darwin's *On the Origin of Species*. While Darwin's bold evolutionary proposition was generally accepted in scientific circles within two decades of its announcement, reticence about the mechanistic details of natural selection led some biologists to develop alternative explanations. This period, from 1880 to the 1920s is called the "eclipse of Darwin" (Bowler, 2003), and a neo-Lamarckian model of evolution was one of several reworkings of Darwinian concepts popular among geographers. Although Darwinian ideas about adaptation and selection were the original impetus, the purposefulness that permeated the environmental deterministic thinking of early modern geographers was derived from Lamarck.

Lamarckian evolution is most often identified with the inheritance of acquired characteristics. Lamarck postulated that behaviors induced by environmental conditions can modify an organism's characteristics. These could be encoded within an organism and passed onto subsequent generations. A frequently invoked interpretation of Lamarckian evolution is the lengthening of giraffe necks through time as each generation stretches upward to obtain leaves for food. Although Lamarckian precepts were weakened by the rediscovery of Mendelian genetics in the first decade of the 1900s, their influence lingered in geography throughout the first three decades of the 20th century. Beyond the lack of awareness about new ideas in genetics and heredity, there were several other reasons why Lamarckism persisted. Darwin's focus on species competition over the ambience and detail of the environment attracted geographers toward Lamarck and his more spatial viewpoint. While Darwin did not overtly incorporate humans in his writings, Lamarck molded his ideas to explain human development in an environmental context.

Lamarckian views allowed geographers to fix their gaze upon the outcomes and course of evolution instead of the process. Because Lamarckian influences were assumed to act over a single generation, geographers were able to speed up the process of evolution for humans so that it might operate over smaller time scales amenable for causal closure and neat, tidy narratives that would sell in the marketplace of ideas. Lamarckian ideas were also more interventionist and idealistic than Darwinian naturalism with its cold inevitability. They replaced the randomness of Darwinism with a sense of responsibility and intent instead of fate and natural selection. Social progress could be greatly accelerated by learning and through the acquisition of habits in response to the environment. It was out of these motivations and desires that environmental determinism originated in early 20th century geography, and it was also where it ran aground.

That environmental determinism led to racist and imperialistic outcomes has been well documented. However, environmental determinists were not uniform in their views (Brigham, 1915; Lewthwaite, 1966; Martin and Martin, 2005). Ambivalence and dissatisfaction about environmental determinism coexisted with its uncritical support. That there were no detailed mechanisms led to some of the opacity about how environmental determinism actually worked and how it could be studied. Calls were made to make the idea of geographical influence more precise and less

superficial. Many recognized the environment as fundamental, but "...the greater part, in a sort of absolution of conscience, name the subject and take leave of it" (Brigham, 1915, p. 6). The incomplete nature of environmental causality was not hidden to geographers of that time, and more knowledge of evolution and biology was recognized as necessary: "So the geographer, if he touches man at all, and the more if he opens the question of geographic influence, must be in daily contact with the principles of biological evolution, so far as the specialists have mastered them" (Brigham, 1915, p. 15).

Environmental determinism was a very pliable concept (Schulzen, 2001). Its application to questions about human–environment interaction depended upon one's comprehension of biology and the mechanisms of evolution known at the time. Its progressive impulse to improve the lives of others enticed idealist goals that were racist and imperialistic. These factors fostered a spectrum of views, from the environment-takes-all determinism of Taylor (1937) to the discussions of ecological and social cooperation in the work of the Russian anarchist-geographer Kropotkin (1972). Recognizing the perils and pitfalls of environmental determinism, many geographers backed away from evolutionary syntheses and disavowed speculation about unmediated environmental influences upon humans. Carl Sauer, for example, rejected geographic environmental determinism and the *a priori* precepts of evolution. In its place, the environment became one of human making: "...all geography is physical geography...not because of an environmental conditioning of the works of man, but because man, himself not directly the object of geographic investigation, has given physical expression to the area by habitation..." (Sauer, 1931, p. 622 as quoted in Solot (1986, p. 509)).

The full disciplinary reaction to environmental determinism is open to interpretation. However, I wish to emphasize the following points. Because of its ethical contradictions and scientific vagueness, an explicit biological foundation was rejected in human geography in general and more specifically in the human–environment subdiscipline. Consequently, what defined environmental causality began to shift away from direct and universalizing mechanisms like climate and evolution toward indirect conceptions of environment through human culture, class, and economics. The environmental determinism that reinforced racial divides through climate and soils gravitated toward one in which the human transformation of the world was a more pervasive environmental influence. Human–environment geography became distinguished by its diversity of ways to define environment through humans. The scaling and malleability of human-constructed environmental influences were prioritized to the near exclusion of biological explanations of causality. Although biogeographers retained their

focus on the biological relevance of environmental causality over the past century, any propensity for them to generalize about the implications of their work for human–environment interactions has been muted up until recently.

This reconceptualization of environment in human geography has undergone several prominent remediations since the geographic determinism of Semple and Huntington, Judkins et al. (2008) reconstructed trends in what has constituted the 'outside' environment, what scales of influence are assigned to them, and the relative strength of their power to effect deterministic outcomes (Table 1). Since the early 20th century, scale and causality have been reconceived in the language of possibilism, systems thought, behavioralism, structuralism and the posthuman integrative human ecologies. Each of these remediations aimed to characterize how different types of environments – households, society, as well as the abiotic – can shape and be shaped by humans. Each remediation of environmental causality was a reworking of geography's ongoing conversation about scale and causality – but conducted at a distance from biological thought and its ongoing interpretation of a more direct interaction between organisms and their environment.

Of late however, these seemingly discrete environmental influences have been deconstructed by geographers to reveal the multiplicity of scales and dynamics that influence them. Neither human environments labeled as households, society, or culture nor the abiotic environment can be resolutely confined to a specific position on a spectrum of scales from local to global. It has been recognized that the term 'scale' and the meanings it frequently and often uncritically elicits falls short of capturing the range of causal relatedness (Marston et al., 2005). Thus there exists a tension between a fixed assignment of a scalar attribute like global and local to an environment with the realization that human as well as natural environments are a mashup of variously scaled influences and spatialities (Leitner et al., 2008; Jessop et al., 2008). Spatialities comprise a larger category of representational forms of which scale is just one. Networks, rhizomes, mobilities as well as flat ontologies and ascalarity have evolved in response to criticisms of the more traditional usages of the term 'scale'.

Nonetheless, geographers continue to rely upon scale to describe, explain, and for some, to predict. From the production and consumption of scale to Tobler's law and hierarchy theory, geographer's invoke scale in the general sense of the word to elicit understanding of causal or correlative relationships in a spatial context. The resolution of data or information (i.e. its grain, detail, or specificity) as well as its spatial and temporal extent help us to draw boundaries between causal knowledge and uncertainty. Other geographers eschew this Cartesian formalism and associate

Table 1

Remediations of human–environmental causality in geography. Adapted from Judkins et al. (2008). The goal is the same in each remediation – to explain how humans shape and are shaped by their environment. 'Environment' can be the household, the society, as well as the ambient biotic and abiotic conditions and resources. Whether these loci for characterizing environment are assigned a weak to strong deterministic influence also varies in each remediation. New loci are chosen in order to include other phenomena and scales at which determinism is hypothesized to originate.

Remediations of human–environment interaction	Scale and relative strength of determinism		
	Weaker	Intermediate	Stronger
Environmental determinism (Semple, 1911; Huntington, 1915)	Household and society		Environment
Cultural possibilism (Sauer, 1925, 1941)	Environment	Household	Society and culture
Systems (Butzer, 1990; Denevan, 1992)	Society	Environment and household	
Behavioralism (Vayda and McCay, 1975; Brookfield, 1964)	Environment	Society	Individuals, small groups
Structuralism (Peet and Watts, 2004; Blaikie and Brookfield, 1987)	Environment and households	Institutions, governments, and policies	
Integrative human ecologies (Zimmerer, 1994; Zimmerer and Bassett, 2003)	Environment and ecological interactions	Household and societies	
Neo-environmental determinism (Diamond, 1997)	Household	Society	Environment

causality to the environment in a more distributed fashion. Although I recognize that scale is ultimately a fallibilist methodology, a piecewise approximation of reality, it has a longstanding place in geography as a causal trope even if it is now considered one of several different spatialities. In the next section, I formally distill how geographers have used scale to conceptualize environmental causality. I build a generalizable framework for scale originating out of epistemology and ontology, two practices that translate across biological platforms. As I eventually argue, partisanship in geography about the nature and meaning of scale and environmental causality has overlooked biological perspectives and the conciliatory positions they present.

3. The moments of scale

“Let us keep what is allowed in the structures embedded in our chosen observational framework separate from what is possible in the undefined world of continuously scaled fluxes.” (Allen and Hoekstra, 1990, p. 11).

In response to the accumulating diversity of scales over which human–environment causality has been remediated, geographers have undertaken an intensive theorization of scale in the last three decades. The scalar causal logics of geographers can be generalized as two strategies (Sayre, 2005; Manson, 2008; Moore, 2008; Herod, 2010). Scale is a practice inherent to observation. What can or cannot be claimed as causally related is a function of scalar extent and resolution. This is the epistemological moment of scale. Our circumscription of causality resides in the scales at which we perceive, delineate, and define a world apart from us. What we can claim to know – our epistemology – arises from the extent and resolution, or grain, of our observations. But scale is also an outcome of complex interactions within and among social and natural processes. Scales are constructed intentionally and unintentionally. This scaling produces outcomes, categories, and boundaries. The interactions of the entities we observe create their scaling and influence attribution of causality. This is the ontological moment of scale.

Preference for one over the other of these moments broadly, but not without exception, demarcates the fuzzy boundary between human and physical geography. It also shapes how each subdiscipline weights the determinism and contingency embedded in environmental influences. In the practice of physical geography, a Cartesian conception of scale is often employed. Observational scales of time and space influence whether causality can be attributed to deterministic or contingent sources. Hierarchy theory, for example, divides processes into levels of different scalar extents and speeds. Causality emerges from interactions among adjacent levels. Scale in this sense reflects its epistemological moment because the obligatory choice of observational and analytical grain and extent determines what one sees. Scale becomes part of the context within which an explanation is verified or rejected. Space is a container for the processes and is itself devoid of causality (Rhoads, 1999; McMaster and Sheppard, 2004). Consequently, causal reasoning – the attribution of determinism or contingency – changes with spatial and temporal scales of observation (Schumm and Lichty, 1965).

As an example, geomorphic processes operating over small spatial extents have often been aligned with deterministic properties (Spedding, 1997). Descriptions are statistical and the processes are stochastic at these small scales, but classical mechanistic deterministic theories hold. At the larger spatiotemporal scales of landscapes, contingency predominates. Timeless deterministic processes such as sediment transport give way to the idiographic and contingent characteristics of landforms (Baker and Twidale, 1991; Harrison, 2001). Contingency is the consequence of the

imperceptibility of initial conditions. In climatology, the epistemological moment of scale has a similar prominence (Phillips, 2001; Vale, 2003). Fundamental physical processes have a deterministic basis, but are deployed in a probabilistic, or “synoptic” understanding of the contingent, regional differences in how these processes play out. For instance, the local microphysics of how water droplets coalesce to form raindrops are relatively deterministic. Broader factors like time of year and location relative to mountains or oceans are the contingent constraint on the distributional patterns of rainfall.

For biogeographers, deterministic and contingent interpretations of nature have also been based on an epistemology derived from the scales of observation (Vale, 1988, 2003). Yet in contrast to geomorphology and climatology, scaling relationships tend to be inverted. Large spatial and temporal scales in biogeography are linked to deterministic processes. Contingency is best understood through small-scale studies that capture the historical and the idiographic. Determinism in biogeography appears at larger spatial and temporal scales as a perceptual smoothing analogous to cartographic generalization.

The epistemological moment of scale can also be defined as the level of detail compiled from cumulative analyses (Vale, 1988; Simandan, 2010). More detail can make an occurrence more unlikely or improbable. The scalar grain or resolution of detail incorporated into a description can shift perception of a deterministic, predictable outcome to one that is idiosyncratic and contingent. Contingency becomes a consequence of having more cognitive resources and more knowledge. The technological feasibility to ascertain initial conditions delineates the deterministic and the contingent. Pascual (2005, p. 104) invoked the mathematician Poincaré to illustrate the evolutionary dynamic embedded in the observer-centric epistemological scalar moment: “As our means of investigation became more and more incisive, we would discover the simple under the complex, then the complex under the simple, then again the simple under the complex, and so on, without being able to predict which state would ultimately prevail”.

Human geographers more frequently acknowledge that scales and scaling are constructed not only by observers, but also by the agents under study. This constructivist approach reflects the ontological moment of scale. It asks how particular scales come into existence for phenomena, and how their relative importance changes over time (Sheppard and McMaster, 2004). Space and time are not static containers for material objects. They are ‘dynamic process manifolds’ (Rhoads, 2006, p. 22) that incorporate the interaction of determinism and contingency. Scales and scaling are generated by the behavior of the phenomena. The unfolding of spatiotemporal processes generates ontology and the attribution of causality to determinism or contingency (Massey, 2005). Contingency arises because of the multiplicity of interactions instead of the limits to ascertaining initial conditions. Scale also becomes an ontological category we can use, refine, or reject. This processual view of causality is akin to self-organization, a term originally coined by Kant to describe organisms (Fox-Keller, 2005; Chapura, 2009).

To effect this scalar logic, human geographers have critiqued dichotomies such as determinism–contingency. They have sought to break down binaries and conjoin them into fields of interaction (Cloke and Johnston, 2005). The networks and hybridity of human geography are attempts to move away from the rigidity of imposing fixed scales of observation and toward something more fluid and responsive to the embodied context of scale and causality (Whatmore, 2002; Robbins, 2003; Latour, 2005; Gandy, 2008). Determinism and contingency do not reside at any particular scale. Instead, they are developmentally intertwined and propagate across scales. For example, structure and determinism are often simplistically assumed to correlate with global processes while

contingency and its enactment, agency, are paired to local processes. However, there is no clean scalar dichotomy of causation (Bendix, 1994; Swyngedouw, 1997a; O'Sullivan, 2004; Chowdhury and Turner, 2006). Agents at the local scale may “jump” to global scales and subsequently rearrange or overthrow structural controls. Scales can be “bent” so that agency can move from one scale to another. Fixed hierarchically-nested scales imposed by observers are not necessarily an effective means to conceptualize causality (Marston et al., 2005).

Why do these moments of scale exist? What motivates their differences? What is the foundation for this duality of scalar moments beyond explanations that foreground methodological fashion, tradition, and positions taken in the interest of academic identity and success? I posit that it is conceptually easier to cleave determinism and contingency when biological agency is taken for granted. In these instances, epistemological moments of scale are more readily adopted. Observers choose to delimit determinism and contingency based on scalar extent and resolution. Subdisciplines of geography that work with organisms – plants and animals as well as humans – find attribution of causation messier, convoluted, and contradictory. Here, the ontological moment of scale gains favor. Determinism and contingency intertwine and arise out of path-dependent and organism-specific contexts. Consider that only human geography and biogeography invoke contingency within smaller spatiotemporal scales where organismal agency more visibly resides. Although not entirely excluded from organismal agency, these same local scales in climatology and geomorphology are ascribed a physical determinism based on the resolving power of technology. For biogeography and human geography, what is deterministic and what is contingent become more challenging to segregate because organisms have a propensity to organize independent of humans and their invention of scale. Organisms impose their own “entangled bank of action and reaction” (Darwin, 1859) upon our observational and analytical lens.

From this biological perspective both conceptions of scale are necessary. Organisms and their interaction with their environment give operational validity to each moment of scale. For example, defining determinism and contingency based on observer-defined scales can achieve a powerful generality for its practitioners. However, we inadvertently dichotomize determinism and contingency in a way that discourages us from working with both simultaneously. Systems of representation freeze the flow of experience and distort what they strive to represent (Harvey, 1991; Massey, 1999; Woodward et al., 2010). Space and time scales of observation constrain the structure and content of explanatory theories by controlling the resolution of information (Church, 1996). Yet life is impelled to scale the world as an epistemological strategy. Life must recognize and exclude extraneous influences that could inhibit the formulation of a reliable ontology of knowledge (Richards and Clifford, 2008). It is necessary at some point to cleave determinism and contingency based on observer-centric scales so organisms can make decisions about what is predictable and deterministic and what is not and to put such a generalization to use. The challenge in this is that the situatedness of organisms in time and space constrains their perception of what can be known. Organisms have a bounded rationality which changes due to cognitive limits, learning, and innovation. They search for scalar solutions to the paradox arising from the necessity of demarcating predictability amid the shifting boundaries of nature's own construction (Proctor, 2001; Valve, 2010).

I propose that this embodiment of scalar moments defines biological scaling, a third moment of scale. Biological scaling acknowledges the multidimensionality of scalar practices. Instead of negating any one type of scaling, it represents a synthesis of the scalar languages and logics across human and physical geography (Taylor, 1982; Smith, 1984; Brenner, 2001; Marston et al., 2005).

Certainly, the categorization of geographers and their scalar practices has exceptions. Physical geographers recognize that abiotic processes can also produce scales and boundaries (although the biotic may always be difficult to eliminate as a factor), and many human geographers rely upon scalar extent and grain to conceptualize causality. But what is more relevant is that biological scaling accommodates the range of viewpoints about scale in geography. Scaling provides an epistemology whose ontologic outcomes shape the pragmatic context of the organism. In other words, epistemology and ontology recursively influence one another. How the world is verified and observed – whether through the senses or indirectly through technology – contributes to the ontologies that become evident in it. As recognized by scholars in philosophy as well as GiScience, epistemology and ontology are developmentally co-constitutive (Schuurman, 2004; Couclelis, 2009). For organisms, the embodiment of both moments of scale in their interaction with the environment becomes the mental and material foundation for what can be very high-stakes assumptions about the predictability of their world and their adaptation to it.

In the next section, I communicate how two areas of recent life science scholarship – epigenetics and niche construction – illustrate biological scaling. They also bring to geography a new organism–environment, one in which Lamarckian inheritance has been reintroduced in a revised form (Gould, 1980; Archer, 1993; Jablonka and Lamb, 1995). Turner (2002, p. 67) observed that “[m]any geographers are probably unaware that elements of Lamarckian evolution have been demonstrated in the natural sciences over the past decade. . .”. Lamarckian organism–environment interactions have been described not only in biology (Jablonka and Lamb, 2006; Varmuza, 2003; Koonin and Wolf, 2009; Bonduriansky and Day, 2009) but also in anthropology (Balter, 2000; Jablonka and Lamb, 1995; Cochran and Harpending, 2009). These new developments may again prompt geographers to consider where and how the life sciences have relevance to their own scholarship (e.g. Whatmore, 1999).

4. The new organism–environment interaction

“New knowledge appears as a reconfiguration of how we conceive the world, rather than a change in the natural world itself.” (Sayre, 2005, p. 282).

4.1. Omics and the extended organism

To talk of genes is to invoke powerful metaphors about inevitability, reductionism, and an aspatial science. Yet over the past decade the singular determinism of the gene has been relinquished by molecular biologists. At the initiation of the Human Genome Project (HGP), it was anticipated that a map of the human genome would allow for a next generation of treatments for diseases with a genetic base. However, if the HGP is judged by this narrow promise alone, it has been a failure (Butler, 2010; Wade, 2010; Evans et al., 2011). Although such criticisms of the HGP are premature – mapping was completed over a decade ago and drug development can require 10–20 years – they allude to a more compelling intellectual development. The primacy of DNA sequence has been deconstructed, not by philosophers, but by biologists (Sarkar, 2005; Neumann-Held and Rehmann-Sutter, 2006; McCabe and McCabe, 2008; Fox Keller, 2010). All the very powerful molecular analysis methods developed for the HGP led to a shift in the perspective of how DNA works and how DNA is intertwined with the organism–environment interaction (Bertolaso et al., 2010).

In effect, the extent and grain of our evolving technologies revealed new uncertainties and ontological surprises within the

genome. The determinism and predictability assumed to originate from DNA sequence was found incomplete. The Central Dogma of DNA, where one gene codes a single protein that in turn can direct and regulate physiological processes, has been replaced by a view of DNA that foregrounds the role of space and place. This new spatial view recognizes a far greater role for the contingencies of the environment to modify DNA expression. Sequence alone is insufficient to account for the volume and detail of the highly complex information pertinent to the essential functioning of living organisms.

As one example, it is now widely acknowledged that environmental conditions can determine genetic expression and heredity without modifying DNA sequence. Epigenetics represents this new perspective. Epigenetics encompasses changes in phenotype caused by mechanisms that modify the activity of DNA but not the DNA sequence itself (Jablonka and Lamb, 1995; Bird, 2007; Bossdorf et al., 2008). Non-DNA biochemicals can interact with the three-dimensional charged surfaces of DNA to facilitate novel modes of transcription and heritability. These epigenetic markers can be contingent upon the environmental conditions interior to and surrounding an organism. If environmentally-induced epigenetic changes occur during crucial stages of life, they can potentially modify behavior, disease susceptibility, and survival (Jirtle and Skinner, 2007; Kaati et al., 2007; Miller, 2010). These epigenetic signals can be passed on from one generation to the next, sometimes for several generations, without changing gene sequence. Genes can thus be “followers” rather than initiators of evolution (Richards et al., 2010; Schwander and Leimar, 2011).

Epigenetics illustrates how the genome has not turned out to be a tidy collection of independent genes, with each gene linked to a single function. Instead, the determinism of a gene to create a specific outcome has been replaced by a field view whereby the developmental propensities of DNA contingently interact with its context (Fox Keller, 2010). Even with similar sequences, contingencies in the cellular and environmental context can result in contrasting phenotypes, the outward appearance of an organism. Ultimately, this introduces more degrees of freedom in the feedbacks and outcomes of the organism–environment interaction. Biologists are now undertaking a human epigenome project to follow up on the Human Genome Project’s discovery of greater environmental contingency to the expression of DNA sequence.

Other developments herald a similar recalibration of environmental causality. Scientists expected to find many more protein-coding genes than they actually did. Instead, long stretches of DNA appeared to not be directly involved in transcription and did not code proteins. These areas of the genome were initially labeled ‘junk’ DNA, the dark matter of the genome. However, more recent work has revealed that junk DNA can function as regulatory DNA. Proteins bind to this regulatory DNA, and control the way

nearby DNA is transcribed into RNA and made into proteins. Elements of the gene are also mobile (‘jumping genes’), further complicating the blueprint analogy for how DNA codes for proteins. Thus, DNA does not synthesize proteins in response to a central on–off switch. Instead, protein synthesis is initiated when different sets of genes are turned on or off in different kinds of cells at different times through gene networks. Then for proteins to become functional, they fold and take shapes that confer activity. No centralized cellular mechanism guides folding. Rather, the subtle chemical push and pull between constituent amino acids self-assembles proteins into their three-dimensional shapes. Positionality matters. Proteins can interact with each other, and small local changes in their shape can greatly modify their function. Consequently, knowing the DNA sequence that is translated into a protein does not provide the full information about the protein’s structure and functional activity in three-dimensional space. Another initiative, proteomics, is now required to characterize the environmental causality of the genome after its mapping in the Human Genome Project. Proteomics deploys an explicitly spatial perspective in its goal of mapping the structures of proteins and the diversity of their functions (Service, 2008).

Although there was an overt reductionist zeal leading into the HGP, the feasibility of its reach has been tempered by a realization of the scope of spatial and environmental influences in and surrounding the genome. Epigenetics, proteomics, and the other omics that accompany them (Table 2) convey how the observational scales where causality was formerly associated have been redrawn, thus complicating any assumption of causal closure being embedded entirely in DNA sequence. The omics illustrate how an organism emerges from the contingent interaction of DNA with the environment around it. Organisms may carry and even reinforce a particular set of omic influences around with them. These dynamics exemplify how the causality of molecular biology has aligned with geography. The landscapes of the cell have a contingent, generative potential (Misteli, 2009). Relationality and context matter. The genome is not held within a fixed container. Instead, it constructs itself outward and inward. There is a more recursive organism–environment interaction compared to the first wave of environmental determinism.

The narrative of the HGP illustrates how our epistemological scaling of the predictability in DNA has been overturned and realigned by the ontological capacities of the genome and its environment. When biologists describe the genotype–phenotype–environment linkage spanned by the omics, they are invoking a spatial dynamism that is geographical, perhaps more so in the tradition of recent human geographic scholarship on scale and environmental causality. An organism is an ongoing, contextual outcome of a causality that propagates among molecular, cellular, organismal, and environmental scales. Its interaction with the environment is

Table 2
The omics of the biological sciences.

Omic	Goal	Examples
Genomics	Sequencing of DNA	Human Genome Project
Epigenomics	Characterization of the heritable changes in the regulation of gene activity and expression independent of gene sequence	Human Epigenome Project
Transcriptomics	Characterization of variability in RNA messages translated from DNA and used by ribosomes to build proteins	Mammalian Gene Collection Project; Mouse Transcription Project; Cancer Genome Anatomy Project
Proteomics	Characterization of structure, function, and modification of proteins after construction by ribosomes	Human Proteome Initiative
Interactomics	Characterization of the network interactions of molecules in the cell	Human Interactome Map
Metabolomics	Characterization of the metabolites (end products) of cellular processes	Human Metabolome Project
Microbiomics	Characterization of human microbial communities	International Human Microbiome Project
Phenomics	Characterization of the phenome, the different phenotypes expressed by organisms. Integrates genetic and environmental influences	Human Phenome Project; for overview see Houle (2010)
Exposomics	Tracking and identification of environmental exposures	For an introduction, see Borrell (2011)

Lamarckian in that causality is spatially distributed and heredity is not strictly genetic. The inheritance of environmental effects can be induced not only by conditions internal and external to an organism, but also by the predictability in their larger environment as it can be shaped by the organisms within it.

4.2. Niche construction

Prediction is a predilection for life. In temporally and spatially varying conditions, organisms need to be able to smooth out the effect of the variation (Holling and Meffe, 1996; Kareiva et al., 2007; Mitchell et al., 2009; Yusoff, 2009). The relevant aspects of the environment must appear relatively constant – deterministic – to the organism's physiology, even though there are fluctuations in the external world (Lewontin, 2002; Inkpen and Wilson, 2004). To make wagers on what is predictable and what is less so, organisms, including humans, invoke pseudosystems, scales of observation that have no recognizable boundaries other than those imposed by the observer (Egner and Elverfeldt, 2009). Organisms rely upon their own scale-bound epistemological capacity, or bounded rationality (Bennett and Tang, 2006; Manson, 2006), to make inferences about what can and cannot be known within an open system (Farina and Belgrano, 2006).

For organisms, uncertainty is reduced by evolving features that allow a degree of control over the spatial and temporal environment (Krakauer et al., 2009). Microbes as well as humans impose modifications on the environment that promote stability relative to their life history traits (Fig. 1). They engineer their habitat as well as the habitat of others (Lawton, 1994; Wright and Jones, 2006; Hastings et al., 2007). Like epigenetics, niche construction reintroduces a Lamarckian view of causality. If the same environmental change is reimposed often by organisms and persists for a sufficient number of generations, the outcome is to canalize interactions between biota and their surroundings. By evolving features that increase the likelihood that these interactions persist, organisms can exert even greater coupling with their environment (Laland et al., 1999; Odling-Smee et al., 2003). Each individual repeatedly changes its own ontogenic environment in the same way because each individual inherits genes that express the same niche-constructing phenotypes. The environment around the organism and its biomodification – its extended phenotype – can be inherited (Dodge and Kitchin, 2005; Corenblit et al., 2008; Phillips, 2009a). Niche construction has affinities to human geography's concern over how individual agency constructs and reproduces (as well as resists and is subverted by) larger structural contexts, which may be political, social, or economic. In this way, organisms, not just humans, are active participants in the production and construction of space and scale (e.g. Smith, 1984; Marston, 2000).

Niche construction is deterministic but unfolds contingently. Determinism is the propensity to ascertain what is predictable in the immediate environment and to modify the environment and other organisms so as to promote this predictability. Contingent is how these deterministic interactions play out for the niche-constructing organism as well as for other life forms entrained in this dynamic. Organisms are not devoid of agency and haplessly tethered to environmental vagaries. Nor are their niche-constructing propensities always adaptive in the long term. In addition, the domain or field of a niche-constructing organism includes not only the spatial configuration of an organism's surroundings, but also the external and internal signals that pass across it (Farina and Belgrano, 2006; Szerszynski, 2010). Niche construction is Lamarckian in that organisms have the propensity to pass these relationships on generationally, especially where the outcomes of this interactivity persist longer than the lifespan of individual organisms.



Fig. 1. Human and non-human ecosystem engineers modify the environment in similar ways to promote predictability. Pre-Columbian farmers on the Guiana coast of South America maintained raised fields to alleviate wet soil conditions (top photo, wet season; second from top, dry season). Since their abandonment, other ecosystem engineers in the form of earthworms (earthworm casings, third photo from top), ants (bottom photo) as well as termites and plants have maintained the microtopographic structure of these human effects as well as the heterogeneity of human-concentrated resources (McKey et al., 2010). As these habitat-modifying processes are passed on generationally, niche construction becomes a mechanism of evolution. Photo courtesy of Dr. Doyle McKey, University of Montpellier, Department of Population Biology.

The omics and niche construction are just two concepts that convey how the organism–environment interaction has been re-worked over the past several decades in the life sciences. Other areas of inquiry are undergoing a similar revisioning. Anthropologists now recognize a neo-Lamarckian component underlying gene–culture evolution (Hayden, 2009; Laland et al., 2010; Richerson et al., 2010). Evolutionary theory is moving away from the gene-centered Modern Synthesis (Huxley, 1942) and toward the more spatial Extended Synthesis of evolution (Whitfield, 2008; Pigliucci and Müller, 2009). The field of ecological complexity has also recognized the propensity for the inheritance of organism–environment interactions. (Chapin et al., 1997; Levin, 1999). Each of these invoke a newly spatialized relationship between organisms and their environment as well as a revised Lamarckian component of inheritance.

In sum, geographers might reflect upon how there is now a much deeper generative unpredictability to the organism–environment interaction originating out of the life science. Although molecules can have an element of self-assembly, epigenetics and the other omics introduce a more dynamic and greater range of potential outcomes and larger state space than what could be contained in a Cartesian view of DNA. At larger spatial extents where organisms and niche construction resolve there is more contingency and even greater degrees of freedom. Self assembly is replaced by self organization (Chu et al., 2003; Halley and Winkler, 2008a,b). Strong emergence arises in cultures and ecosystems, where patterns are even less amenable to reductionist explanation (Delehanaty, 2005). This dynamic, constructivist potential of inhabited space runs counter to the rigidity in process and outcome that characterized the evolution-inspired environmental determinism coinciding with North American geography's entry into the academy.

5. Fusing the biological and the geographical

In this section, I distill how biological scaling and the new organism–environment interaction exemplified in recent life science scholarship might inform geography. Yet for some geographers, a legacy of nature skepticism and the distrust of grand metanarratives have withered any desire to filter geography through biology. But to discuss biological capacities and attributes does not automatically imply a crude reductionism or inflexible causal determinism. Biological ideas are not inherently conservative or discriminatory in a moral-political sense, and they can provide philosophical advances as well as practical demonstrations of phenomena and their organization (Clifford, 2008; Gandy, 2008; Castree, 2009b). The precepts below hopefully assuage any fears of a resurgent, totalizing neo-environmental determinism. Bringing biology into geography, not as a dominating, fashionable meta-narrative, but as another locally coexisting epistemology, would enhance the pluralistic vibrancy of intellectual geography. As Castree remarked in a recent essay (2009a), Darwin's ideas can be used as a heuristic device, a hook “upon which we could readily hang some of our own arguments and research findings”, so that we might participate in broader conversations about life.

5.1. Organisms practice an epistemological moments of scale to ascertain local predictability

Life is dependent upon determinism. Life must cleave signal from noise, determinism from contingency, in order to search for the solutions that lead to identity and survival. Whether phenomena are deterministic or contingent depends upon the scales detected, analyzed and communicated by an observer, human or non-human (Platt, 1948). Evolutionary change can tune scalar epistemologies to allow determinism to emerge and contingency

to fade. Technology and culture can function as lens that also shape epistemological assumptions about causality. The tools used to discern the scales over which local predictability can be perceived may be thumbs, mandibles, or neurons. They can also be microscopes, computers, maps, or language. The narrative of the genomic revolution, for example, conveys how technological change shifted our epistemologies about the genome from one that expected determinism and predictability, to one that recognized much more contingency and open-endedness. The resolution of information, whether it is solely biological or coupled to bodies via technologies, is a scaled observation. In niche construction, organism practice an epistemological scaling to secure predictability. They perform their evolutionary technologies to sense and to reinforce the configuration of the environment around them.

But tools and culture do not always open up a wider range of phenomena to causal classification. Through power or tradition, boundaries can be imposed that coerce or obscure epistemologies and thus constrain the perception of any scalar determinism and contingency. Predictability can be socially constructed. The quality of being predictable does not imply a universal trueness, only that it has local value in a particular context for a given organism. Organisms also differ in their awareness of and responses to ambiguity in knowledge and the certainty of causality. Humans, for example, have constructed elaborate social and economic systems for working with and manipulating such uncertainties, for better and for worse (Yusoff, 2009).

5.2. The ontological moment of scale fosters unpredictable but generative aspects to the interaction of organisms and environment

Biological causality does not reside only with the observer. One's observational frame intersects with what is possible amid organizational flux and adaptation. Organisms have a distributed causality of shifting ultimate and proximate influences. Their entanglements multiply the sources and attributes of causality, even in abiotic systems (Phillips, 1995). Organisms can also jump and rearrange scales. They can reshuffle into spatial ‘fixes’ (Harvey, 2001) to solve local crises. By valuing scale solely as an epistemological lens, we overlook the dynamics of systems to organize and surprise, to conform to our perceptions or to exceed them. “The world is no longer a causal machine – it can now be seen as a world of propensities, as an unfolding process of realizing possibilities and of unfolding of new possibilities” (Popper, 1997, p. 18). Biological scaling in this sense is a performative geography. Boundaries change and so do the entities that are defined by them.

The omics arose out of the recognition that our ontology to describe the structures and processes that demarcate the boundaries among genes, organisms, and environment was insufficient. The ontological capacities of the genome were far more generative than originally anticipated. Similarly, niche construction does not play out in a tidy ontological manner. Niche construction unfolds simultaneously among multiple organisms. The potential entrainment and inheritance of an environment can become a source of new interactions, adaptation, and unexpected outcomes. Instead of a predictable unreality, there is more of an unpredictable reality. Laws operate in the domains of genes through ecosystems, but behavior cannot be entirely predicted. This structured unpredictability, or deterministic uncertainty, is a source of novelty. Through niche construction and the genotype-to-phenotype linkages spanned by the omics, organisms can be thought of as diversity roulettes or Darwinian machines that deterministically generate novelty (Plotkin, 1997; Pave, 2007). Prigogine (1997, p. 72), as quoted in Massey (1999, p. 33) observed that “[n]ature is indeed related to the creation of unpredictable novelty, where the possible is richer than the real”. Other geographers have articulated similar ideas although for the most part they have been human geogra-

phers (Thrift, 1999; Clark, 2005; Marston et al., 2005; but see Rhoads, 2006).

Yet this is not to suppose that the outcomes of an organism's interaction with the environment will always be optimizing. And just because an organism's interaction with the environment can become entrained and foster Lamarckian mechanisms of organism–environment inheritance does not mean it is adaptive in the long run. For example, the observational scales that define global climate modeling and the communication of climate change are reproduced and canalized through a network of individuals, institutions, and economies (Demeritt, 2001; O'Keefe et al., 2010). Their configuration thwarts evolution of a forceful, yet equitable human response attuned to local context. From a biological standpoint, human niche construction and an epistemological scalar rigidity can foster behaviors at odds with the diversity of human as well as non-human ontological discrepancies emerging out of the biosphere.

5.3. Environmental determinism in the context of organisms is not an inviolable force but a propensity for a range of outcomes

Life is performative and capable of generating novelty. However, predictability and boundaries are fundamental for life. In the organism–environment interaction epistemological scaling provides the orderliness of boundaries to allow memory and stability to persist. Ontological scaling contributes the looseness and flexibility to allow exploration, invention, and self-organizing propensities. Thus deterministic relationships must be realized from an organismal point of view amid the flux from which organisms evolved. Final reconciliation between these two worlds lies in conceiving an intermediate to contingency and determinism. Biologists, ecologists, and some geographers have proposed a generalization of the Newtonian idea of a force to describe biological determinism (Popper, 1997; Ulanowicz, 1997; Warf, 2009). Forces are idealizations and exist only in isolation. A propensity is the tendency for a certain event to occur in a particular context. Propensities are similar to the concept of probabilism, except here it has been elucidated from biological ideas.

Propensities are a form of teleology which is phenomenological. They are anchored in the senses and cultures of organisms. The concept of *teleonomy* is used in biology to denote this biologically-based behavior. Teleonomy is a pragmatic enterprise. It is self-constituting, adaptable within bounds, yet not gifted with an omniscient foresight of future outcomes to guide the present. For any organism, closing the gap between epistemological and ontological moments of scales would indeed be a strategic adaptation, a way of narrowing the distance between representation and reality. However, organisms require this gap out of a necessity for maintaining adaptive capacities (Allen and Holling, 2010). Any papering over of biological causation with formal probability theory is tenuous (Ulanowicz, 2009a). Following human geography's call for relinquishing fixed conceptual categories of scale, the

dialectical relationship between epistemology and ontology in biological scaling insures that the association of causality with a specific scale or spatiality will vary across time, space, and from organism to organism. No matter what name we attach to it, scaling cannot be fixed or done away with because it is inherently a biological activity.

5.4. Biological scaling has relevance to geographic thought and methods

Ties can be made to quantitative geography as well as qualitative geography. In an intermediate position between determinism and contingency there is a radius of effect that implies the processes of nature have local manifestations (Phillips, 2004). This should sound familiar to quantitative geographers as an extension of Tobler's law. In the context of biological scaling, that near things in space are more related than things at a distance reflects a Lamarckian organism–environment causality. Organisms are locally intersecting realizations of their scalar moments within a heterogeneous environment. There emerges from this dynamic a range in time and space over which the constitutive feedbacks between organism and environment may propagate or be inherited. Autocorrelation, the way in which these relationships and their patterns repeat themselves locally, is an outcome of biological scaling. It is not just a statistical artifact to be removed. In this sense, biological scaling may have facets that can be visualized (Simonsen, 2004). Geographers, ecologists, and physical scientists have already proposed a variety of topological perspectives that capture aspects of biological scaling across different contexts (Table 3). Some of these topologies are solely conceptual. Others are more mathematically defined. However, they each fuse absolute and relative distances. Scales and spatialities cross and fold in on one another. Autocorrelation can be local, but the relationships that cause it can reappear at different, more distant locations. Within these dynamics there is a persistence, or 'stickiness' to the organism–environment interaction that in turn shapes the predictability for its expression.

For more qualitative geographies, biological scaling provides a conciliatory point of view on the scale debates and their sometimes competing spatialities. For example, I used the term 'scale' in this paper in reference to its more traditional geographic meaning. This was in part out of a need for clarity. A fixed definition offers more interpretative predictability. I also relied upon its traditional meaning because this conception of scale captures the way many geographers think. In many a tool box, scale and scaling denote the demarcation of levels or boundaries that may originate from an outside observer or from the interactions of entities themselves. Yet my reliance upon traditional scale does not necessarily exclude or overlook the full range of spatialities operative in the organism–environment relationship. Indeed, scalar moments and biological scaling for any organism are more realistically an amalgam of spatialities drawing from evolutionary and ecological phenomena.

Table 3

Material outcomes of biological scaling amenable to mapping. These 'lumpy' assemblages have a propensity to persist through time and space. Yet they are also malleable, adaptive, capable of reconfiguration through transitory or oscillatory dynamics.

Organism–environment ontologies	
Assemblages and new materialist taxonomies of causality	DeLanda (2006) and Robbins and Marks (2009)
Emergence, phase space, ontological sites, and non-essentializing scalar causality	Marston et al. (2005), Jones (2009) and Woodward et al. (2010)
Centripetal activity in biological and ecological interactions	Ulanowicz (1997, 2009a,b)
Textural discontinuities, lumpiness in organisms and environment due to cross-scale interactions	Holling (1992), Allen and Holling (2002) and Allen (2006)
Stability domains and topographies of resiliency in coupled human–natural systems	Peterson et al. (1998) and Gunderson (2000)
Modularity and self-organization in complex adaptive systems	Levin (1999, 2005) and Malanson (1999)
State space and structural geographies of biological evolution	Smith (1989, 2005)
Ecological and bioinformatic topologies	Kemp and Tenenbaum (2008) and Prager and Reiners (2009)
Thresholds, regime shifts, and hysteresis geometries	Vale (1982), Scheffer et al. (2001) and Scheffer (2009)

One might consider the omics as the different spatialities of the genome. Networks, positionality, and mobilities are operative in cells to ecosystems. Spatialities, and not just scale, are representational tools that conjoin the biological and the human as well as human and physical geographers. My reliance on the common usage of scale was an epistemological choice to maintain coherence, and to avoid a multiplicity of ontological description that might obscure my arguments.

6. Toward a material, evolutionary geography?

To an extent, worries over a biologicalization of geographic concepts like scale may be a bit late. The outlines of biological scaling and a more distributed organism–environment interaction are already found in geographic scholarship. We have not yet turned entirely away from trying to articulate an environmental causality that distances itself from the past yet still retains a biological component. I would even argue that this biological turn has been underway for a decade or more. Physical geographers are (again) recognizing that organisms complicate environmental causality (Naylor et al., 2002; Stallins, 2006; Phillips, 2009b). But the richer analogues for biological scaling and the new organism–environment interaction are best exemplified in the work of posthumanist geographers. In posthumanism, the identities of people and organisms are co-constitutive. The human is “...an effect of ongoing and ceaseless ontological play” (Castree et al., 2004, p. 1354; Latour, 2005). Posthumanist geographers foreground the distributed nature of environmental causality. They are skeptical about inflexible interpretations of where causality in human–environment systems is embedded. The social and the material become blurred. Posthumanism seeks to bring coherency in a world where causation is more distributed and without clear boundaries (Hayles, 1999; Haraway, 1990, 2008; Parisi, 2007; Hird, 2009, 2010).

In reaction to posthumanism, geographers began to consider non-human organisms in and of themselves. A fascination with humans and a propensity to refract our thoughts about the non-human around our identity is certainly useful (Wolch and Emel, 1998). But as Sarah Whatmore advised in Castree et al. (2004, p. 1362), an untapped resource are the “...the biophilosophies that place earth life rather than human being at their centre”. Perhaps the anthropocentrism of posthumanism was to a degree evolutionarily unavoidable. But it made visible that scale and environmental causality have been theorized almost entirely from the perspective that they are uniquely human practices. Furthermore, the ontological and epistemological moments for delineating scalar causality were often collapsed in posthumanism (Sayre, 2005). This typically resulted in a hyperconstructivist world in which the need for the perception of predictability was absorbed into a world of continual flows and frictionless circulations (Woodward et al., 2010). Any lumpiness or stickiness arising from interactions to promote persistence in the organism–environment interaction was downplayed. By completely dissolving the boundaries of humans, posthumanism inadvertently diminished our shared propensity with life to make gestures toward predictability and to organize into locally persistent yet finite material assemblages.

Many of the same geographers who defined as well as critiqued posthumanism have also contributed to a resurgent materialism in human geography. This new materialist turn (Whatmore, 2006; Robbins and Marks, 2009; Shaw et al., 2010) is perhaps where biological scaling and the new organism–environment causality may be most likely to continue to flourish. New materialism puts non-humans on the stage with humans in a form of ‘critical animism’. Like the posthumanists, new materialists also aim to map the distributed nature of causality. But instead of denaturalizing

the interactions of organisms and their environment, they are given more grounded instantiations that do not derive exclusively from an abstracted, universalizing social knowledge. Subjectivity, representation, and reality share the same evolutionary context. New materialism valorizes the deterministic propensities that create local boundaries and impart a degree of persistence to the assemblages they demarcate (Woodward et al., 2010).

New materialism also places more emphasis on the concept of scalecraft. As it pertains to humans, scalecraft was originally defined as the practices to implement processes by which “...individuals, social groups, or governing bodies produce and use scale to create advantage, to establish associations, connections, or solidarities across social divides and to represent their interests amidst oppressive or difficult conditions” (Fraser, 2010, p. 332). However, by their aliveness, all organisms practice scalecraft. They scale and respond to the rescaling of the world by other life forms in order to create their own associations, connections, and solidarities. Scale is not just a heuristic device for humans. Scalecraft is an imperative of biological agency and adaptation (Head, 2010).

Yet to lump humans and other organisms together to understand scale and environmental interactions is not to demote human uniqueness. Much of the geographic scholarship rightly recognizes that there are distinctive, even perverse human tempos and intensities of our irreparable interactions with the non-human world. We have an intractably self-conscious intellect, hyperevolving technologies, and a vast array of potentially malleable social, cultural and institutional arrangements. Geographers have rigorously described how humans and their coupling with the environment are shaped by these factors. But to assume that we are so separate as to withhold a biological lens to these interactions, to restrain thinking about the metaphorical and material commonalities humans have with life, is to be trapped by the idea that our uniqueness alone defines the parameters by which we judge our place.

What does the human share with non-human life? All life depends upon biological information encoded in the nucleic acids that comprise DNA. All living things respond to their environment. Living things acquire material and energy. Selection is a substrate neutral principle that can explain the continuing-change characteristic of living systems. If the nature–culture debates of a couple of decades can provide any compromise, it is that humans are both separate from and part of their environment. Within this paradox, we practice the epistemological moment of scale to affect predictability and to promote it in the environment. Simultaneously, other organisms are embedded in a world that scales itself. Scale, as a broadly conceived performance with the environment, is something we also share with non-humans organisms.

But if we grant our commonalities with other life forms permission to reenter geography, what does it mean for human–environment geography? Where and to what extent do the new organism–environment interaction and biological scaling dovetail with the socio-cultural influences and environmental feedbacks commonly cited as driving the majority of human–environment interactions? First of all, it would be unreasonable to assume a tit-for-tat replacement of the current human–environment interaction paradigm with an evolutionary, biological one. There is too much illuminating, dextrous scholarship in political ecology, land change science, and in critical geography to imagine it could or even ever should be distilled into evolutionary or sociobiological principles. Nonetheless, the ideas in this paper that define a new organism–environment interaction – Lamarckian modes of inheritance, omic modifications of DNA, and niche construction – are emerging in several areas of scholarship in which human–environment geographers participate.

Geographers as well as anthropologists and biologists now recognize that there is an interactive capacity of culture, adaptation, and evolution that far exceeds any one-way influence of

environment. Knowledge is not incidental, but is involved in society whether it is human or non-human society. Knowledge can be passed on through culture as social learning as well as behavioral inheritance systems like software, books, data, and oral traditions (de Waal, 2001; Thrift and French, 2002; Dodge and Kitchin, 2005). Human uniqueness is now thought to be more dependent on inter-generational cultural transfer than conventional Darwinian selection processes. These transferences are identified as Lamarckian in that some heritable, adaptive changes come not from natural selection, but from the actions of internal systems conditioned to generate non-random guesses in response to environmental situations (Boyd and Richerson, 2005; Kronfeldner, 2007; Varki et al., 2008).

Recent empirical evidence corroborates this dynamic. During the Neolithic Revolution, human groups organized into larger social groups and became distanced from direct exposure to the nature that preceded this transition. Genetic evidence indicates that selective human evolution began to speed up rather than slow down at this point in time, approximately 10,000 years ago (Hawks et al., 2007; Richerson et al., 2010). Cultural context now appears to be as relevant for the expression of natural selection as an undomesticated nature (Williamson et al., 2007; Hawks et al., 2007). Our vastly humanized environments have an evolutionary component, perhaps even a stronger one, now that culture has emerged.

Other examples of the new organism–environment interaction also have relevance for a wide range of human geography. Social networks have been shown to transmit or increase the probability of certain health-related behaviors, like diet, exercise, and smoking (Christakis and Fowler, 2007). Health scholars now speak of the “diseaseome”, the interacting networks of genetic, cellular, and social interactions implicated in disease. Genetic studies of people conceived during famines reveals that the effects can be passed on generationally. The children of mothers who were food limited during the Dutch winter of 1944 and the Great Chinese Famine of the late 1960s had epigenetic ‘tags’ that altered gene expression and increased the incidence of obesity and schizophrenia (Ahmed, 2010). In the field of behavioral epigenetics, biologists and social scientists explore how modes of living, from raising children, exposure to stress, and the proximity of acute poverty can alter DNA expression and health outcomes (Miller, 2010; Powlledge, 2011).

Rightly so, there are moral and ethical questions being raised about the suppositions underlying these studies. But just as important, there should be questions raised about any findings. What if

the culture of poverty plays into the activation of epigenetic mechanisms that can influence the health potentials of subsequent generations (Miller, 2010; Cohen, 2007)? What if the emergence of transitions like the Industrial Revolution were preceded by an evolutionary-genetic component (Clark, 2007)? If our genome is far more sensitive to our cultural environments of working and living, should geographers be interested? Although it is not expected that geographers learn genetic sequencing to participate, how might we contribute to these scholarly dialogues? What remains to be seen is the extent geographers can be receptive to ideas that stir up old insecurities about using biological concepts, and how they can be reimagined and remade to inform major questions in human–environment geography.

7. Closing

Scale has had a long history of migrating back and forth between geography and the life sciences (Meetmeyer, 1989; Wiens et al., 2006). Now, even our posthuman philosophies and the spatialities of critical geography are being recognized in biology. The distributed causality of actor network theory has been suggested as a means to characterize ecosystems, whose malleable boundaries challenge materialist claims of their existence (Schizas and Stamou, 2010). The intricate, contextual linkages among the ways to define a species – one can use morphology, reproductive viability, genetics, geographic location – is indeed as topologically complex as Deleuze and Guattari’s (1987) rhizomatous taxonomy of life. Epigenetics and niche construction argue for distributed definitions for the gene (Hopkin, 2009; Pigliucci and Müller, 2009) similar to ones drawn from social theory, where the networks and assemblages of objects, people, and scientific practices shape identity. These cross-fertilizations illustrate how geography has a timely opportunity to benefit from a deeper interdisciplinarity with the life sciences (e.g. Baerwald, 2010) and to advertise and export our sophisticated understanding of scale and spatialities to more encompassing biophilosophies.

To move in this direction, I have defined a biological scaling for geography and described the new organism–environment causality embedded in it (Table 4). Biological scaling is anchored in a pluralistic view of scale. Organisms illustrate the necessary fusion of epistemological and ontological moments of scale. Life is impelled to scale the world in a Cartesian sense as a strategy for reducing uncertainty. Yet life also manipulates, reworks, and reconfigures

Table 4
The new organism–environment causality and a comparison to its older biological counterpart.

Property	Causality early 20th century environmental determinism	New biological causality of the early 21st century
Scaling	Ascalar, unidirectional	Multiple dimensions of scale; biological and dialectical
Mode of expression	Force	Propensity
Influence on explanation and inquiry	Brought causal closure, finality of mechanism	Necessitates causal openness
Nature of the environment	Climatic, abiotic, fixed, external to organisms	Includes cultural, biotic and abiotic feedbacks; external and internal to organism
Ontological form and their boundaries	Well-defined	Boundaries less apparent and not fixed
Epistemological agency	Observer only	Relative to organism and observer
Superorganismal properties	Present	Absent
Teleology	Master plan, predestination	Self-assembly and self-organization
Causality	Fixed	Open-ended, generates novelty yet contained with phase space of possibilities
Inheritance	No mechanism detailed	Postgenomic, neo-Lamarckian
Role of space	Passive, container	Constructivist, yet also necessarily passive
Locus of mechanism	Organism	Molecular through cultural
Boundaries between environment and interacting entities	Drawn by observer	Self-demarcated by entities and drawn by observer
Potential for critical reflection and an evolutionary geography	Low, closed to argument	High, promotes critical thought

scale – intentionally and unintentionally – to make what defines our ontologies and the causality behind them unpredictable but also more generative. Insofar as there are deterministic relationships associated with biological scaling, they are more of a propensity than an inviolable force. Life participates in a boundary conflict. It pits the necessity of shaping a local world to have stable borders and horizons against a necessity for scalar instability and ontological uncertainty as a means to retain adaptive capacity.

In this way, the scalar practices of organisms are a biological expression of the modifiable areal unit problem. Scale, boundaries, and their ongoing negotiation could be considered a defining feature of life. Organisms remake boundaries to promote and inherit their own version of stability and predictability. Yet other organisms are also involved in this same game and seek to reconfigure these boundaries. The century long and still unfinished debate in ecology over the niche concept conveys this transitional nature of organisms and boundaries. As a caveat though, this biocentric reinscription of the modifiable areal unit problem does not rely upon a territorial or planar 'scale' to denote boundaries. Boundaries can be networks, as in those that link parent to offspring. There are also the networks that link phylogeographic relatedness through evolutionary time. The metapopulation and metacommunity concepts from ecology capture how organisms are linked across islands of unsuitable habitat, with dispersal leapfrogging back and forth across. Thus organisms perform and negotiate for predictability within a very heterogeneously defined concept of scale, one that is more akin to the diverse spatialities described by human geographers. Wimsatt (2007) refers to 'causal thicket', situations of disorder with boundary ambiguities, to define the living world. Any Ockham-like simplicity provided by singular view of scale, causality and finality of boundaries may be fruitful (even exploitative) in an epistemological sense, a productive way of securing predictability. But it does not acknowledge the full interplay of scalar epistemologies and ontologies among organisms that create dynamic boundaries and catalyze the adaptive underlying life.

Weaving biology into scale offers a conciliatory view of recent scale debates. Scale theorists are correct in collapsing the primacy of territorial, tiered scalings of phenomena to reveal a richer diversity of spatialities. The concept of an individual, a household, society, culture, or the environment cannot be reified to belong to a particular scale or level. The world is indeed interconnected. But at the same time, there is a propensity for entities to have scalar affinities. Via organisms and cross-scalings with their environments, a collection of ideas, practices, and forms emerge to define and to situate a working material assemblage. It is through the activity of organisms that these assemblages acquire their 'lumpiness' and transitory modularity. We may then attach terms, such as household, society, or culture in order to use them. As an illustration of this logic, consider that all organisms are tethered to the Big Bang. Everything is star dust as the saying goes. Even though such connectivity can have important explanatory relevance, other causal structures may not have the same degree of dependence. Aspects of the world were fixed in the first few minutes after the Big Bang. Others are more recent and potentially transitory, like retroviruses or human social arrangements (Mitchell, 2009). What becomes materially relevant as a working unit is an environment, defined by and contained within a variety of scales, that an organism modifies so as to procure predictability. Organisms may, and with some expense, promote the inheritance of this environment and reinforce the feedbacks that contribute to its persistence.

In closing, biological scaling allows us to distance ourselves from the old determinism of the environment making us to one that says organisms make us. Organisms have made us by modifying our environment and our evolution, true. But organisms have also shaped us by virtue of what an organism does. We are

organisms, and the nature of organism–environment causality provides an additional framework for comprehending how humans shape and are shaped by their environment. Yet the biological scaling and causality I have described in this paper do not decommission existing ideas about environmental causality in geography with a universalizing evolutionary explanation. At the least, a biological contextualization of scale and environmental causality balances out the anthropocentric tone of many discussions about scale in geography.

I expect there will be reticence if not outright resistance to the biological view of scale and the human–environment interaction presented in this article. One could claim that looking to biology for their insights on the organism–environment interaction would only broaden geography's intellectual trade deficit (Sui, 2010). Others might claim that it heralds only another rediscovery of old-school environmental determinism (O'Keefe et al., 2010). However, evolution and the life sciences have permeated inquiry to where no one discipline could claim to have a copyright on their use. The biological causality I have defined in this paper is not a one-way impress of environment, but a generative, open-ended dialectical process of scalar interactions that already has analogues in geography (Sheppard, 2008). Maintaining an awareness of current biological and evolutionary thought should be considered essential for any discipline that studies the human–environment relationship. For geographers, the new organism–environment interaction provides a material perspective on human–environmental causality. Yet its greater relevance for geography may simply be the more nuanced conceptual model of how environmental influences work. This time around geographers have a well-honed sensitivity for the social context of scientific knowledge. Hopefully, we will not mistake the accumulation of new biological ideas and information with their automatic and irresponsible misuse.

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