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SHORT ARTICLE

Biomass and Effects of Airborne Ultrafine Particulates: Lessons About State Variables in Ecology

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Ecological science has long had problems with theory progress, partly because there is no clear account of how ecological systems evolve. Moreover, such a deterministic account may never be possible, given the evolutionary foundations of ecology, its complexity and uniqueness, the absence of natural kinds in biology, and no universal species concepts to fix properties determining species membership. Given this situation, how is theory progress in ecology possible? This short article suggests one way.

Difficulty Determining State Variables in Ecology

Ecological state variables are problematic partly because they are different for different ecological schools. Ecosystems versus community theorists, for instance, typically employ different state variables to study the same phenomena (Ramos-Jiliberto et al. 2004; Wildi 2010).

Ecosystems biologists tend to pursue more complex, abstract accounts of theory that seek greater realism through greater (3+) numbers of state variables, such as metabolic energy rate of all ecosystem individuals. Community ecologists, however, tend to pursue simpler, more concrete accounts of theory, using fewer (1–2) numbers of state variables, perhaps because they generally believe that dynamic, two-population relationships—like competition, mutualism, parasitism, and predation—are foundational in ecology. They say that although wild populations are part of ecological networks with many state variables, complex communities and real ecological systems often can be conceived as a net of binary trophic interactions—a simpler version of more complex processes. They also note that mathematical theory is well developed for two-dimensional systems of first-order differential equations, but more difficult for higher-dimensional models (DeAngelis et al. 2001), models rarely fully studied. Likewise, they say identifying all state variables is difficult, given their being affected by the number of equations, monotonicity, variables' interdependency, time-related autonomy, time delays, etc. Thus, although some ecologically important processes, like trophic cascades, require 3+ dimensions/state variables (Arim and Marquet 2004), and although using only 2 state variables often is inadequate to explain real networks (Yoszis 2000), using 2 state variables dominates fields like population biology (Ramos-Jiliberto et al. 2004).

A second reason ecological state variables are problematic is that, even within a given ecological school, often scientists have trouble measuring/determining state variables (Hughes 2012). A third reason for problems is that ecologists frequently attribute different meanings to the same state variable, e.g., resilience (Brand and Jax 2007).

The first reason for ecological-state-variables problems seems not particularly worrisome, as it may result from different ecological camps' operating at different spatiotemporal scales. The second reason also appears not especially worrisome as, given time and effort, different measurements may converge. However, the third reason for ecological-state-variable disagreement is troublesome because it seems likely to block some further ecological progress. Why?

Meaning Variability in Ecological State Variables

Meaning differences for the same state variable preclude conceptual coherence—something arguably responsible for

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most recent evolutionary-biology progress (Mayr 1988). Ecological-theory progress likewise may be slow because of lack of conceptual coherence in key ecological concepts, like stability. Thirty years ago prominent ecologists catalogued various incompatible meanings attached to the concept of stability, e.g., resilience, persistence, resistance, variability, etc. (Pimm 2004), and yet these incoherent meanings remain (Justus 2007). Such differences block coherent science and threaten its use in important areas such as restoration ecology.

Different meanings/state variables in the same ecological area also are problematic because they seem unlikely to aid future theorizing. At a minimum, successful theorizing requires different scientists to mean the same thing when they use the same terms. Moreover, because some ecological state variables are compatible with different models of biological/ecological mechanisms and structures, they seem to be overly general/abstract/definitional, to have little explanatory/predictive value, and thus more like "theological ecology" (Simberloff 1983). After all, if the same state variables are compatible with inconsistent accounts of biological mechanisms/structures, they likely are "heuristically bankrupt," unable to promote further scientific progress (Shrader-Frechette and McCoy 1993). How might ecology progress, despite the possibility of never finding precise, agreed-upon state variables? One approach, outlined here, is for ecologists to learn from other biological disciplines—such as epidemiology—whose simpler, better-developed theory might provide state-variable insights.

Epidemiological State Variables for Biomass Effects

To illustrate how conceptual clarification of epidemiological state variables might provide lessons for ecology, consider the key epidemiological state variable for predicting increased particulate-matter (PM) health effects, like lung cancer, asthma, heart attacks, bronchitis, etc. This is PM-concentration in some air volume, e.g., m^3/time, e.g., day. Historically, PM has been fine (PMF), diameters 2.5–0.1 micrometer (μ)—and coarse (PMC), diameters 10–2.5 μ—both of which are characterized via mass-concentration/time. However, new nano- or ultrafine PM (PMUF)—diameters <0.1 μ—has been discovered in recent decades, and it is not yet regulated, despite no safe dose of PMUF (Pope et al. 2009, 2002; Pope 2003). The PMUF-regulatory/state-variable loophole exists partly because PMUF characteristics are still being discovered and are not functions of the existing PMF/PMC state variable, mass-concentration/time (Environmental Protection Agency (EPA) 2012). Also, coal-incineration effects have prominence, and 95 % of coal-plant PM is PMF, whereas PMUF = 4–7 % of coal PM (Linak et al. 2002). However, most biomass-plant-particulate releases are PMUF (Yinon 2010), mostly carbon black (CBPMUF)—60 % of which is released globally from biomass/biofuels incineration (Bond 2007). Because biomass/biofuel supplies most alleged renewable energy, is expanding massively, and yet is more hazardous than coal (Booth 2012), this PMUF state-variable/regulatory loophole is disturbing. To regulate biomass/biofuel harms, scientists must discover PMUF state variables.

Why is PMUF much more hazardous than PMF/PMC? All PM can be inhaled, but only PMUF is typically not released from the body. It can remain in the lungs or migrate, via blood, to other organs (Belpoggi 2012), causing harms like chronic inflammation, cytotoxicity, cellular damage, tissue proliferation, reactive-oxygen-species generation, mutagenic events, and cancer (International Agency for Research on Cancer (IARC) 2010). Yet, scientists/regulators are unsure about how to regulate PMUF, as the PMF/PMC state variable, mass-concentration/time, grossly under-predicts PMUF harms.

Some biologists argue that differences between PMUF:PMF harms are better explained by the (numbers of PMUF particles):(numbers of PMF particles) ratio, when mass is equal. As particle size decreases, they say numbers of particles required to constitute a given mass increase exponentially (Byrne and Baugh 2008). For instance, for 10 μ/m^3, only 1 PMF, but roughly 20,000 PMUF, are needed (EPA 2004; Reiley 2006). How could one incorporate this proposed-state-variable, particle number, into effects calculations if it increases exponentially and is not easily measured?

Avoiding New and Problematic Epidemiological State Variables

If new PMUF state variables appear needed to explain observed epidemiological relationships, yet face measurement and incoherence problems—given different, mass-based PMUF/PMF/PMC state variables, what can be done? One way to avoid these problems involves three steps. (1) Determine what state variable(s) best approximates PMUF:PMF effects, given well-understood PMF effects. (2) Use this "best" state variable to "bound" relative PMUF:PMF effects.(3) Convert/translate this new, approximate, bounded, state variable into a surrogate, so that PMUF/PMF/PMC can all be expressed in terms of the same, mass-based, state variables.

Can (1)–(3) be done? Regarding (1), scientists recently concluded that, given equal masses, PMUF surface area (not particle number) better predicts health harms, relative to PMF (Renwick et al. 2004; Oberdörster et al. 2005;

Renwick et al. 2004; Monteiller et al. 2007; Ayre et al. 2008; Sager et al. 2008; Sager and Castranova 2009). Given equal masses, animal-experiment data show that, given 65 times greater surface area (because of smaller particles), CBPMUF causes 65 times more inflammation/cytotoxicity than CBPMF (Sager and Castranova 2009). Therefore, correctly assessing PMUF risks may require a new, more problematic state variable, surface area.

Yet, regarding (2), if one can "bound" PMUF effects (give least-case-effects estimate), expressed in terms of this new, surface-area state variable, one might be able to avoid introducing the new variable. One way to bound these effects is to determine least amount of relative harm of PMUF:PMF, given equal masses. But least-amount relative harm of PMUF:PMF, given equal masses, large PMUF size-ranges, and PMF 2.5 µ (for which much data exist), arises when PMUF is largest (0.1 µ), and therefore has the smallest surface area. Thus, by using PMUF:PMF surface-area ratios, when they are 0.1 and 2.5 µ, respectively, one obtains the smallest PMUF effects, relative to PMF 2.5 µ effects (when masses are equal). Therefore, one can roughly "bound" PMUF harms—clarify them by (3) attempting to express the new, bounded, surface-area state variable in terms of an approximate surrogate—the old, mass-based state variable.

Regarding (3), for equal masses, (PMUF 0.1 µ):(PMUF 2.5) surface area = 25:1; the least amount of PMUF harms/effects, relative to PMF 2.5 µ harms/effects (for which much data exist) = 25. Thus, given equal masses, to roughly predict best-case/least-harm PMUF effects—at least until state-variable science improves—one could multiply PMF effects by 25—a mass-based approximation of the state variable, surface area. For smaller PMUF, effects would rise proportionately higher and use larger approximation factors. How significant is using this approximate state variable to measure/regulate PMUF harms?

Benefits of Approximate Conversions of Biomass-Effects State Variables

Recall that biomass/biofuels-incineration is, by far, the largest source of both PMUF and allegedly renewable, global energy; yet, its health harms are far worse than those of coal (Booth 2012). To determine the benefits of approximate PMUF-state-variable conversions, one must assess biomass PMUF health effects. What are health effects of a small biomass plant, like that proposed for the small town of Jasper, Indiana, by Twisted Oak Corporation (TOC)? The plant would release 25 tons/year of no-safe-dose PMUF (TOC 2010; Shaddix 2011), given that each ton of *Miscanthus-giganteus*-biomass input provides 16,441,827 Btu (Wang et al. 2012), and TOC says it would use 100,000 tons/year *Miscanthus* and release 0.03 pounds UFPM/million Btu (TOC 2010; Shaddix 2011).

If these 25 tons/year, Jasper-biomass-plant PMUF were PMF—which are much less hazardous than PMUF, as revealed earlier—government data show they would cause these additional, premature, avoidable harms/year (Schneider 2000; Schneider 2004): 1.6 deaths, 1.2 hospital admissions, 1.4 emergency-room visits, 2 heart attacks, 0.8 bronchitis cases, 29.2 asthma attacks, and 167.7 lost-work days. Using the previous multiplier (25) to predict least-harmful PMUF effects, as a function of PMF, 25 tons of currently-unregulated PMUF from the small Jasper plant would cause roughly the following additional, premature, avoidable harms/year: 40 deaths, 30 hospital admissions, 35 emergency-room visits, 75 heart attacks, 20 bronchitis cases, 730 asthma attacks, and 4,193 lost-work days.

If preceding arguments are correct, it makes sense to assess/regulate PMUF by using an approximate, bounded (e.g., low-harm estimate), mass-based-state-variable factor of at least 25, as a surrogate for the surface-area state variable—until science develops further. Using mass-based approximate state variables provides scientifically better measures than using no factor, and it allows closing the PMUF-scientific/regulatory loophole. Obviously this approach makes sense, given the life-and-death consequences of saving at least 40 lives/year for each of thousands of global biomass plants. The good is not the enemy of the perfect. Good, approximate, state-variable measures are better than no measures.

Benefits of State-Variable Approximations for Ecology

Would the preceding epidemiological steps (1)–(3) help with ecological-state-variables problems—at least until ecological science improves? The value of proposals like (1)–(3), in translating ecological findings into agreed-upon state variables, accepted by ecological consensus, is illustrated by the successful 1973 US Endangered Species Act (ESA). Many scientists say ESA became law only because ecologists at the time generally agreed on the diversity-stability thesis—on using the state variable, biodiversity, to measure/predict ecological stability. Thus, ecologists 40–50 years ago were able to illustrate, for example, that because more developed, less species-diverse, lands have more pest outbreaks, promoting biodiversity promotes stability. Without this ecological clarity, via the state variable, biodiversity, and diversity-stability theses, experts say ESA would never have passed (Commoner 1971; Congress 1973; Goodman 1975; Myers 1983).

Of course, ecologists now recognize exceptions and counterexamples to the diversity-stability thesis, such as salt marshes and the rocky intertidal. The diversity–stability thesis also fails on other empirical and mathematical grounds, despite its being the best-available-ecological science for ESA (Shrader-Frechette and McCoy 1993).

What is the best-available, not perfect-and-unavailable, science today, in terms of ecological state variables? Determining best-available science arguably means, in part, finding common ground among different state variables, all of which have some predictive power in different situations. Recall the preceding epidemiological steps (1)–(3), for dealing with problematic situations of multiple state variables. These steps include finding (1) the best-approximate state variable; (2) least-harm bounds on it; and (3) ways to convert it into already existing, easily measurable, approximate state variables.

Though no full ecological-state-variable conversions exist, there are many examples of possible partial conversions. Consider a recent British conversion. These ecologists developed a model, based on a new state-variable metric—ratio of survey area to species-average-biogeographic range—that predicts the biodiversity measure of species-abundance distributions across different scales. Moreover, this new model prediction, apparently consistent with recent empirical evidence for a universal species-area curve (Rosindell and Cornell 2012), appears to unify ecology in terms of fewer, common, state variables.

Another ecological conversion translates five conflicting, ecological-state-variable metrics for biodiversity (abundance-energy or abundance-mass relationships across species, mass- or metabolic-energies distributions of individuals in and across species, species-abundance distributions, species-area relationships, and species-level occupancy distributions across space), into a new, common state-variable metric. To predict the scaling forms of different state-variable metrics, the authors used an information-based method to express old, state-variable metrics in terms of 4 new state variables: ecosystem area, total species number in any specified taxonomic group in the ecosystem, number of individuals in all species in the ecosystem, and summed metabolic-energy rate for all such individuals (Harte et al. 2008). Conceivably, this conversion might illustrate one possibility for achieving ecological consensus on biodiversity state variables.

Of course the two preceding conversions are partial and need further examination. The second conversion applies only to macroecology, and neither addresses the problem of whether to use species-area relationships/other measures of biodiversity. However, at least they express different biodiversity metrics in terms of four new, common state variables, or express different scales of one biodiversity metric in terms of one parameter—and thus promote possible ecological-state-variable consensus. Obviously these/other conversions may not be the best, may not focus on the most relevant state variables, may not answer the questions that ecologists (not physicists) most want answered, may be too abstract to have strong empirical/predictive relevance, and may not provide explanatory, rather than purely descriptive, state variables. Nevertheless, these conversions might be heuristically helpful for achieving common ecological-state-variable metrics, thus progress in ecological theory.

For instance, suppose ecologists—battling polluters/developers required to remediate their ecological damage—needed an agreed-upon measure of resilience, in order to restore damaged areas. Given ecologists' 10 different accounts of resilience state variables (Brand and Jax 2007), polluters/regulators could avoid performing/funding restoration by claiming any proposed restoration of resilience was based on arbitrary/non-binding state variables for resilience. Such problems could doom environmental restoration. Yet, if scientists used something like (1)–(3) above, to express different resilience accounts in terms of approximate, common, state variables, they might promote both ecological understanding and environmental restoration.

Conclusion

With more ecological work on approximate state-variable conversions, three benefits may follow. Ecologists may be better able to (a) talk to each other, in the same theoretical language; (b) assess possible theory progress in ecology; and (c) offer science-related policymakers more unified, best-available-science about biodiversity.

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