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Developing a predictive science of the biosphere requires the integration of scientific cultures

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Increasing the speed of scientific progress is urgently needed to address the many challenges associated with the biosphere in the Anthropocene. Consequently, the critical question becomes: How can science most rapidly progress to address large, complex global problems? We suggest that the lag in the development of a more predictive science of the biosphere is not only because the biosphere is so much more complex, or because we do not have enough data, or are not doing enough experiments, but, in large part, because of unresolved tension between the three dominant scientific cultures that pervade the research community. We introduce and explain the concept of the three scientific cultures and present a novel analysis of their characteristics, supported by examples and a formal mathematical definition/representation of what this means and implies. The three cultures operate, to varying degrees, across all of science. However, within the biosciences, and in contrast to some of the other sciences, they remain relatively more separated, and their lack of integration has hindered their potential power and insight. Our solution to accelerating a broader, predictive science of the biosphere is to enhance integration of scientific cultures. The process of integration—Scientific Transculturalism—recognizes that the push for interdisciplinary research, in general, is just not enough. Unless these cultures of science are formally appreciated and their thinking iteratively integrated into scientific discovery and advancement, there will continue to be numerous significant challenges that will increasingly limit forecasting and prediction efforts.

biosphere | three cultures of science | science | Scientific Transculturalism | Earth Sciences

One of science's grand challenges is understanding the structure, dynamics, and evolution of the biosphere. The ultimate goal is to develop quantitative, predictive theories grounded in underlying principles and supported by data, observation, and experiment (1). There are two principal reasons for creating such a broad, integrated science of the biosphere. The first is the traditional philosophical aim of any science, namely to develop a deep fundamental understanding of an important aspect of nature. The second reason is the mounting urgency to respond to an increasing number of significant biosphere challenges threatening human well-being and socioeconomic life (2–5). For instance, we would like to be able to forecast the future of biodiversity and ecosystem functioning, predict with reasonable accuracy the onset and extent of the next pandemic or when the tropical forests of the Amazon will reach a potentially catastrophic tipping point of collapse and what the ramifications of such tipping points will be, including their timing, magnitude, and impact (Box 1). Equally important is to identify the dominant critical parameters and dynamics that underlie these threats and then craft a quantitative strategy for minimizing negative consequences and mitigating potential disasters. However, the complexity of the biosphere is characterized by biological processes operating across a vast range of spatial and temporal scales.

From enzymes to the biosphere, biological processes operate across a staggering ~37 orders of magnitude in mass and the multilevel interactions among the various organizational levels within the biosphere make the challenge of developing a predictive science of the biosphere daunting. While multilevel interactions and the extraordinary complexity of ecology and the biosphere pose huge challenges, it does not preclude

Box 1.

Crucial questions for a science of the biosphere:

How will climate warming alter life on Earth?
How important are changes in biodiversity to human well-being?
What is needed for a sustainable future?
Can we predict essential biosphere measures including:

- Ecological collapses (when and how fast) and species extinctions;
- Shifts in ecosystem functioning; Duration and widespreadness of epidemics;
- Shifts in regional agricultural productivity;
- Positive and negative feedbacks between the biosphere and climate system;
- Origin of new diseases;
- Shifts in pollutant concentrations in the atmosphere and ocean;
- Eutrophication of the ocean; Human habitability zones and migrations?

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the possibility of discovering effective theories and emergent mechanisms (6).

There is an increasing urgency to accelerate the science of the biosphere. First, we have limited resources, capacity, and time for intervention, action, and conservation, so more precise predictions are needed for efficiency. Second, there is considerable uncertainty about how the biosphere would shift if some policies emphasized radical new interventions beyond carbon emission reduction and standard conservation techniques. This requires new types of fundamental understanding to evaluate the effectiveness and consequences of any new course of action. While the urgent focus here is prediction, science requires first developing knowledge and understanding (7, 8). Understanding is the primary and ultimate goal, but prediction, integral to understanding, is the more immediate goal for society and application (9).

How can science most rapidly progress to address large, complex global problems such as those in Box 1? The Earth sciences are a case in point, having successfully predicted the developing climate crisis by integrating fundamental theory with increasingly more sophisticated observations and experiments incorporated into simulation frameworks[*]. Indeed, atmospheric and ocean science has correctly predicted global temperature changes and increasingly more detailed past, current, and future predictions of shifts in temperature and circulation patterns (10, 11). Similar efforts to successfully predict analogous phenomena in the biosphere have arguably lagged (1, 12).

For example, there is still considerable fundamental disagreement and uncertainty about how the biosphere, including feedback with human activities, will respond to increases in atmospheric CO_2 and the subsequent changes in ambient temperatures (13–15). Similarly, debates persist related to i) when or if specific tipping points exist (16–21), ii) whether global biodiversity is decreasing (22, 23), iii) what the rate and impact of the current wave of extinction of species in the Anthropocene are (24, 25), and iv) the long-term effects of geoengineering, such as iron fertilization (26). Further, there is considerable uncertainty in how the entire Earth System will respond to climate change due to the uncertainty in the biosphere's response (14). This highlights the critical need to generate basic predictions rooted in more fundamental principles and develop a deeper understanding of the interconnections between the multiple components of the biosphere.

We suggest that the lag in the development of a more predictive science of the biosphere is not only because the biosphere is so complex or because we do not have enough data or that we are not doing enough experiments (1, 12) but also in large part because of unresolved tension between the three dominant scientific cultures that pervade the research community. By scientific culture, we mean the sociological definition of the process by which information and knowledge is discovered, shared, discussed, and understood (27). Another way to define culture would be what constitutes understanding and/or explanation for a given system, problem, or question. These three cultures operate, to varying degrees, across all of science. However, within the biosciences in particular, they remain relatively separated, and their lack of integration has restrained their potential power and insight—a classic case of "the whole being less than the sum of its parts." Although these cultures overlap and share similar directions and purposes, they are relatively distinct. They can be summarized as follows:

(i) The variance culture, originating from natural history and the study of the qualitative variability and diversity occurring in nature. It is arguably the basis of modern biology, including molecular biology, genetics, and numerous fields that currently do not rely much on natural history. This culture emphasizes detailed observations and focuses on differences and deviations. It leans more toward experimental and observational methods of investigation. Questions typically focus on the processes generating variation in the natural world (28). This focus often comes at the expense of seeking to model, integrate, and generalize information or to understand what framework explains the central tendency around which variance occurs.

(ii) The exactitude culture, named after the Borges short story "On Exactitude in Science" (29), strives to account for all of the known Scientific understanding at an increasingly finer resolution to most faithfully and accurately capture, predict, and interrogate a system of interest. The exactitude culture emphasizes incorporating more detail, typically focusing on specific problems or phenomena and more general concepts or understanding. Exactitude culture is in contrast to the movement toward simplification and generalization (29). Approaches include detailed statistical modeling, machine learning (ML), and AI untethered to parsimony and assessing competing models based on information criteria. Models tend to be phenomenological with many parameters, often disconnected from underlying principles (30), which can lead to overfitting. This culture emphasizes the importance of detailed dynamics, mechanisms, and interconnections within specific contexts.

(iii) The coarse-grained culture focuses primarily on abstraction and simplification and the search for generalities that transcend diversity and variance and can be encapsulated in underlying parsimonious principles (30). This culture sacrifices detail and accuracy for generality and provides principled baselines for defining and exploring variation and further refinement at progressively finer scales. This approach can include mathematical derivations of probabilistic outcomes or take the form of a parsimonious statistical theory. This culture may exclude details that could be important for opening up new lines of discovery and progress and, in specific cases, give poor predictions.

We contend that the rate at which science progresses, the depth and rigor of our understanding, and our ability to predict depend on the healthy integration of these three cultures. The inherent tug-and-pull between the three cultures will likely accelerate the process of scientific self-correction of misconceived worldviews and paradigms. With balanced integration between them and interlocutors who promote communication, scientific understanding remains cohesive, and progress is maintained. Integrating these three cultures mirrors the long-standing arguments for the importance of interdisciplinarity,

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[*] https://www.nobelprize.org/prizes/physics/2021/press-release/.

where historians and philosophers, in particular, have argued that individual disciplines are often defined by arbitrary divisions or arise out of institutional convenience (see ref. 31 for a review). An appropriate emphasis on each of the three cultures is closely related to the need for interdisciplinary efforts and synthesis (see also ref. 32). Historically and currently, the biological sciences overemphasize the exactitude and variance cultures and underutilize coarse-grained cultures (30, 33–35).

Our focus on differing cultures harkens back to C.P. Snow's arguments on the barriers separating science from the humanities (36). Indeed, Snow emphasized that separating their distinct worldviews has slowed progress in our understanding of the human condition. Similarly, the diverse cultures within science originate from the 19th-century (37) division of natural philosophy into specialized fields, a split driven by varying methodologies for investigating nature. This fragmentation has resulted in a lack of understanding and appreciation of each's strengths, limitations, and unique advantages and drawbacks, depending on the problem. Furthermore, developing a more rigorous science is impeded when these cultures operate in isolation, without the benefit of cross-fertilization. The advancement of each culture is crucially dependent on shared insights and methodologies.

Below, we briefly overview the three different cultures operating in science:

The Variance Culture

Within biology, Marston Bates defined natural history as "the study of life at the individual level—of what plants and animals do, how they react to each other and their environment, how they are organized into larger groupings like populations and communities" (38). A common thread in natural history is the inclusion of a descriptive component. Because of the focus on description and the science of individuals and the importance of "place-based" observations (39), natural history is more focused on describing differences (i.e., variance, diversity, interconnections, and variability) or the necessary detail to characterize a given location or system of study. Principles of abstraction and parsimony are generally not one of its core components. Much of the focus and central insights of biological science have been the discovery of the laws generating and maintaining biological variation as epitomized by the Darwinian theory of evolution by natural selection and its elaborations, such as the genetic laws of inheritance, the evolutionary synthesis, and the discovery of the genetic code. But a complete theory of biology also requires a comparable focus on understanding the origin, dynamics, and laws governing the mean values of traits, behaviors, and so on, if only to define a meaningful baseline for quantitatively defining what variance is; in other words: variation with respect to what? Furthermore, understanding smaller-scale phenomena often does not translate to predictable community structure at larger scales (40). Emergent behavior is a critical component of biological systems, communities, and complex systems (6).

The Exactitude Culture

Inspired by Borges' parable of the "life-sized map" described in his fictional story "On Exactitude in Science" (29), where he "imagines an empire where the science of cartography becomes so exact that only a map on the same scale as the empire itself will suffice.........[S]ucceeding Generations... came to judge a map of such Magnitude cumbersome... In the western Deserts, tattered Fragments of the Map are still to be found, Sheltering an occasional Beast or beggar." The drive to add more detail and myriad subdominant, often minute, effects to incorporate greater biological realism plays a more central role than the drive to simplify and start with the best first approximation that captures the dominant essential features. A Borges culture minimizes abstraction at the expense of detail and inessential complexity.

To quote (30), there is "a growing infatuation with ever more complex models. It's gotten to the point where some models look as inscrutable as nature itself. With numerous adjustable parameters, these models are generally unfalsifiable, so that the opportunity to learn from a wrong prediction is short circuited." Demand for more biological realism and complexity to already complex models is increasing, but acquiescing to this demand may prove counterproductive. For example, a large body of research comparing older and more recent climate change forecasts and simulations concludes that while the push for increased spatial resolution of newer simulations has improved predictions, the overall improvement in performance is relatively minor (11). There is some improvement for certain variables, regions, and seasons; for others, there is little difference or even sometimes degradation in performance, as greater complexity does not necessarily imply improved performance (see ref. 41).

Similarly, the development of coupled ecosystem climate modeling has increasingly examined the physical, chemical, and biological processes by which terrestrial ecosystems affect and are affected by climate (42). These approaches have incorporated increasing modules of realism (43), including how plants compete for light, functional differences between vegetation types, variations in plant hydraulics, various plant functional traits that influence growth, and more details of life history differences (12, 44). While incorporating such detail has appeal in the sense that fewer ecological processes are "missing" (45), the pull to add more and more components can also be counterproductive by obscuring the primary biological drivers of ecosystem and biosphere functioning and yielding greater uncertainty and compounding error among multiple parameters (46, 47).

The drive to add more components of the biosphere to these models has several consequences. For example, the drive for greater realism without a clear infrastructure or conceptual framework to support (48) the proliferation of additional parameters also introduces the risk of overfitting. Further, the predictive success of complex models can be difficult to assess because it is often unclear which functions, assumptions, and inputs may be responsible for departures of predictions from observed data (44, 49). These issues create difficulty in summarizing, understanding, and assessing the robustness and generality of predictions (44). A recent review suggested forecasting efforts should focus on increasingly shorter time scales to project "the state of ecosystems, ecosystem services, and natural capital, with fully specified uncertainties" (49). Predictive success is expected through local "calibration" of functions and model parameters. However, as foreshadowed by Borges, the concern is that the loss of generality inherent in focusing on local time and spatial scales may ultimately limit the impact and utility of the predictions. The key to exactitude culture is to ask what is achieved by adding new details. In some cases, adding detail can improve predictions and performance. In other cases, additional details lead to overfitting and compounding parameter uncertainty, making models difficult to understand and deploy.

The Coarse-Grained Culture

This is epitomized by the classic observation of Newton (Box 2), that only having theories of unique events is generally not of interest. We need generalizations and coarse-grained theories and models that capture the essence of the problem and provide a leading approximation that acts as a point of departure (30) for adding more detail. The initial focus is to develop simple, tractable, mechanistic models with relatively few variables and parameters. These may be caricatures of the system, but they play a crucial role because they attempt to incorporate the important variables and essential features that determine the system's organization, structure, development, and dynamics (35). The emphasis is on making these models falsifiable so that they can be appropriately modified when their predictions are confronted with data. Coupled with the development of such models is the parsimony of parameters; consequently, it is critical to identify appropriately aggregated system variables that encompass subsets of the detailed variables in traditional complex models.

A potential problem can occur when precision, realism, and the uniqueness of the system under study are sacrificed to generality. Macroecological theories, such as the neutral theory (50) metabolic scaling theory (51), and the maximum entropy theory of ecology (52), have been successful in predicting a large number of phenomena, including species richness, productivity, abundance distributions, and growth curves, and scaling laws with a small, efficient group of parameters and assumptions. However, this may hamper the inclusion of important contextual details of specific systems that may not have been included in more general models. For example, assumptions like "demographic neutrality" or "space-filling networks", while mathematically tractable and useful as leading approximations, are sometimes difficult to extend to specific ecological systems.

Another challenge in a coarse-grained culture is identifying the fundamental principles. Success can be stymied by starting from the wrong principles. The tension is that, on the one hand, to quote—Vlad Taltos (Issola, Steven Brust). "Everyone generalizes from one example. At least, I do". On the other hand, to quote Ruth Bader Ginsburg, "I am fearful, or suspicious, of generalizations… They cannot guide me reliably in making decisions about particular individuals[†]." However, the power of a parsimonious, principled, coarse-grained approach is that it is typically falsifiable. A well-defined theory with specific testable predictions proven wrong by confrontation with data can provide important insights for moving a field in the right direction.

Given a system with such a high degree of complexity, how do you identify the general principles underlying that variance? We contend that the answer lies in the integration of the three cultures.

Box 2.

The coarse-grained culture formalized by Newton.

Isaac Newton's Mathematical Principles of Natural Philosophy (1687), where he states several "Rules of Reasoning".

Rule I. No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena.
Rule II. Therefore, the causes assigned to natural effects of the same kind must be, so far as possible, the same. Examples are the cause of respiration in man and beast, or of the falling of stones in Europe and America, or of the light of a kitchen fire and the Sun, or of the reflection of light on our Earth and the planets.
Similarly, in Newton's Untitled Treatise on Revelation (section 1.1).

> "choose those constructions which without straining reduce things to the greatest simplicity… Truth is ever to be found in the simplicity, and not in the multiplicity and confusion of things."

How to Synthesize the Three Cultures; Scientific Transculturalism

Ultimately, the real challenge in addressing the problems of the biosphere is to produce an integrated conceptual framework leading to models whose predictions are trustworthy enough to guide the decisions of conservationists and policymakers (53). We have argued that biology has struggled to address this challenge because the three cultures remain only loosely interconnected, with the coarse-grained culture playing a relatively minor role. The issue for biology was pithily expressed by the biologist and Nobel Laureate Sidney Brenner: "Biological research is in crisis, …Technology gives us the tools to analyse organisms at all scales, but we are drowning in a sea of data and thirsting for some theoretical framework with which to understand it. Although many believe that "more is better", history tells us that "least is best". We need theory and a firm grasp on the nature of the objects we study to predict the rest" (54).

Why does the speed of scientific progress depend on integration? To quote the biologist J.B.S. Haldane, "In scientific thought we adopt the simplest theory which will explain all the facts under consideration and enable us to predict new facts of the same kind"[‡], and similarly echoed by the physicist A. Einstein, "everything should be as simple as possible but no simpler." Inspired by these quotations, we argue that the integration of the three cultures is the mechanism for developing the "simplest" yet most effective scientific framework. We believe this occurs because i) integration exposes assumptions much more clearly via a healthy tension between the cultures, which leads to a transparent understanding of the key variables and mechanisms driving the system; ii) integration increases the effectiveness of predictions by avoiding

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[†] Ginsburg, Ruth Bader. "Some Thoughts on the 1980's Debate Over Special Versus Equal Treatment for Women". Law & Ineq. 4 (1986): 143.

[‡] J.B.S. Haldane In 'Science and Theology as Art-Forms', Possible Worlds (1927), 227.

issues of overfitting and overparameterization and by continually challenging theory with data; and iii) integration provides a mechanism of iteration between (i) and (ii) which more rapidly provides refinements to the assumptions and predictions and guides new data collection (49, 55). We refer to this integrated paradigm as Scientific Transculturalism. We provide a mathematical formalism of Scientific Transculturalism in Box 3.

In Scientific Transculturalism, each science culture is cognizant of and informed by the others. Variance culture is used

Box 3.

A heuristic formalism of Scientific Transculturalism:

To elucidate the differences and linkages between the three cultures (Fig. 1), we outline a formalism to illustrate what we mean conceptually by Scientific Transculturalism.

Consider a general system, whether the entire biosphere or a specific ecosystem or organism, characterized by all N possible independent variables $\{x_j\} \equiv x_1, x_2, \cdots\cdots\cdots, x_N$. These are the input, or basis, for constructing a theory, a model, or a numerical simulation of the system. In science, we are typically interested in measuring, calculating, or deriving various emergent properties of the system: $\{Y_i\} \equiv \{Y_1,\ Y_2,\ \cdots\cdots\cdots\ Y_m\}$. In terms of this general framework, the three scientific cultures can be summarized symbolically as follows:

i) The Variance Framework - This framework focuses on understanding and categorizing the diversity of a given system. It starts with collecting as many observations for both the Y_i and $\{x_j\}$ as possible. Each observational datum, Y_i^O, is collated and effectively used to construct a norm or average, $\tilde{Y}_i$, from which the variance is determined:

$$\Delta Y_i = Y_i^O - \tilde{Y}_i.$$

The set of Y_i^O provide the observational foundations for building theories, which in turn iteratively provide feedback on the variance by associating $\tilde{Y}_i$ with expectations from coarse-grained theories (see iii below).

ii) The Exactitude Framework - In the extreme version of this framework, all possible N independent variables, $\{x_j\}$, are included, so each derived quantity Y_i can be formally expressed as a function of all of the $\{x_j\}$:

$$Y_i = F_i\left[x_1, x_2, \ldots x_N\right].$$

Typically, the number of calculable properties of the system (and consequently, the number of predictions), m, is much smaller than the number of input variables, N; i.e., $m << N$. A large number of variables usually means that the system cannot be solved analytically or even approximately. Hence, solutions and predictions often take the form of simulations or numerical computations.

iii) Coarse-grained or Zeroth-Order Framework - This approach starts by significantly reducing the number of independent input variables, $\{x_j\}$, to a relatively small subset deemed to be the major determinants of the system's essential features, thereby capturing most of the variation. Consequently, the derived or predicted quantities are idealized norms, or average approximations, $\{\overline{Y}_i\}$, to the exact, $\{Y_i\}$ which can be formally expressed as

$$\overline{Y}_i = f_i[x_1, x_2, \ldots x_n].$$

In this case, the number of input variables, $n \ll N$, and the predicted quantities, $\{\overline{Y}_i\}$, are idealized approximations to the equations governing the exact $\{Y_i\}$. Similarly, $m \gg n$, meaning that the number of predicted quantities (m) is typically much larger than the number of input variables or parameters n, which potentially comes at the cost of accuracy.

The coarse-grained average, $\{\overline{Y}_i\}$, can be identified with the averages from variance culture, $\tilde{Y}_i \approx \overline{Y}_i$, implying that variation, ΔY_i, derives from the set of subdominant ($N - n$) variables neglected in the coarse-grained framework. If the exactitude framework could accommodate all N contributing variables and, therefore, accurately predict the measured Y_i^O, then we can likewise identify $Y_i \approx Y_i^O$.

This formalism illustrates the three cultures are defined by focusing on different subsets of $\{x_j\}$ and $\{Y_i\}$, and different mappings from $\{x_j\}$ to $\{Y_i\}$. As discussed in the main text, Scientific Transculturalism yokes together the three cultures to address a common problem, such as those in Box 1. The intersection between the three cultures can accelerate the pace of science by appropriately iterating between different treatments of $\{Y_i\}$ and $\{x_j\}$. Initially, large sets of $\{Y_i\}$ and $\{x_j\}$ are observed from which simple regularities can be extracted and fundamental theory built which predicts $\{\overline{Y}_i\}$ from a reduced $\{x_j\}$. This theory then feedbacks on the observations by defining new types of expected averages. It can be elaborated through exactitude culture to more accurately predict specific contexts using expanded sets of $\{x_j\}$.

to observe phenomena and characterize diversity, and coarse-grained culture is used to identify regularities, fundamental mechanisms, and foundational theories from the observations. Exactitude culture should be used to build models that mirror the theory and add successive layers of detail to integrate available data. Variance culture is used iteratively and concurrently to evaluate the performance of these models and provide feedback on the theory by pointing out contexts or outliers where theories fail. Indeed, this is how many past scientific advances have occurred.

In the biosphere sciences, the separation of the cultures has not always been the case. In the history of the development of biosphere science, there are several cases where Scientific Transculturalism has led to key revolutions and greatly increased fundamental insights and the rate of scientific progress.

The first is the history leading to the Modern Evolutionary Synthesis (1930 to 1950). Wallace and Darwin, working initially within the variance culture, used myriad observations to eventually infer and propose a coarse-grained general mechanism for evolution by natural selection. This case also illustrates the rapid iteration between two of the cultures where their work also drew upon the earlier coarse-grained theories of Malthus, Lyell, and von Humboldt (56). This iteration may have been responsible for such a rapid scientific revolution. Later, this theory was combined with observations from genetics to produce more general mathematical theories for population genetics, which in turn have been elaborated with exactitude culture to make a variety of specific predictions for new types of data (57).

A second example is climate science. Here, coarse-grained culture characterized the early development of climate physics (58), which was initially used to apply the basic equations of hydrodynamics (the Navier–Stokes equations) to new types of meteorological and oceanic observations stemming from variance culture. The initial theoretical work was to find the appropriate reductions and approximations that effectively predicted weather and circulation patterns (59). As the field progressed, exactitude culture was used to build more accurate theories, adding important complications of the atmosphere and ocean, such as temperature and salinity effects, and an ever-refining understanding of vorticity and turbulence. These more complicated models were tested against massive new datasets (variance culture) and were also rereduced into coarse-grained perspectives that can be readily understood and checked. This iterative structure, although idealized in our representation, involved all three cultures and led to the impressive ability to forecast local weather days in advance, a general and effective understanding of past and present climate, the ability to predict atmospheric dynamics on other planets, and exoplanets, and ultimately, the recent Nobel Prize in physics.

A third nascent example is the recent Madingley Model efforts to model the biosphere (53). In the spirit of Scientific Transculturalism, it is a mechanistic general ecosystem model that is a detailed, but not too detailed, model of the biosphere. Based on a set of fundamental ecological processes, it simulates a coherent global ecosystem consisting of photoautotrophic and heterotrophic life (60). This and other efforts (61) are an ongoing attempt at Scientific Transculturalism on a broad scale for the biosphere.

"*I am among those who think that science has great beauty.*"—Marie Curie[§]

How can we inspire the integration of scientific cultures in developing the science of the biosphere? Scientific Transculturalism is the process of leveraging the differing cultures of science to solve complex problems efficiently. We propose multiple solutions for bringing researchers of all cultures together, mirroring similar efforts over the last 25 y to encourage greater interdisciplinary collaboration in science. Past investments of federal funding agencies in interdisciplinary research have begun to break down the barriers between disciplines successfully. Interdisciplinarity is now widely accepted as increasingly important for addressing the major challenges we face in the 21st century (62). So it is, we believe, with Scientific Transculturalism. Consequently, the next step is a distinct and potentially more daunting challenge, separate from, but in addition to, integrating across multiple disciplines. Integrating the three cultures in science requires focusing on projects that merge their differing approaches and thinking, focusing on how scientists interact with those teams.

We suggest four key recommendations:

First, a potential catalyst for promoting the integration of scientific cultures might well be inspired by integrating insights from the history of science and, in particular, from the burgeoning new study of the "science of science" (63–65), into the practice of how science is actually done. In other words, learning from the perspective of those whose prime intellectual focus is addressing how did, and how does, science happen could help guide practitioners in understanding how successful science can be accomplished. Specifically, the scientific community needs to continue to engage more fully with scholars studying the history and philosophy of science and technology to gain an outside perspective. Similarly, the same issues of the three cultures apply to historians and philosophers of science themselves, who would also benefit from viewing debates, controversies, and progress in science through the lens of Scientific Transculturalism or as the result of the interplay and degree of integration of the three cultures.

Second, we encourage the support of workshops, outreach activities, novel integrated courses, and flagship projects that demonstrate a requirement for input from all three cultures where tradeoffs of their integration are openly discussed and debated (Fig. 1). This would mirror past successful efforts of federal funding agencies to foster interdisciplinary research but expand that thinking to integrate fundamentally differing scientific approaches.

Third, undergraduate and graduate education, curricula, and training should emphasize the utility and tradeoffs of each of the three cultures to address major challenges. In particular, biology departments should foster a culture of closely integrated coarse-grained thinking with detailed observations and specific models.

Fourth, we suggest that the scientific reward system of departments, higher administration, funding agencies, and professional societies consider how other evaluation metrics could be improved by including considerations of Scientific Transculturalism.

[§] "Madame Curie: A Biography". Book by Eve Curie Labouisse translated by Vincent Sheean, 1937.

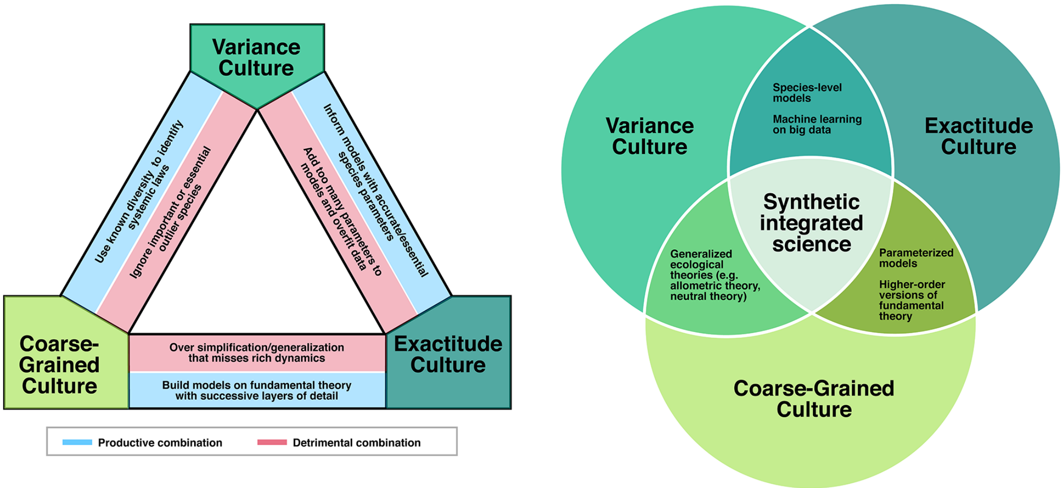

Fig. 1. The integration of scientific cultures. The act of intersecting the three science cultures (Scientific Transculturalism) comes with the opportunity for positive and negative combinations. As noted in blue and red, each culture alone, and in pairs, has benefits and detriments that can limit progress. These can be avoided by integrating the three and being aware of the detriments of each. The intersection between cultures can both leverage their strengths through positive synergies (in blue) and enhance their weaknesses through combinations that take the worst of each culture (in red). Scientific Transculturalism is the act of merging the intersections between each culture and focuses on developing science that lies in the intersections bringing novel synergy and the potential for more rapid scientific advancement. Synthetic, synergistic, and integrated science occurs when all three cultures are merged. The figure provides a few examples of the fields already defined by the intersection of each culture.

Fifth, journals could play a central role in promoting papers that integrate across science cultures and encourage editors to guide referees in reviewing such manuscripts. These practices are already being experimented with by PNAS through consultative review. Our arguments go well beyond the necessity for encouraging interdisciplinarity, which focuses on bringing together different expertise to solve a problem (9, 66), to urgently encourage transcending cultural practices that approach science differently. We need a new type of cultural integration or reintegration at the level of the entire field, strongly supported by scientific societies, academic institutions, and funding organizations.

Conclusions

Humanity's response to global environmental challenges requires biology to be more quantitatively predictive and to be able to forecast the future with a greater degree of confidence in future scenarios, and an understanding of the consequences of proposed interventions (49). To accelerate the pace and efficiency of science, it is necessary to strongly encourage a proactive appreciation of and a formal engagement in integrating the three scientific cultures. Scientific Transculturalism is the process of integration of the three cultures—variance, coarse-graining, and exactitude. Scientific Transculturalism is a critical step in stimulating and accelerating a science of the biosphere capable of tackling some of the greatest challenges facing our society (Box 1).

There is nothing to indicate that the scientific method will ultimately fail in ecology, nor that new regularities, predictive theories, and understanding can't be developed. The last 30 y has seen advances in ecological theories, modeling, and our understanding of biodiversity on the planet that do illustrate regularities and new types of prediction. Theories include the metabolic scaling theory (51, 67), maximum entropy theory (52), neutral theory (50), species coexistence theory (68), trait optimality theory (69–71), and many others (33). Our ability to monitor and understand global biodiversity is also rapidly increasing (72, 73). These are all ingredients priming us for rapid scientific integration through Scientific Transculturalism.

One major challenge for the community is harnessing and guiding the increasing role of big data, ML, modeling, and statistical complexity, which in our framework falls under the exactitude culture. Multiple aspects of science have undoubtedly been and will be accelerated by data-derived modeling (74). The tradeoff here is that, on the one hand, ML and AI often provide impressive accuracy based on existing data, but, on the other hand, they can also overfit past data and generally do not provide transparent models which reveal mechanisms (75, 76). Consequently, ML and AI are often very good at short-term predictions but tend to be suspect for longer-term forecasting. We worry that this invokes a *deus ex machina* paradigm in addressing and developing a science of complex adaptive systems and pushes us away from underlying mechanistic understanding.

It is unclear whether including more biological realism, detailed mechanisms, and parameters into already complex forecasting models will improve predictions without a concomitant expansion of theory and understanding. The field's general view of ML and data-derived modeling is that it is an advanced form of regression (75). Thus, while ML provides impressive new abilities, it also suffers from the same challenges as more simple regression approaches and the typical challenges associated with exactitude culture. In contrast to ML, coarse-grained approaches can make reliable predictions beyond the boundaries of the input data, provide unique lenses to analyze data that reveal new simplicities, and avoid overfitting. However, regression approaches, including ML, can often be useful for predictions in cases where theory is lacking or for in-sample applications. In addition, interesting and powerful coarse-grained ML approaches are being developed (e.g., refs. 77–80).

It is important to emphasize that these three scientific cultures are not rigid structures, nor do they fall into neat, bounded groups. Rather, each consists of differing shades of emphasized thinking and mindsets that overlap to varying degrees. Similarly, fields may undergo many cycles of transitioning between dominance or codominance as one or two cultures become overrepresented, just as physics may be overly coarse-grained in some subdisciplines. Biology was once more driven by coarse-grained culture and is now more dominated by variance and exactitude cultures.

We have argued that the reason for the relatively slow pace of a general science of the biosphere is that biology has not developed a healthy integration of the three cultures of science. Further, progress in all aspects of Earth System science will benefit from a more open discussion on how to integrate best and iterate the process of science through the lens of each culture. Our solution emphasizes Scientific Transculturalism, which recognizes that the push for interdisciplinary research is just not enough. An important next step is the integration of the three cultures. Scientific Transculturalism makes an explicit effort to recognize the limits of research within each specific culture and to encourage interactions that leverage the strengths of each culture. Unless these cultures are formally appreciated and their thinking iteratively integrated into scientific discovery and advancement, our forecasting, prediction, and understanding of the biosphere will continue to be limited.

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