Synthetic chemicals as agents of global change

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Though concerns about the proliferation of synthetic chemicals – including pesticides – gave rise to the modern environmental movement in the early 1960s, synthetic chemical pollution has not been included in most analyses of global change. We examined the rate of change in the production and variety of pesticides, pharmaceuticals, and other synthetic chemicals over the past four decades. We compared these rates to those for well-recognized drivers of global change such as rising atmospheric CO_2 concentrations, nutrient pollution, habitat destruction, and biodiversity loss. Our analysis showed that increases in synthetic chemical production and diversification, particularly within the developing world, outpaced these other agents of global change. Despite these trends, mainstream ecological journals, ecological meetings, and ecological funding through the US National Science Foundation devote less than 2% of their journal pages, meeting talks, and science funding, respectively, to the study of synthetic chemicals.

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When Rachel Carson wrote "The most alarming of all man's assaults upon the environment is the contamination of air, earth, water, and sea with dangerous and even lethal materials" (Carson 1962), she raised grave concerns about the proliferation of pesticides in the US. At that time there were 200 pesticides on the US market, and the World Health Organization estimated that nearly one million metric tons of pesticides were being applied to the Earth's land surface annually (WHO 1990). The publication of Carson's (1962) book helped to launch the field of ecotoxicology and has been widely credited with catalyzing the modern environmental movement. The novel chemical entities created by the chemical industry have been recognized as one of the critical markers of what defines the modern era as the Anthropocene (Waters *et al.* 2016), a new geologic epoch. Many of these novel chemical entities are pesticides and pharmaceuticals – organic chemicals that are specifically designed to kill or prevent the growth of unwanted organisms (weeds, pathogens, pests), or to interfere with organismal biochemistry (UNEP 2013). Although calls to study the environmental effects of contaminants were included in early assessments of global human impacts (Vitousek *et al.* 1997; Tilman *et al.* 2002), synthetic chemicals have subsequently been largely ignored in efforts to address planetary change (Nelson 2005; Rockström *et al.* 2009; but see Vörösmarty *et al.* 2010; Stehle and Schulz 2015). Recent initiatives have also acknowledged that insufficient information is available to assess the environmental impacts of these novel chemical entities.

In a nutshell:

- The diversity and quantity of synthetic chemicals created, distributed, and released into ecosystems have been increasing at rates greatly surpassing those of other drivers of global environmental change
- Both international trade and long-distance hydrologic and atmospheric transport effectively distribute synthetic chemicals globally
- Despite the rapid pace and global scale of synthetic chemical enrichment of ecosystems, ecologists are giving little attention to assessing this type of pollution
- Applying ecological concepts, methods, models, and data on populations, communities, and ecosystems is critically important to understanding, predicting, and managing the environmental impacts of synthetic chemical pollution

Extensive toxicological research demonstrates that a large number of synthetic chemicals adversely affect model organisms under laboratory conditions. The well-controlled exposure experiments generating this evidence are critical in determining the mechanisms and modes of toxicity of chemicals. However, classic toxicological testing results are insufficient to understand and predict the individual and collective impact of synthetic chemicals once they enter ecosystems. In particular, synthetic chemicals and their breakdown products may become either more or less toxic as a result of their reactions or interactions with a range of other chemicals in natural environments, or as a consequence of transformations by organisms or exposure to natural light. Further, the customary tests of single compounds on single organisms on which toxic chemical regulation worldwide is mostly based do not provide insight into the movement of contaminants through food webs; cannot capture the broad range of indirect effects mediated through species

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interactions (Kidd *et al.* 2014); do not measure differential harm to species that may result in local species loss and community shifts (Halstead *et al.* 2014); and cannot predict whether contaminant exposure leads to direct or indirect alterations of core ecosystem functions such as primary production, nutrient retention, or carbon sequestration (Bernhardt *et al.* 2010; Rosi-Marshall and Royer 2012; Rosi-Marshall *et al.* 2013). Clearly, understanding the environmental impacts of synthetic chemicals in the real world requires ecological investigations in complex systems in addition to controlled toxicological testing in highly simplified laboratory settings (Bernhardt *et al.* 2010; Halstead *et al.* 2014; Gessner and Tlili 2016).

Synthetic chemicals and their derivatives can create long-term environmental problems. Many pesticides and pharmaceuticals are persistent or "pseudo-persistent", meaning that either they are very slow to degrade or their constant use leads to continuous release into the environment at rates exceeding degradation rates. For compounds resisting effective biological degradation, environmental impacts persist long after their toxicity is discovered and therefore well after effective measures can be taken to discontinue their production and proliferation. Such long-term legacies have been well established for chlorofluorocarbons (CFCs), which will degrade the stratospheric ozone layer for the next century (Adams and Halden 2010), and for polychlorinated biphenyls (PCBs), which will continue to accumulate in fish, fish-eating birds, and humans for many decades (Beyer and Biziuk 2009). The legacy effects of these particular classes of compounds can be assessed because CFCs and PCBs are among the few synthetic chemicals that have been banned by widely adopted international treaties. In contrast, there is grossly insufficient information to assess the environmental persistence, pseudo-persistence, and long-term impacts of synthetic chemicals that are the most widely used today (Arnot *et al.* 2006; Muir and Howard 2006).

Why has ecology as a discipline focused so little attention on the problem of contaminants in ecosystems? Has the production and diversification of synthetic chemicals escaped attention because their rates of change are dwarfed by a broad range of other established drivers of global change (as defined by the Millennium Ecosystem Assessment [MA 2005])? How much ecological science funding or space in mainstream ecological journals is being devoted to this issue? To answer these questions, we synthesized information from numerous regional and international reports and databases and performed an analysis of relevant contents in publications, presentations at a recent large scientific meeting, and funded research grant proposals.

Methods

All data sources used to understand the trends in the production and diversity of synthetic chemicals are described in WebPanel 1. To allow meaningful comparisons, all trend data is reported relative to the year 1970. One exception is the US global market value for pharmaceuticals, because the earliest date for which we could locate data was 1975. Thus, all data were expressed relative to the reference year according to:

$$\Delta X = (X_t - X_{\text{ref}})/X_{\text{ref}} \qquad \text{(Eq 1)}$$

where X_t is the value of any variable of interest in year t and X_{ref} is the value of that same variable estimated for the reference year 1975 for the global market value of pharmaceuticals and the reference year 1970 for all other variables.

We examined the prevalence of synthetic chemical impact research reported in mainstream ecological journals, presented at a recent ecological meeting, and supported by funding from the US National Science Foundation (NSF), in the following ways. For journal articles, we performed literature searches using the ISI Web of Science on 17 Apr 2015. We limited the results to the 20 ecology journals with the highest impact factor for the period 1970–2015 (Table 1). For meeting presentations, we downloaded the titles and abstracts for all presentations at the 100th annual meeting of the Ecological Society of America (ESA; 9–14 Aug 2015; Baltimore, MD). For major NSF funding, we examined the titles, abstracts, and budget amounts for all grants currently funded by NSF's Division of Environmental Biology (DEB; grants active as of 1 Jan 2016; database downloaded from www.nsf.gov/awardsearch). Within each dataset we used a wide variety of search terms (*pharmaceutic* OR emerging contamin* OR synthetic organic chem* OR pesticid* OR personal care product**) to identify papers, presentations, and grants that mentioned synthetic chemicals in their titles or abstracts. For the journal articles, we compared the rate of return for our synthetic chemical search terms to those for (1) global climate change (*climate chang* OR global warming*); (2) elevated CO_2 ((*elevated OR rising*) *AND* (*CO_2 OR carbon dioxide*)); (3) habitat loss (*habitat loss* OR agricult* expans* OR land use chang**); (4) biodiversity loss (*global biodiversity*); and (5) nutrient pollution (*NO_x OR ammonia volatilization OR nitrate pollut* OR ammon* pollut* OR N_2O OR nitrous oxide OR nitrogen deposition OR excess nitrogen* OR excess phosph* OR eutrophication OR nutrient pollution OR nitr* pollut* OR phosph* pollut**). For meeting presentations and NSF grants, we report the proportion of all talks and funds that mention or focus on synthetic chemicals and compare the results to those mentioning either nitr* or climate change.

Results

The rate of increase in the production and diversification of pharmaceuticals and pesticides exceeds that of most previously recognized agents of global change

Table 1. The 20 ecology journals included in our literature analysis of publication trends on global-change drivers (see Figure 2), including information on the number and proportion of publications in each journal identified by our synthetic chemical search terms

	Journal title	*Thomson Reuters Impact Factor (2014)*	*Google Scholar h5-index*	*Publications with synthetic chemical terms*	*Total publications*	*% of papers*
Top 20 average impact factor (1970–2015)	*Journal of Applied Ecology*	4.6	52	104	4637	2.24%
	Ecological Applications	4.1	55	84	3754	2.24%
	Annual Review of Ecology Evolution and Systematics	10.6	39	4	349	1.15%
	Ecological Modelling	2.3	43	82	7402	1.11%
	Oikos	3.4	46	86	7803	1.10%
	Ecology Letters	10.7	85	12	2329	0.52%
	Biological Conservation	3.8	62	36	7062	0.51%
	Conservation Biology	4.2	57	21	4992	0.42%
	Trends In Ecology & Evolution	16.2	89	18	4380	0.41%
	Evolution	4.6	56	31	8255	0.38%
	Proceedings of the Royal Society B-Biological Sciences	5.1	80	35	9749	0.36%
	Molecular Ecology	6.5	78	21	7265	0.29%
	Journal of Experimental Marine Biology and Ecology	1.9	35	19	8304	0.23%
	Global Change Biology	8.04	90	8	3844	0.21%
	Journal of Animal Ecology	4.5	47	8	4112	0.19%
	Marine Ecology Progress Series	2.6	48	22	14399	0.15%
	Oecologia	3.1	44	15	12009	0.12%
	Ecology	4.7	62	12	11026	0.11%
	American Naturalist	3.8	46	4	6385	0.06%
	Journal of Ecology	5.5	54	1	4246	0.02%
	Grand total			**623**	**132302**	**0.47%**
Other journals	*Agriculture Ecosystems & Environment*	*3.4*	*55*	*470*	*5392*	*8.72%*
	Frontiers in Ecology and the Environment	*7.4*	*53*	*32*	*2696*	*1.19%*
	ISME Journal	*9.3*	*78*	*13*	*1604*	*0.81%*
	Functional Ecology	*4.8*	*48*	*21*	*3414*	*0.62%*
	Methods in Ecology and Evolution	*6.6*	*46*	*4*	*689*	*0.58%*
	Ecotoxicology	*2.7*	*36*	*517*	*1986*	*26.03%*
	Environmental Science & Technology (ES&T)	*5.3*	*117*	*2328*	*34160*	*6.81%*
	ES&T papers with ecolog OR ecosystem**			*150*		*0.44%*

Notes: Such articles are poorly represented even in journals dedicated to applied ecology. We chose those 20 publications with high impact factors over the course of the entire period of analysis (1970–2015) so as not to skew trends toward recently created journals. For comparison, a list of "other journals" is appended below that have high impact factors or high prevalence of articles including our search terms.

and matches the rate of increase in global N fertilizer use (Figure 1, a and b). The economic value of the chemical industry as a whole, and of its pharmaceutical and pesticide sectors, is increasing at a rate more than double that of any other global-change factor (Figure 1c).

We found that within mainstream ecological journals, studies of contaminant effects on populations, species, communities, and ecosystem processes lag well behind research on other, well-recognized drivers of global environmental change, with less than 1% of all papers in the 20 most highly cited ecological journals over the past 25 years referencing any type of synthetic chemical (Table 1 and Figure 2). Beyond these mainstream ecological journals, we found contaminant search terms were most prevalent in the journal *Ecotoxicology* (26% of all papers). These terms were present in ~7% of the papers published in the journal *Environmental Science and Technology*, but were only accompanied by ecological terms (ecolog* or ecosystem*) in <1% of all papers (Table 1). The ecology journal with the highest proportion of papers that included our contaminant search terms was *Agriculture*, *Ecosystems*

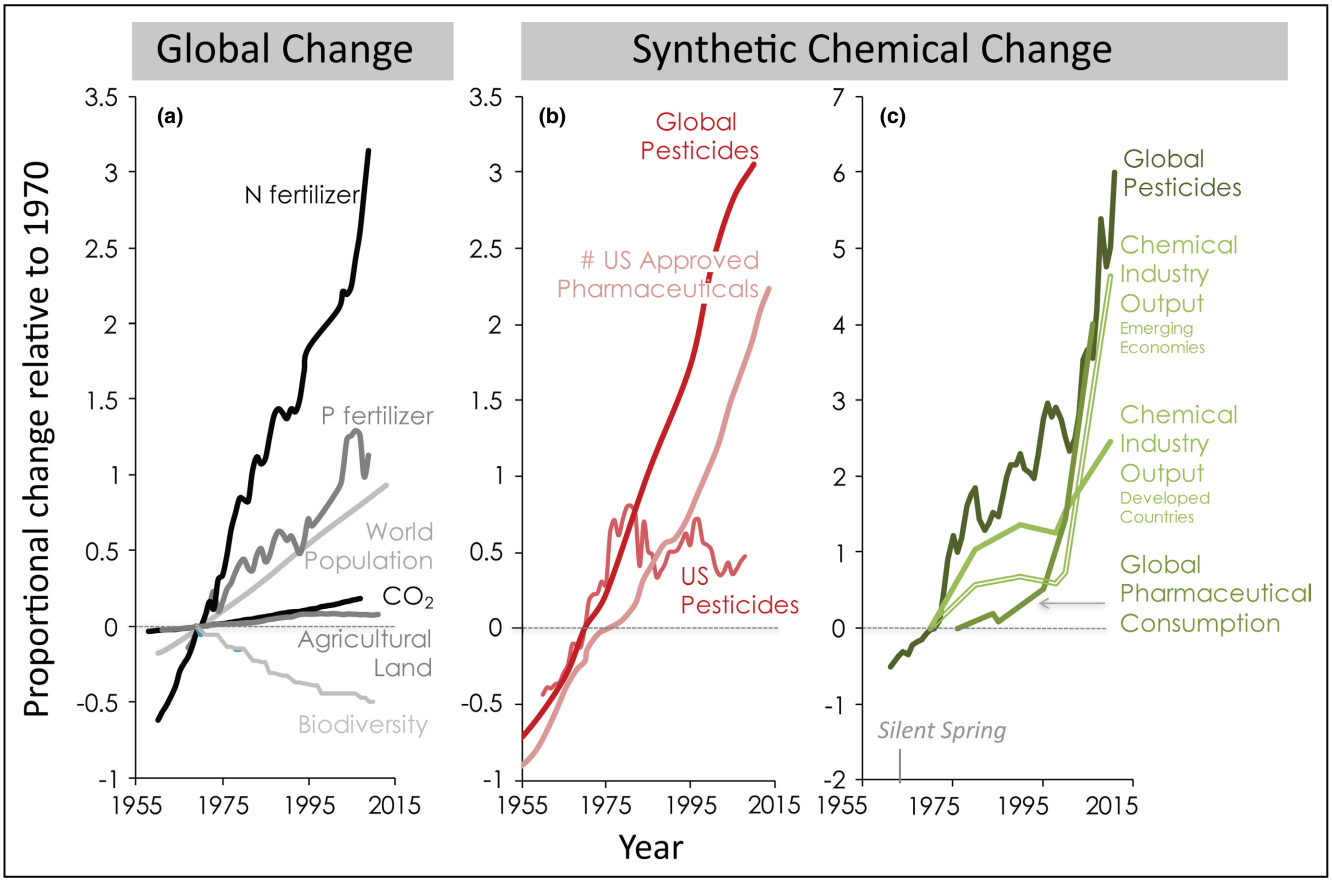

Figure 1. *(a) Trajectories for drivers of global environmental change as defined by the Millennium Ecosystem Assessment (MA 2005); (b) increases in the diversity of US pharmaceuticals and the application of pesticides within the US and globally; (c) trends for the global trade value of synthetic chemicals and for the pesticide and pharmaceutical chemical sectors individually, used as a proxy for the mass of chemicals produced in the absence of national or international estimates of the amounts of pharmaceuticals and chemicals produced. All trends are shown relative to values reported in 1970, with the exception of pharmaceutical consumption, where the earliest data reported are from 1975. Expenditures in (c) were adjusted for inflation by the Consumer Price Index, as reported by the US Department of Labor Bureau of Labor Statistics using 1982–1984 as a base before relating prices to 1970 and 1975 values. All data sources are described in WebPanel 1. The most recent estimates included in (a) are 116 × 10^6 metric tons N fertilizer, 38 × 10^6 metric tons P fertilizer, 7.1 billion people, 384 parts per million by volume (ppmv) CO_2, and 4.9 billion ha agricultural land. In (b), the most recent values are 6 × 10^6 metric tons pesticides, 1467 US-approved pharmaceuticals, and 0.23 × 10^6 metric tons of US pesticides. In (c), most recent estimates are \$29 billion for global pesticides, \$1900 billion for industrial chemicals in emerging economies, \$760 billion for global pharmaceutical consumption, and \$2300 billion for industrial chemicals from developed countries.*

and the Environment, where a large number of papers specifically discussed the impacts of pesticides (Table 1). Presentations at international meetings are another indicator of disciplinary interest in topics that may be more inclusive than disciplinary journals. At the largest-ever conference of international ecologists (the ESA's 2015 meeting had more than 5000 attendees), only 1.3% of the presentations (51 out of 3810 abstracts) included any of our contaminant search terms (Figure 3a). In comparison, 13% of all presentations referenced "nitrogen" and 22% referred to "climate change" (Figure 3a).

This lack of attention in mainstream ecological journals and conferences is consistent with the limited investment in ecological research on contaminant impacts from the major funding agency for ecologists in the US (the NSF DEB). Less than 3% of all current research grants (23 of 1078) and total funding (\$9.4 million out of \$356.9 million; all monetary values in this paper are reported in US dollars) included any of our search terms in the project title or abstract (Figure 3b). Of these 23 projects, only a single Doctoral Dissertation Grant (for \$20,252, or 0.006% of all current funds) was aimed at studying the ecological impacts of synthetic chemicals. The remaining 22 proposals either listed one of our synthetic chemical search terms among other agents of environmental change or mentioned the possibility of drug discovery as part of the motivation for their work. In contrast, grant proposal titles and abstracts including the words "climate change" or "nitrogen" accounted for 23.4% of total funding (~\$83.7 million). The ratio of publications and funds devoted to contaminant research relative to those for nitrogen or climate-change research was consistent

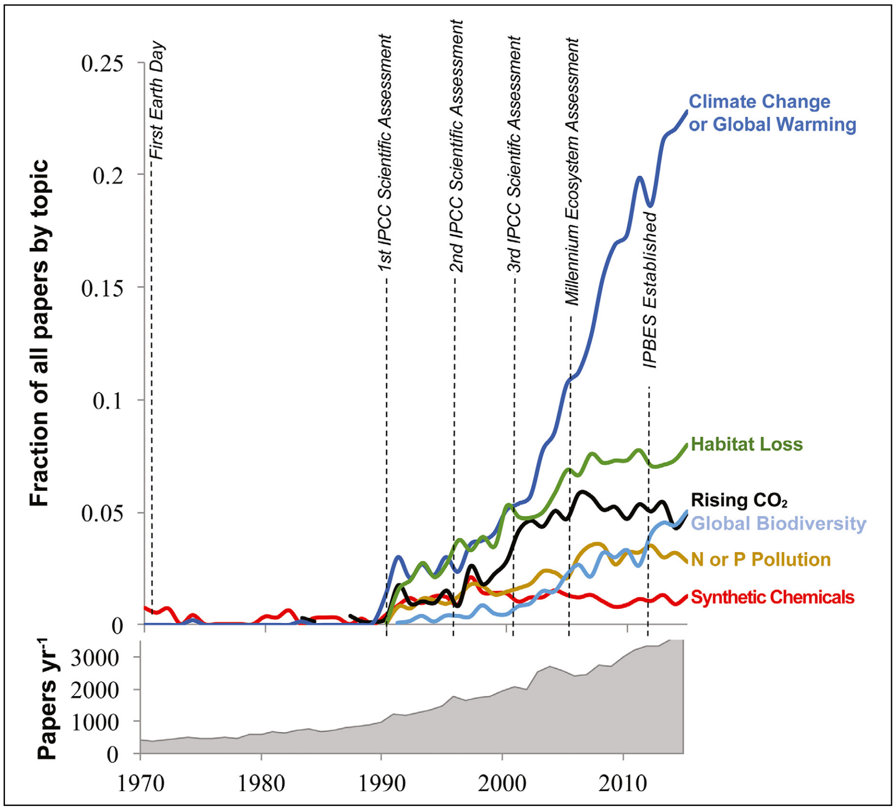

Figure 2. *Total publications and the proportion of published papers including global-change driver terms in the top 20 ecology journals (Table 1) according to the highest total citations reported in the ecology section of the ISI Web of Science for the period 1970–2015.*

between mainstream ecology journals and NSF funding (Figure 3, a and b).

Discussion

Our analysis demonstrates that synthetic chemicals are increasing as or more rapidly than other agents of global change. Recognizing that this proliferation is a global environmental problem is a first step toward developing worldwide solutions. These man-made compounds are increasing in their total quantity, diversity, and geographic expansion at rates at least on par with, and generally exceeding, the rates of change for elevated atmospheric CO_2, nutrient pollution, land-use change, and biodiversity loss. To qualify as a global driver according to the Millennium Ecosystem Assessment (MA 2005) requires (1) global distribution, (2) exponential change related to human population and economic growth, and (3) known impacts on organisms. Our analysis and literature synthesis demonstrates that synthetic chemicals clearly meet all three criteria.

Despite the rapid proliferation in the total amount, diversity, and targeted toxicity of many synthetic chemicals, our literature search revealed that publication on this topic in mainstream ecological journals has remained static for decades. This finding is in stark contrast to the rapid increase in the relative abundance of journal articles focused on other drivers of global change since 1990. We suggest that the lack of knowledge about how synthetic chemicals alter ecological processes represents a critical blind spot in the rapidly developing field of global ecology. More importantly, the resulting ignorance among scientists – about how synthetic chemicals affect biodiversity and ecosystem functions – represents a critical knowledge gap that is likely to impede society's ability to achieve many of the Sustainable Development Goals (UN 2015).

Our study suggests that the NSF DEB – the primary funding agency for US ecological research – is not currently funding ecological research on contaminants. This needs to change. The NSF funds research on rising atmospheric CO_2 levels and temperatures, declining stratospheric ozone concentrations, disrupted biogeochemical cycles, freshwater shortages, loss of biodiversity, and fundamental reshaping of the planet's land surface. Clearly, synthetic chemicals will add to and interact with these other widely recognized drivers of global change in altering Earth's biosphere. A failure to fund and conduct basic research on the role of these compounds in Earth's ecosystems will hinder future understanding of the drivers of planetary change. We must not exclude contaminant research from mainstream ecology, while research on chemical pollution that drives climate change (CO_2, N_2O, and CH_4), nutrient pollution (N and P), and acid rain (SO_x and NO_x) is treated as central to ecological science. It is time to remove this artificial intellectual barrier so that we truly are studying the biosphere of the Anthropocene.

Despite substantial overlap in research interests and numerous calls for better integration (Cairns 1988; Chapman 2002; Van Straalen 2003; Relyea and Hoverman 2006; Rohr *et al.* 2006), a historical disciplinary divide between ecologists and ecotoxicologists still hampers progress in predicting and preventing environmental harm by synthetic chemicals. We hypothesize that limited funding for research projects that bridge across environmental chemistry, toxicology, and ecology severely constrains interdisciplinary progress. The resulting lack of integration compromises our ability to understand how contaminants are transported, transformed, and assimilated in natural environments and the extent to which the pervasive influence of contaminants alters the structure and functioning of ecosystems

(Schwarzenbach *et al.* 2006; Malaj *et al.* 2014). Such information is critical to understand the constraints set by the ubiquity of synthetic chemicals in protecting, managing, and restoring ecosystems. Recent actions by the NSF to fund multidisciplinary studies of the environmental impacts of nanomaterials provide one visionary example of how strategic investments can support and maintain the necessary intellectual and conceptual bridges between these disciplines. Similar initiatives, especially at the international level, would facilitate comprehensive assessments of the role of synthetic chemicals as drivers of global environmental change. One of the primary initial needs for closing the gap between toxicology and ecology is to conduct a formal assessment of the funding "landscape" for research on the ecological impacts of contaminants. Here we report only a limited analysis, which documents a lack of investment by the NSF in research on this topic. A more thorough investigation of the true extent of current opportunities for funding at this interdisciplinary interface across all major science funding agencies is required to fully comprehend the growing mismatch between the amount and diversity of synthetic chemicals that humans are adding to the Earth (Figure 1) and the limited supply of funds available to understand the scope of this environmental problem.

A marked increase in publications on global-change drivers other than synthetic chemicals coincides with the first scientific assessment report of the Intergovernmental Panel on Climate Change (Houghton *et al.* 1990). It remains to be seen whether a similarly ambitious international effort to focus research and attention on biodiversity loss (the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services [IPBES; www.ipbes.net]) will lead to a correspondingly large increase in the rate of knowledge generation on biodiversity loss. We suggest that a major internationally coordinated effort to understand the ecological impact of synthetic chemicals is central to the success of the IPBES and IPCC initiatives and is long overdue. Our argument for this position has four parts. First, synthetic chemical contaminants are ubiquitous in the environment, and ever-improving analytical methods are uncovering a complex mixture of man-made chemicals present in every ecosystem, including remote areas such as Antarctica (Kolpin *et al.* 2002; Muir and Howard 2006; Sánchez-Bayo 2011; Stehle and Schulz 2015). Second, despite a conspicuous absence of environmental impact assessments of the ecological effects of synthetic chemicals at the global scale (Steffen *et al.* 2015), a growing body of research is demonstrating that synthetic chemical exposures have important ecological consequences, many of which are indirect and mediated by ecological interactions (Relyea and Hoverman 2006; Rohr *et al.* 2006; Rosi-Marshall and Royer 2012; Halstead *et al.* 2014; Gessner and Tlili 2016). Third, many synthetic chemicals are persistent or pseudo-persistent in the environment, with their ecological and, indeed, their evolutionary consequences likely to persist long after their release. Finally, synthetic chemical loading will interact with other agents of global change at both local and global scales, but the current understanding of these interactions is extremely limited (Rohr *et al.* 2011; Landis *et al.* 2014).

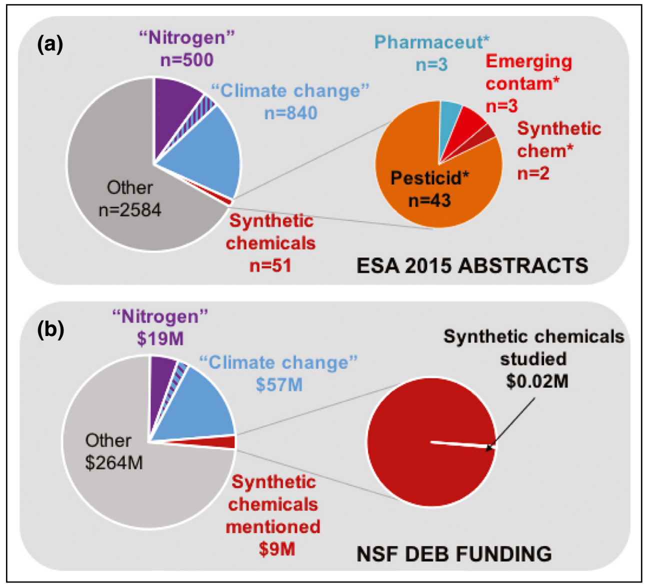

Figure 3. *Titles or abstracts including the terms "nitrogen", "climate change", or our suite of search terms for synthetic chemicals: (a) proportion of all submitted abstracts at the 2015 meeting of the Ecological Society of America; (b) proportion of all grants currently funded through the US National Science Foundation's Division of Environmental Biology (NSF DEB).*

Additional and improved research on the role of contaminants in the environment is a necessary step toward more effective governance of the global proliferation in synthetic chemicals, but research alone will be insufficient unless the following core needs are realized. First, the production and trade networks of all synthetic chemicals produced in large quantities or of particular concern must be tracked. Second, information on chemical hazards should be as widely available as the chemicals themselves. The costly repetition of historical mistakes made by industrialized countries must be avoided in emerging economies by ensuring that authorities and citizens of every nation have ready access to information about the health and environmental risks associated with the synthetic chemicals they manufacture and use. While much of this information is increasingly available online (eg the US Environmental Protection Agency's ECOTOX database; https://cfpub.epa.gov/ecotox/index.html), much more effort is required if relevant toxicity information is to reach end users who lack access to internet database resources. Third, a proactive rather than reactive approach needs to be established as a principle in evaluating the global hazard potential of new synthetic chemicals. To achieve this, ecologists and other environmental scientists will need to be engaged in the process of vetting new chemicals, with the goal of identifying both modern and potential future contaminants of broad concern and developing strategic plans for preventing, limiting, or mitigating their release to ecosystems. Although far from perfectly effective, the IPCC and the IPBES should serve as models for such coordinated international effort in the synthesis and transfer of information aimed at closing knowledge gaps, and underpinning policy initiatives for appropriate and potent international treaties.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1450/suppinfo

