later attributed to trace amounts of iron in the samples (*7*). Ferromagnetic graphite, upon proton irradiation (*8*), was difficult to attribute to magnetic impurities, but was not well understood, owing to the variety of defects formed upon high-energy ion bombardment. Graphene was first isolated around this time as well, and was quickly incorporated into high-quality spin valve devices, analogous to those used in hard disk drives. Such devices provided additional evidence for magnetic carbon, as a signature of spin scattering was observed due to magnetic moments formed when the graphene was exposed to hydrogen or bombarded to create vacancies (*9*). These results were consistent with magnetometry measurements that showed evidence for paramagnetism (*10*). However, neither of these approaches were able to observe ferromagnetism, and the atomic origin of the moments could not be directly determined.

González-Herrero *et al.* study one fundamental building block of this magnetic state—namely, individual hydrogen adatoms and dimers with controlled sublattice site and spacing. Graphene growth, hydrogenation, and characterization were all performed in the same ultrahigh-vacuum chamber, which was critical in overcoming shortcomings of prior approaches. Few-layer graphene was grown by heating a SiC single crystal, thus minimizing the possibility of magnetic impurities or contamination from the environment. Relatively low-energy atomic hydrogen from thermal cracking of H_2 yielded a low surface coverage of a single class of defect, rather than the variety of defects and complexes produced by high-energy ion irradiation. Lastly, in situ scanning tunneling microscopy (STM) was used to characterize the quality of the sample before and after hydrogenation and to directly probe the electronic states associated with individual hydrogen atoms on the surface. This method avoids the ensemble averaging typical of more conventional magnetic characterization techniques.

> ***"...one can imagine storing information at unprecedented densities by painting magnetic bits on graphene canvases."***

To prove that the hydrogen adatoms were magnetic, the authors drew insight from the Anderson model of impurity magnetism, a model that predicts sensitivity to doping. This was observed by the collapse of a spin-split doublet of states into a single state, upon n-type or p-type doping of the graphene. More quantitative density functional theory (DFT) calculations validated this interpretation and provided insight into magnetic ordering between adatoms. Experimentally, González-Herrero *et al.* were able to directly probe interactions by using STM atomic manipulation to form hydrogen dimers with varying spacing and sublattice site. As explained by the DFT calculations, and realized experimentally, dimers on the same sublattice create an imbalance and order ferromagnetically, whereas dimers on opposing sublattices maintain the balance and are nonmagnetic. These interactions persist at relatively large separations compared to conventional magnets based on more localized atomic orbitals.

There are several key challenges toward realizing robust magnetic graphene for applications. First, the sensitivity of the magnetic state to doping offers the opportunity for control with a gate electrode, but may be problematic in typical graphene devices, where charged impurities in a SiO_2 substrate create random puddles of n- and p-doping. Future work could probe whether wide band-gap graphane is as vulnerable to charge puddles, or reduce their influence through sandwich structures of other 2D materials, such as boron nitride. Second, although longer-range magnetic ordering is promising, it also places a premium on control over the hydrogen adsorption site. This atomic-scale precision is very difficult to realize on a large scale, though preferential adsorption may be possible by breaking the degeneracy of the sublattices through interactions with other graphene layers or other 2D materials in close registry. Ferromagnetic ordering above room temperature has been predicted for magnetic graphene, but it remains to be seen if this target can be realized experimentally. If these challenges can be met while preserving the intrinsic quality of graphene for electron and spin transport, then graphene may indeed become a leading candidate material in the roadmap for next-generation information technologies based on electron spin. ■

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BIG DATA AND BIODIVERSITY

Filling in biodiversity threat gaps

Only 5% of global threat data sets meet a "gold standard"

By **L. N. Joppa,*† B. O'Connor, P. Visconti, C. Smith, J. Geldmann, M. Hoffmann, J. E. M. Watson, S. H. M. Butchart, M. Virah-Sawmy, B. S. Halpern, S. E. Ahmed, A. Balmford, W. J. Sutherland, M. Harfoot, C. Hilton-Taylor, W. Foden, E. Di Minin, S. Pagad, P. Genovesi, J. Hutton, N. D. Burgess**

POLICY

The diversity of life on Earth—which provides vital services to humanity (*1*)—stems from the difference between rates of evolutionary diversification and extinction. Human activities have shifted the balance (*2*): Species extinction rates are an estimated 1000 times the "background" rate (*3*) and could increase to 10,000 times the background rate should species threatened with extinction succumb to pressures they face (*4*). Reversing these trends is a focus of the Convention on Biological Diversity's 2020 Strategic Plan for Biodiversity and its 20 Aichi Targets and is explicitly incorporated into the United Nations' 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs). We identify major gaps in data available for assessing global biodiversity threats and suggest mechanisms for closing them.

Reducing rates of biodiversity loss and achieving environmental goals requires understanding what is threatening biodiversity, where risks occur, how fast threats are changing in type and intensity, and what are the most appropriate actions to avert them (*5*). A UN report proposed specific policy recommendations for mobilizing the "big data" revolution for sustainable development and environmental protection (*7*). The combination of crowd-sourced data, large-scale ground-based monitoring schemes, and satellite earth-observation missions is seemingly capable of unprecedented insight into global threats to biodiversity and how human interventions are altering those threats [e.g., (*7*)].

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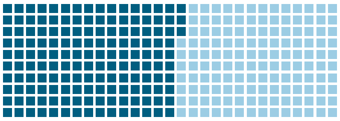
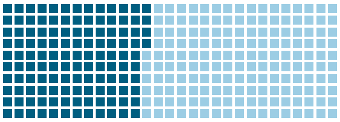
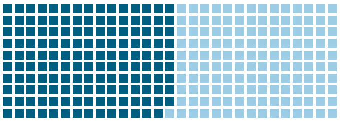
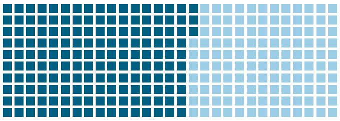
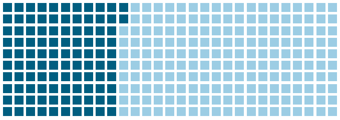
Qualifying attributes of biodiversity data sets

Five data-set attributes considered key for use in biodiversity threat assessments.

ATTTRIBUTE	DEFINITION AND JUSTIFICATION
Freely available - 153 data sets (53%) 	These data sets are freely available (at least for noncommercial use). Being freely available is necessary, but insufficient, as a free data set may be impossible to access, depending on the technical capacity of users.
Spatial resolution - 124 data sets (43%) 	These data sets are at a gridded spatial resolution of ≤10 km × 10 km or are stored in vector format. Of species on the IUCN Red List, 23% have ranges smaller than 1000 km^2, which could be covered with no more than 10 grid cells, a minimum desirable resolution for most analyses.
Up to date - 149 data sets (51%) 	These data sets were produced within the last decade: a time frame sufficiently recent to inform current and future policy.
Repeated - 163 data sets (56%) 	These data sets are available for at least two time points. Changes over time are fundamental for many conservation assessment criteria and for understanding impacts of regulatory policies.
Assessed for accuracy - 112 data sets (39%) 	These data sets are likely either direct observations or modeled data sets that have been assessed for accuracy at a global scale. Conservation assessments are generally subject to independent review, and data sets used must be of sufficient scientific rigor.

DELUGE OR DROUGHT? We used a threat classification scheme (*8*) (see the graph) that, although not without shortcomings (*9*, *10*), has been widely deployed for tens of thousands of conservation assessments for species, sites, and projects. By "threat," we mean "The proximate human activities or processes that have caused, are causing, or may cause the destruction, degradation, and/or impairment of biodiversity targets" (*8*). Determining the impact of a threat on a species or ecosystem is a separate process often included in a conservation assessment. We followed a structured data collection procedure and associated each data set with one or more classes of threat [see supplementary materials (SM) for details]. We omit three threat classes from our analysis: two (Geological Events; Other Options) are not exclusively anthropogenic; one (Climate Change and Severe Weather) received comprehensive treatment by the Fifth Assessment Report for the Intergovernmental Panel on Climate Change. We restricted our search to spatial data sets with a global extent. We assume that the data sets identified by this initial search will grow as additional data sets and metadata become known or are created. Over time, we recommend inclusion of the numerous available regional data sets (even if they do not meet data set attributes identified here) to create more globally representative information.

We identified 290 unique data sets (table S1) across nine threat classes from data sources ranging from remote sensing via satellites to citizen-science initiatives (fig. S1). Six data providers account for more than a fifth of the entire catalog of data sets. This apparent data deluge is misleading: Our analysis reveals how little is actually available, at the global level, about the spatial and temporal distribution of anthropogenic threats to biodiversity.

In order to assess whether data on different threats were available in proportion to their importance for biodiversity, we used threat information (for threatened taxa that have been comprehensively assessed) from the International Union for Conservation of Nature's Red List of Threatened Species (IUCN Red List), the repository of information on the global extinction risk of species. We find that the frequency of threats to marine or terrestrial and inland water species on the Red List is disproportionate to the availability of data sets on those threats (see the graph and table S2). Biological Resource Use (including direct and indirect impacts of hunting, fishing, and logging) is one of the most common threats to species, yet accounts for just 5% of threat data sets.

To assess how much threat information is available and actionable, we examined the data sets with respect to five desirable data attributes (see the table above and table S1). We note that determining accurate attribute values was often difficult because of a lack of formal metadata, which creates uncertainty in the absolute number of data sets that might satisfy all criteria. Regardless, only 14 data sets (5%) satisfy all five attributes and not all threat classes are represented (see fig. S2, SM, and table S1 for details). Data sets that do comply are often applicable to only a few taxa or habitats.

BUSINESS MODELS. The conservation community should aspire to at least one "gold-standard" data set—that meets at a minimum all five attributes in the table and is applicable to as many taxa as possible—for each class and subclass of threat. This will require working with data providers to develop business models that leverage new, longer-term funding mechanisms and partnerships with government and the private sector.

Partnerships with data owners and creators. In certain instances, data required for effective conservation policy already exist but are not accessible [e.g., owing to access cost, commercial considerations, or intellectual property (IP) arrangements] to organizations or agencies mandated to conserve biodiversity. Sometimes these data result from taxpayer-funded initiatives that can result in major success stories (*6*). In 2008, NASA announced the free, public release of the Landsat image archive, dating back to 1978. This empowered the scientific community to begin studies of land cover change at an actionable resolution. Since then the European Space Agency opened the Sentinel Scientific Data hub, a free and open-access data portal for imagery from the Copernicus Sentinel missions, and the French Space Agency declared 5-year-old or older SPOT satellite data free of charge to noncommercial users.

Private-sector data also have potential to fill major gaps. Gaining access will require partnerships that respect the IP of companies and the right of conservation organizations to use data for conservation actions. One such agreement between the UN Environment Programme (UNEP) World Conservation Monitoring Center and the IHS Company enables detailed and comprehensive data on oil and gas activity worldwide to be used for biodiversity assessments. More broadly, the conservation community should

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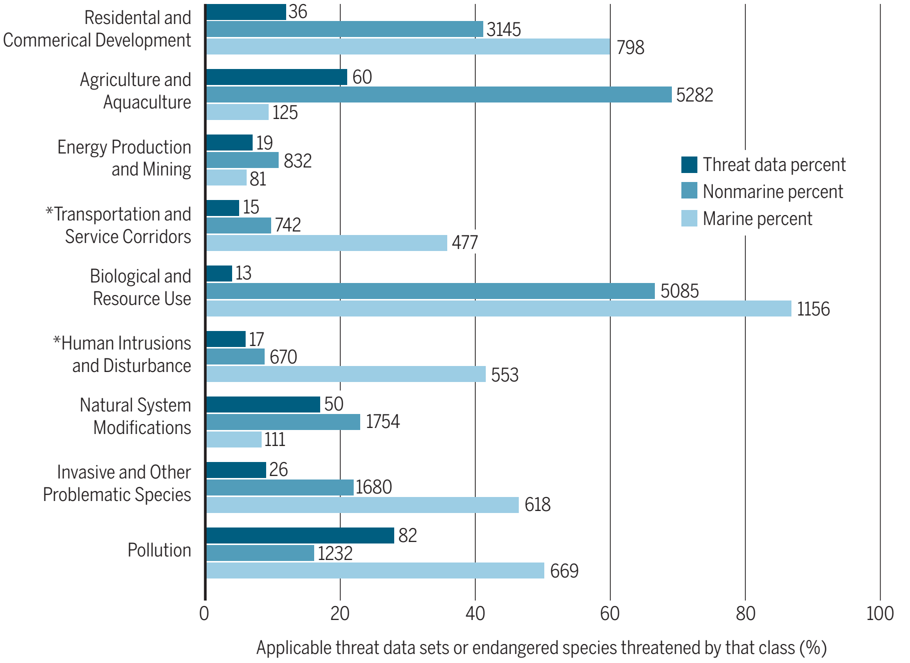
Data sets and types of threats

The percentage of all threat data sets (dark blue) that relate to each threat class and the percentage of threatened terrestrial and inland water (medium blue) and marine (light blue) species on the IUCN Red List affected by each threat class. Number of data sets or species in each class is indicated beside each bar. Threat classes not covered by a single data set are denoted by an * in the figure labels. See table S2 for details on species included.



emulate the UN's Data for Climate Action initiative, which is laying the groundwork for working with the private sector to access big data—with options ranging from companies making data freely available to arrangements for scientists to access data within the company's protected network.

Funding mechanisms. In July 2015, the UN's Third International Conference for Financing for Development produced a comprehensive framework—the Addis Ababa Action Agenda (AAAA). The AAAA specifies >100 measures for how to finance the sustainable development agenda and explicitly recognizes the need to fund "science, technology, innovation and capacity building," as well as "data, monitoring and follow-up" (*11*). The AAAA "encourage[s] the mobilization of financial resources from all sources and at all levels to conserve and sustainably use biodiversity and ecosystems." This is an important recognition of the need to finance the achievement of SDG 15 (the most relevant to halting the loss of biodiversity), although critically missing is any specific mention of the need to fund the data required to achieve that goal.

THE DATA PIPELINE. For many threat classes the creation of a gold-standard data set need not start from scratch. Existing data sets and data pipelines, if provided with appropriate resources or mandates, can be scaled up. We highlight this potential with two issues where data scarcity on threats is a major obstacle.

Invasive and problematic species. Invasive alien species homogenize global biodiversity and are a significant threat to native species, particularly those endemic to islands and specific ecosystems. National and regional policy mechanisms are in place to prevent, control, and minimize the impact of alien species. Effective policy must be empowered with comprehensive data on which species are where and pathways by which they move (as the European Union's legal framework explicitly requires). These data allow implementation agencies to monitor transmission routes, prevent invasive species' entry or departure, and respond rapidly to early detections. The Threatened Island Biodiversity Database and the IUCN's Global Invasive Species Database are backed by international institutions and networks of experts and, if appropriately resourced, are capable of scaling up to meet the five key data attributes in the table.

Land use and cover change. Habitat loss is a leading cause of biodiversity decline, and most countries have local, regional, and national legislation protecting natural landscapes. Yet globally, we do not have a standard land use and cover change assessment tool for biodiversity conservation end users. New and standardized land cover change detection approaches for the 2000–2010 interval are emerging, at both high (30-m) (*12*) and moderate (300-m) resolution (*13*). Although these products have promise, it is impossible to obtain a global and standardized overview of how natural landscapes are changing on a time scale that allows appropriate conservation action. Changing this requires breaking the practice of repeatedly modifying remote-sensing algorithms—interesting for the field itself but exasperating for end users—and, instead, agreeing to a series of global maps comparable through time and space.

To be useful, threat data sets must be integrated with conservation assessment processes. The IUCN Red List compiles input from >10,000 species experts into easily and freely available conservation assessments for nearly 80,000 species that influence international and national policy mechanisms. Connecting such efforts to gold-standard data sets for each major class of threat will help bring actionable insights into what conservation actions are needed, and where, for the most imperiled species and populations. In so doing, we can better leverage the technology of the Information Age to counter biodiversity loss, a defining feature of the Anthropocene. ■

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