LETTERS

Multiple pathways to conservation success

Corey C. Phillis[1*], Sacha M. O'Regan[1*], Stephanie J. Green[1*], Jeanette E.B. Bruce[1*], Sean C. Anderson[1], Jennifer N. Linton[1], Earth$_2$Ocean Research Derby**, & Brett Favaro[1,2]

[1]Earth$_2$Ocean Research Group, Department of Biological Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada
[2]Department of Fisheries and Aquaculture, Vancouver Island University, Nanaimo, BC, V9R 5S5, Canada

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Correspondence
Corey C. Phillis, Earth$_2$Ocean Research Group, Department of Biological Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada.
Tel: 778-782-9427; fax: 778-782-3496.
E-mail: cphillis@sfu.ca

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* Authors contributed equally, listed in reverse alphabetical order.
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Abstract

Conservation successes can and do happen, however, the process by which society achieves them remains unclear. Using a novel culturomics approach, we analyse word usage within digitized texts to assess the chronological order in which scientists, the public, and policymakers engage in the conservation process for three prominent conservation issues: acid rain in North America, global DDT contamination, and the overexploitation of African elephants for ivory. Variation in the order and magnitude of sector responses among the three issues emphasizes that there are multiple pathways to conservation success and that science is just one component. Our study highlights that while scientists can initiate the process, policy change does not occur in the absence of public interest. We suggest that the fate of conservation action is not solely determined by the scientific soundness of the conservation plan, but rather requires the engagement of scientists, public, and policy makers alike.

Introduction

Unprecedented levels of human disturbance increasingly challenge our ability to conserve nature across the globe (Millennium Ecosystem Assessment 2005; Sutherland *et al*. 2009). Despite the remarkable growth of conservation science as a formal discipline since the foundational text of Soule and Wilcox (1980), a disconnect remains between research products and policy makers' need to influence conservation action (Robinson 2006). To translate research into conservation outcomes, scientists are recognizing they must engage with the overall conservation process (e.g. Holling and Meffe 1996; Knight *et al*. 2008; Black *et al*. 2011; Kassen 2011; Martin *et al*. 2012). Yet while conservation successes can and do happen (Sodhi *et al*. 2011), the process by which society addresses environmental problems remains unclear. Understanding the most effective approaches to elicit change is therefore a critical element of ensuring effective conservation science.

Recently, Baron (2010) conceptualized the conservation process as a reactionary pathway in which three main sectors of society—scientists, the public, and policy makers—interact. Within this pathway, scientists are first to identify a conservation problem, which we define as having two parts: human-mediated causes (i.e., stressors) and ecological responses (e.g., Sutherland *et al*. 2009; Figure 1). However, products of scientists' research focus do not lead directly to effective policy change; given that societal values dictate the goals of conservation

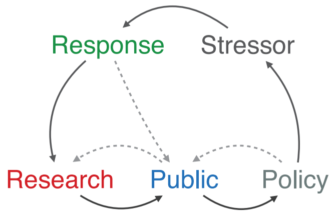

Figure 1 The conservation process conceptualized as a reactionary pathway where science motivates public interest, which leads to policy action (solid lines). However, the realized conservation pathway has never been quantified and may take different forms (dashed lines).

policy, a degree of public interest and social consensus on the problem's importance is needed (Brown *et al*. 2010). As public awareness of the problem increases, public pressure is directed at policy makers to create societal change that resolves the problem (Figure 1). Existence of such pathways has been qualitatively proposed (Downs 1972; Baron 2010; Brown 2010); however, no one has quantitatively assessed this process for real-world conservation problems.

In this study, we employ a novel data-driven analysis of the pathways to conservation success by assessing the chronological order in which scientists, the public, and policymakers engage in the conservation process. We use methods from the field of culturomics, an emerging discipline that captures cultural trends by quantitatively analyzing word use over time in digitized texts (Michel *et al*. 2011). Michel *et al*. (2011) first established the field of culturomics using the Google Books database. Our approach builds upon their method in two important ways. First, the inherent lag-time to print for books diminishes their ability to track cultural trends in real-time and institutes a filtering of what is of interest (Schwartz 2011). We address this issue by focusing on news periodicals and peer-reviewed journal articles, which may better reflect real-time interest in a topic. Second, by analyzing autonomous digitized databases of periodicals and peer-reviewed literature, we independently track interest in a given topic across multiple societal sectors. By merging this culturomics analysis of sector-specific literature with policy and environmental data, our study assesses how science, public, and policy sectors interacted to address three classic conservation problems.

Methods

Case studies

To assess the process by which society addresses conservation problems, we selected three well-documented case studies that satisfied two criteria: (1) a clear causal link had been established between an anthropogenic stressor and ecological response, and (2) policy changes to societal practices had been made in an effort to ameliorate the problem. Below we provide a brief description of each conservation problem.

The production of acid rain

Acid rain occurs when combustion emissions, primarily sulfur dioxide (SO_2) and nitrogen oxides (NO_x), react with water and oxygen molecules in the atmosphere to produce acidic compounds, which act as a stressor on ecosystems by reducing the pH of rainwater (Likens *et al*. 1972). The "acid rain" phenomenon began in the 1950s (Likens and Bormann 1974) due to changes in industrial practices (e.g., increased use of natural gas) and personal habits (e.g., increased vehicle use) that increased emissions of SO_2 and NO_x into the atmosphere (Gorham 1955; NADP 2011).

Dichlorodiphenyltrichloroethane (DDT) contamination

DDT was first synthesized in 1874 in the United States, and was used as a pesticide to prevent the spread of typhus and malaria (by killing mosquitoes), and to prevent destruction of forests and cropland (Friedman 1992; Turusov *et al*. 2002). Research has shown DDT persists in the environment and in animal tissue for years after exposure (Lopez-Carrillo *et al*. 1997). Although definitive impacts of DDT on human health have yet to be determined, there is conclusive evidence DDT concentrations above certain threshold levels can cause reproductive complications for wildlife (Longnecker *et al*. 1997; Turusov *et al*. 2002).

Overexploitation of African elephants for ivory

The overexploitation of African elephants for ivory was the critical driver of Africa-wide (particularly East African) population declines in the species during the latter half of the 20th century (Milner-Gulland and Beddington 1993). In 1989, the Convention on International Trade in Endangered Species (CITES) instituted an international ban on ivory exports (Stiles 2004).

Quantitative metrics

For each case study, we identified quantitative metrics for each conservation problem (i.e., stressor and response), the contributions of scientists and the public to the conservation process, and the date of policy actions. We describe each metric below.

Table 1 Data sources and units for the metrics we used to describe each 'Stressor' and 'Response' for three conservation issues: the production of acid rain, DDT contamination, and the overexploitation of African elephants for ivory. The search terms used to gather data from Web of Science (WOS) and Google News Archives (GNA) are listed for each issue.

Conservation issue	Stressor	Response
Acid rain		
GNA: Acid and rain WOS: "Acid rain"	1950–2011: United States gross emission of SO_2 and NO_x (10^6 tonnes year^{-1}) (NADP 2011)	1965–1972: mean annual pH of rainwater from New Hampshire, USA (Likens and Bormann 1974) 1978–2010: United States mean annual pH of rainwater (NADP 2011)
DDT contamination		
GNA: DDT WOS: "DDT" OR "Dichlorodiphenyltrichloroethane"	1950–1985: Global DDT use (kt year^{-1}) (Sun *et al*. 2005)	DDT concentration (% of maximum) within: 1967–2004: Mt. Everest ice core (Wang *et al*. 2008) 1968–1972: polar bear tissue (Hudson Bay, Canada) (Braune *et al*. 2005) 1966–1995: Arctic char tissue (Sweden) (Lindell *et al*. 2001)
Elephant ivory trade		
GNA: Elephant and ivory WOS: "African elephant" OR "Loxodonta"	International ivory export (tonnes year^{-1}) was used as a proxy for the number of African elephants killed year^{-1} for tusks: 1950–1978 (Pearce 1989) 1979–1987 (IUCN trade estimates; Luxmoore *et al*. 1989) 1989–2009 (Illegal post-ban trade was estimated as 10× the reported annual volume of illegal international ivory seizures; Miliken *et al*. 2009)	Africa-wide African elephant population size (millions year^{-1}): 1952–1986 (modeled estimates; Milner-Gulland & Beddington 1993) 1979 (Douglas-Hamilton 1979) 1984 (Douglas-Hamilton 1984) 1987 (Douglas-Hamilton 1989) 1989 (Pearce 1989) 1995 (Said *et al*. 1995) 1998 (Barnes *et al*. 1998) 2002 (Blanc *et al*. 2002) 2007 (Blanc *et al*. 2007)

Stressor and response

For each case study we gathered time-series data on the human-mediated stressor driving the conservation problem, as well as the resulting ecological response from peer-reviewed and grey-literature sources (Table 1). We collected data that corresponded with the broadest available spatial scale of the respective case study: United States for acid rain, Africa-wide for ivory, and global scale for DDT.

Research

Peer-reviewed research papers are written for a scientific audience and reflect research interests of specific disciplines. We quantified research output from scientists for each case study over time by recording the number of peer-reviewed research articles indexed in the Web of Science (WOS) "Science Archives" containing one or more keywords per year between 1900 and 2008 (Table 1). Because WOS indexes pre-1990 articles by title only, we restricted our search to terms found in the title of "article" documents in the Sci-Expanded database, including results from all languages and with lemmatization turned off. We accounted for the increasing number of peer-reviewed research articles published over time by standardizing our results by the total number of articles within the WOS Sci-Expanded database per year. Whereas some search terms, particularly non-technical terms such as "acid rain," only appear in English research articles and our searches will only return digitized texts, our standardization procedures make it unlikely our time series are temporally biased.

Public

Periodicals are written for a broad, general audience, and therefore presumably reflect topical interests of readers at the time of publication. We quantified public

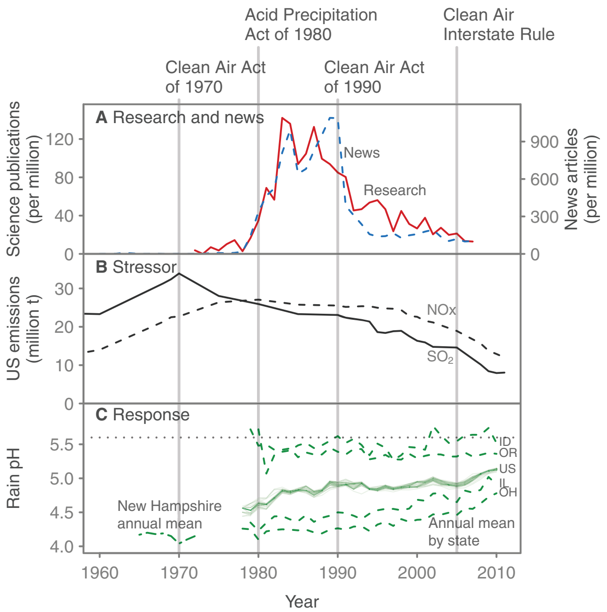

Figure 2 The production of acid rain. (A) Public and scientific interest is quantified as news (dashed line) and research (solid line) publications on an annual basis, respectively. (B) Magnitude of the stressor is quantified by annual US NO_x (dashed line) and SO_2 (solid line) emissions. (C) System response is measured as the pH of US rainwater. Dashed lines (1980–2010) represent the states with the lowest (OH), and highest (ID) median pH and the most positive (IL) and most negative (OR) slopes. The solid lines represents the median mean pH across all sites jack-knifed by excluding one state at a time and recalculating the trend. See Table 1 for data sources.

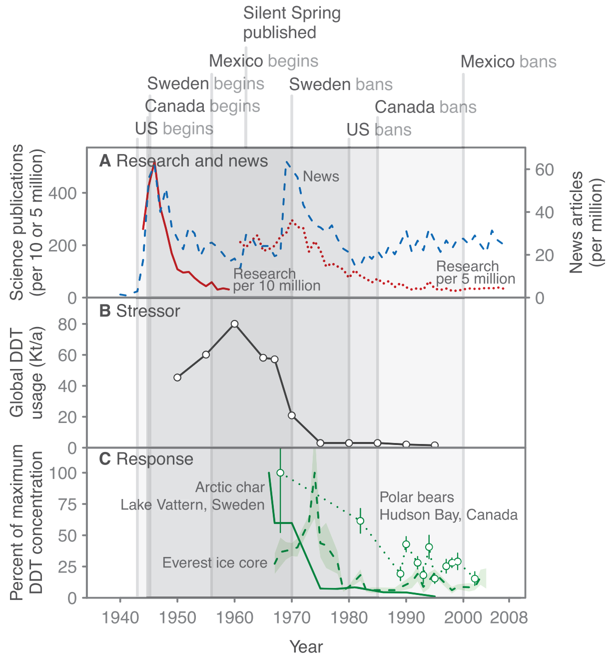

Figure 3 DDT contamination. (A) Public and scientific interest is quantified as news (dashed line) and research (solid line) publications on an annual basis, respectively. (B) Magnitude of the stressor is quantified as total annual global DDT use. (C) System response is quantified as the mean concentration of DDT in Mt. Everest ice core (dashed line), Arctic char tissue (solid line) and polar bear tissue (dotted line), scaled to the maximum value in each time series. Confidence intervals on the Mt. Everest ice core and polar bear data are single standard deviations above and below mean estimates. Shaded regions indicate when the United States, Canada, Sweden, and Mexico began and subsequently banned use of DDT. Darker regions indicate multiple countries using DDT. See Table 1 for data sources.

interest in each conservation problem as the number of archived print and online news articles containing at least one of our chosen keywords (Table 1) in each year between 1900 and 2008, obtained by searching the Google News Archives database and enumerating results by year via the Archive Timeline function (the functionality of which has recently been changed, see discussion; Google Product Team 2011). We accounted for increases in the number of digitized and online media sources over time by standardizing our results by the number of articles within the Google News Archives in the same year which contained the word "the" (to approximate the total number of articles indexed).

Policy

We anticipated that inflection points for changes in public and scientific interest would coincide with major policy changes. We therefore identified dates of major policy events for each conservation issue. We identified policy changes that were at the spatial scale relevant to the stressor and response data for each case study.

Results

Between 1940 and 2007, the number of news articles indexed by Google News and science publications indexed by WOS increased substantially (news: 2.8 million to 27 million articles year^{-1}; science: 23,427 to 929,425 publications year^{-1}; Figure S1). The volume of news and research publications for our three case studies was markedly different, with the greatest annual research output for DDT (maximum = 5209 publications million^{-1}; Figure 3), followed by acid rain and the elephant ivory trade (142 and 55 publications million^{-1}, respectively; Figures 2 and 4). In contrast, the maximum annual number of news publications about acid rain (1090 articles million^{-1}; Figure 2) greatly exceeded that for DDT and the elephant ivory trade (64 and 22 articles million^{-1}, respectively; Figures 3 and 4). The ratio of news to research output was therefore 25–50 times greater for acid rain than for DDT or the ivory trade (Figure S2).

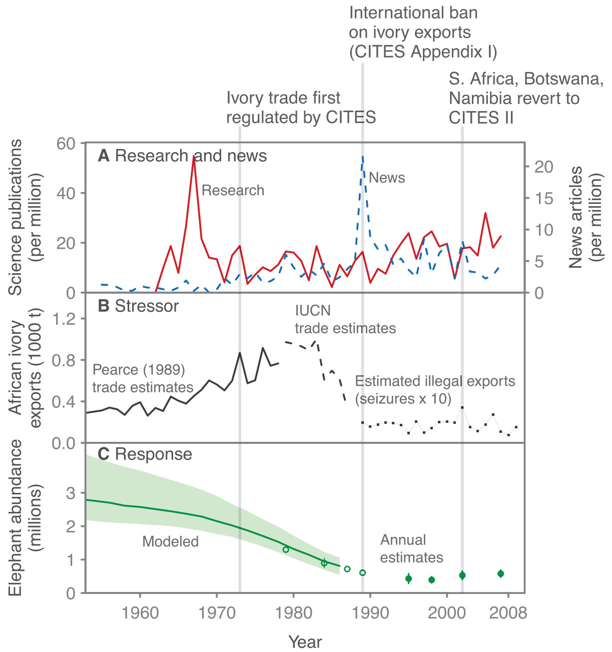

Figure 4 Overexploitation of African elephants (*Loxodonta spp.*) for ivory. (A) Public and scientific interest is quantified as news (dashed line) and research (solid line) publications on an annual basis, respectively. (B) Magnitude of the stressor is quantified as annual African ivory exports given by Pearce (1989; solid line) and IUCN trade estimates (dashed line). The dotted line represents seizures multiplied by ten to approximate illegal exports. (C) System response is quantified as Africa-wide elephant population abundance. The solid line and shaded area represent modeled estimates, open circles are average continent-wide estimates, and the solid circles are from the African Elephant Database. See Table 1 for data sources.

The production of acid rain

Acid rain was first identified as a significant conservation issue in 1974 (Likens and Bormann 1974), despite the fact SO_2 emissions peaked in 1970 (33.9 Mt year^{-1} in the United States). The first scientific evidence of acidic rainfall in the United States (Likens and Bormann 1974; minimum pH of 4.04 in New Hampshire in 1970; Figure 2A and C) marked the start of a rapid increase in research and news output on acid rain through the late 1970s (Figure 2A). In 1978, the US began a national monitoring program to record the pH of precipitation (NADP 2011). In 1980, NO_x emissions peaked at 27.1 Mt year^{-1} in the United States. In the same year, the US enacted the Acid Precipitation Act, which established broad objectives to manage output sources and develop plans to mitigate the effects of acid rain. Research and news output for acid rain peaked twice—in both cases the research output peak occurred prior to the news output peak (research: 1983 and 1987; news output: 1984 and 1989; Figure 2A). The US Clean Air Act of 1990 targeted NO_x emissions and by 2007 NO_x emissions had returned to 1960 levels (Figure 2B). Research and news output dropped substantially after the introduction of the Clean Air Act of 1990, and since the mid-1990s has remained relatively constant (~10% of peak levels; Figure 2A). The median of mean rainwater pH by state has generally become less acidic since at least 1978 to a minimum acidity of 5.12 in 2010 (Figure 2C). The Clean Air Interstate Rule, which further regulated SO_2 and NO_x emissions, was associated with a negligible increase in news coverage, suggesting interest in the issues appears to have largely waned in public and scientific sectors.

DDT contamination

News and research output for DDT peaked in 1946 (5209 publications million^{-1} and 62 articles million^{-1}, respectively) as its application as a pesticide following World War II became known (Figure 3A). Global DDT use peaked at 80.1 kt year^{-1} in 1960 (Figure 3B; Sun *et al.* 2005). In 1962 Rachel Carson published Silent Spring (Carson 1962), which focused on the environmental toxicity of DDT. This publication was associated with a large increase in news articles on environmental consequences of DDT use. Over this period global DDT usage dropped quickly (Figure 3B). In 1969 Sweden became the first nation to ban production and use of DDT (Turusov *et al.* 2002). In the same year, the number of news articles on DDT peaked a second time at approximately the same volume as in 1946 (Figure 3A); research publications referencing DDT peaked a year later at ~10% of their initial peak volume. As global DDT use dropped, there were concomitant reductions in DDT concentration within tissues of Arctic char (*Salvelinus alpinus*) in Sweden (Lindell *et al.* 2001), polar bears (*Ursus martimus*) in Hudson Bay, Canada (Braune *et al.* 2005), and in ice cores drawn from Mount Everest (Wang *et al.* 2008) (Figure 3C). By 1975, global DDT use had diminished to ~3 kt year^{-1}, and has since remained relatively constant (Figure 3B). Both news and research outputs declined in the 1970s, but while research publications on DDT declined to 1% of peak volume, news articles on DDT remain at 50% of peak volume and are holding relatively steady (Figure 3A).

Overexploitation of African elephants for ivory

Research on African elephants (*Loxodonta* spp.) peaked in 1967; however, this peak corresponded with only nine publications (Figure 4A). The first major policy intervention to regulate the elephant ivory trade was in 1973, when CITES was first established and began regulating international elephant ivory trade to stem observed population declines (Stiles 2004). Annual Africa-wide ivory exports peaked at ~1,000 t year^{-1} in the early 1980s (Pearce 1989; Figure 4B), coinciding with a decline in modeled African elephant abundance (Milner-Gulland and Beddington 1993 Figure 4C). Despite ongoing declines in African elephant abundance, news and research publications did not substantially increase until 1989, when CITES Appendix I banned international export of African elephant ivory products (Figure 4A). Following the ban, ivory exports inferred from illegal-seizure data have remained at a constant level (Figure 4B). Despite regional recoveries, continent-wide African elephant abundance remains at ~1/5 of 1960 modeled abundance (Blanc *et al*. 2002; Blanc *et al*. 2007; Figure 4C). In recent years news publications on elephant ivory have returned to pre-ban levels, while scientific publications have increased modestly since the institution of the 1989 export ban.

Discussion

By simultaneously tracking word use in peer-reviewed journals and digitized news periodicals, human-induced stressors, environmental-response data, and policy events, we reveal how research, public, and policy sectors interact to achieve conservation outcomes for three classic conservation problems. The order of science-, public-, and policy-sector responses varied for each issue, emphasizing that there are multiple pathways to conservation success (Figure 5).

The problem of acid rain production closely followed the conceptualized conservation pathway (Figure 1), with scientific interest preceding public interest, followed by policy change (Figure 5A). Policy change, in turn, alleviated the stressor and subsequently improved the system's response (Figure 5A). We observed a similar pathway for the problem of DDT use (Figure 5B), but with one key difference: public interest preceded scientific interest, and appears to have sparked a feedback loop between the two sectors prior to policy change. While scientific interest in the overexploitation of African elephants for ivory also preceded public interest (Figure 5C), unlike the other case studies, the timing of peaks in research and public interest appeared uncoupled (Figure 5C). Additionally, while public interest corresponded to the timing of policy change, it is likely this interest was in response to policy change, rather than a driver of it. Whereas there is observable improvement in the stressor (i.e., reduction of ivory trade), the ecological response has been slow to recover (i.e., suppressed African elephant abundance; Figure 4C).

We propose that three factors may influence the pathways by which conservation issues are addressed. First, high scientific uncertainty may present a barrier to stimulating public interest and policy change, as well as inadvertently encouraging divisiveness in societal values (Brown *et al*. 2010). This disconnect likely stems from the fact that policy makers and resource managers must act more decisively than researchers, who temper conclusions and recommendations with statements of uncertainty (Rosenberg 2007). Second, for complex problems, or problems less clearly linked to human-induced causes, evaluating the drivers and status of the problem is more difficult. For example, there are ongoing challenges to the recovery of African elephant populations, including

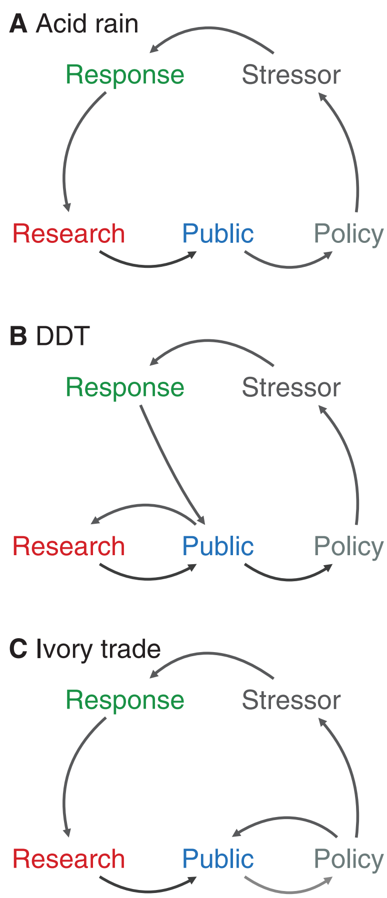

Figure 5 The conservation process as interpreted for each case study. (A) Scientific interest in acid rain production preceded public interest, and was followed by policy change, similar to the reactionary pathway conceptualized in Figure 1. Policy change resulted in the alleviation of the stressor and subsequent improvement of the system's response. (B) DDT contamination followed a similar pathway to that of acid rain production. A key difference for this issue is that public interest preceded scientific interest, and appears to have sparked a feedback loop between the two sectors prior to policy change. (C) Again, research interest preceded public interest into the overexploitation of African elephants for ivory. While public interest corresponded to the timing of policy change (grey arrow), it seems likely this interest was in response to policy change.

long generation time, poaching, habitat degradation, and difficulty enforcing regulations in unstable countries (Blanc *et al*. 2007; Bouche *et al*. 2011; Douglas-Hamilton 1984, 2009; Lemieux and Clarke 2009; Wittemyer *et al*. 2011). In contrast, the stressors behind DDT contamination and acid rain production are straightforward. Third, public support for policy changes can lag behind or reject scientific consensus if the actions would be costly or divisive (Brown *et al*. 2010). To this end, the strength of coupling between public and scientific interest may relate to whether the problem is perceived as directly impacting human well-being (e.g., effects of DDT contamination vs. African elephant declines). However, changes in policy could also come about because of cultural, economic, and political factors at regional or global scales as worldviews change.

Future research could advance our culturomics analysis in three directions. First, we found the volume of research articles steeply declined following policy change. This pattern could reflect waning research interest in the problem. Alternatively, it could reflect a shift of responsibility toward governments and NGOs after policies are implemented. Furthermore, the media may report less on an issue as it becomes common parlance, despite continued public interest. To accurately track post-policy research interest, future studies could include grey literature in addition to primary sources. Second, researchers could incorporate spatial and temporal dynamics of language into future analyses. Over time, word-switching (i.e., changing terminology used to describe an issue) could occur, complicating our ability to track conservation problems over long time scales (Michel *et al*. 2011; Petersen *et al*. 2012). For example, our analysis suggests legislation in the 1950s and 1960s targeting "acid rain" occurred in the absence of news output or scientific evidence. However, news articles employed the terms "air pollution" and "smog" in pre-1970s publications. Moreover, our method would have missed local non-English-language publications. Third, continued application of culturomics to conservation science requires access to easily searchable, open-access databases. Interfaces such as the Google News Archive Timeline are vital tools to researchers. Google News has since removed the Archive Timeline (Google Product Team 2011). Whatever the reasons for this change, restricting public access to data limits the utility of culturomics techniques.

Researchers could apply our methods to other scientific and public interest data sources. The open science movement (e.g., Woelfle *et al*. 2011) provides high-frequency near-real-time data sources such as Twitter (http://twitter.com/), scientific blogs (e.g., http://blogs.nature.com/), and preprint archives (e.g., http://arXiv.org). These data may allow for more rigorous statistical evaluation of scientific and public interest with the potential to infer causal links. For example, combined with higher-frequency data, researchers could use our methods to quantitatively assess the role of advocacy in accelerating the pace of conservation-related policy change.

Our study highlights two key lessons for conservation scientists. First, we re-emphasize that science is just one part of the pathway to success. Scientists can initiate the process, but policy change does not occur in the absence of public interest. Policy is formed through the lens of the public (Brown *et al*. 2010). If scientific suggestions do not resonate with the public, policy makers are unlikely to enact policies that ameliorate environmental stressors. Second, to effectively engage the public, scientists must focus on results with the greatest certainty. This will strengthen public confidence in science and garner support for the problems at hand (Olson 2009).

We emphasize that conservation issues are context-dependent, and that generalizations managers make using our approach must take this into account. By selecting classic conservation issues that have received scientific, public, and policy attention, we described conservation pathways when things go right. Developing a quantitative perspective of the conservation process will require an unbiased sampling of conservation issues across a broad range of outcomes. This perspective could allow managers to identify failings in an active conservation process and adjust course, and incorporating social media data could enable them to make these adjustments in real-time.

Many conservation challenges lie ahead; some will be met with success while others will not. The fate of conservation actions is not solely determined by the scientific soundness of the conservation plan, but rather requires engagement of scientists, public, and policy makers alike. We demonstrated how a culturomics approach can track the progress of a conservation issue, incorporating data from all sectors of society involved in the conservation cycle. Using this method, it may be possible to identify management strategies that successfully engage all three sectors of the conservation pathway and lead to policy implementation—ultimately improving the efficiency with which we address conservation problems.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Figure S1. Between 1950 and 2008, the total annual number of news articles and scientific publications digitally archived has increased. (A) Articles within Google News Archive containing the word "the," and (B) publications indexed within the WOS.

Figure S2. The annual ratio of news publications within Google News Archive to research publications within WOS for acid rain, DDT, and elephant ivory.