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Mapping Industrial Influences on Earth's Ecology

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Keywords

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Abstract

As anthropogenic transformation of Earth's ecology accelerates, and its impacts on the sustainability of humanity and the rest of nature become more obvious, geographers and other researchers are leveraging an abundance of spatial data to map how industrialization is transforming the biosphere. This review examines the methodologies used to create such maps and how they have enhanced our understanding of how societies can abate biodiversity loss, mitigate climate change, and achieve global sustainability goals. Although there have been great advances over the past two decades in mapping industrial transformations of ecology across the planet, the field is still in its infancy. We outline future research directions to better understand anthropogenic transformation of the biosphere and the utility of integrating global maps of socioeconomic, ecological, biodiversity, and climate data to explore and inform potential pathways of human-driven social-ecological change.

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1. INTRODUCTION

Human societies have reshaped Earth's ecosystems for millennia. It is now established that by at least 10,000 BCE, all human societies across Earth employed ecologically transformative practices to sustain themselves, including hunting, fishing, cultural burning, and the propagation, tending, and domestication of favored species and commensals that have shaped ecosystems across the terrestrial, freshwater, and marine biosphere (1, 2). Consequently, most terrestrial and coastal ecosystems have been directly influenced by human land- and sea-use practices for thousands of years (3, 4). Nevertheless, the emergence and rapid spread of large-scale industrial societies over the past 300 years vastly accelerated and intensified trends toward biotically homogenized terrestrial and aquatic ecosystems. Over this short period in Earth's history, large-scale human settlements and infrastructure, resource extraction, the mechanization of land management, and other transformative practices have considerably modified the ecology of many ecosystems (1, 5, 6). Across Earth, most highly biodiverse and productive land- and seascapes have thus been reshaped to support growing human populations (7, 8).

Biosphere: the global ecosystem composed of all living organisms (biota) inhabiting Earth's surface layers, together with their interactions with each other and the nonliving (abiotic) components of the Earth system

Industrial societies: larger-scale societies leveraging technological displacement of labor inputs, energy resources, and mass production to sustain their populations

This dramatic anthropogenic transformation of the biosphere by industrial societies over the past few centuries, and its so-called Great Acceleration since the 1950s (9), has disrupted biodiversity, climate systems, and ecosystem functioning across the planet (7, 10, 11). Understanding recent industrial transformations of Earth's ecosystems has therefore become an important science and policy contribution by environmental scientists, ecologists, and biogeographers worldwide (**Figure 1**) (12, 13). The maps scientists have produced have not only helped to illustrate the unprecedented extent and degree of biosphere transformation caused by industrial societies but have also informed the priorities for environmental action and remediation (1, 14).

Yet these maps, like all maps, have their limitations. The many ways that people, social groups, and societies perceive, experience, interact with, and shape nature are as diverse as people and

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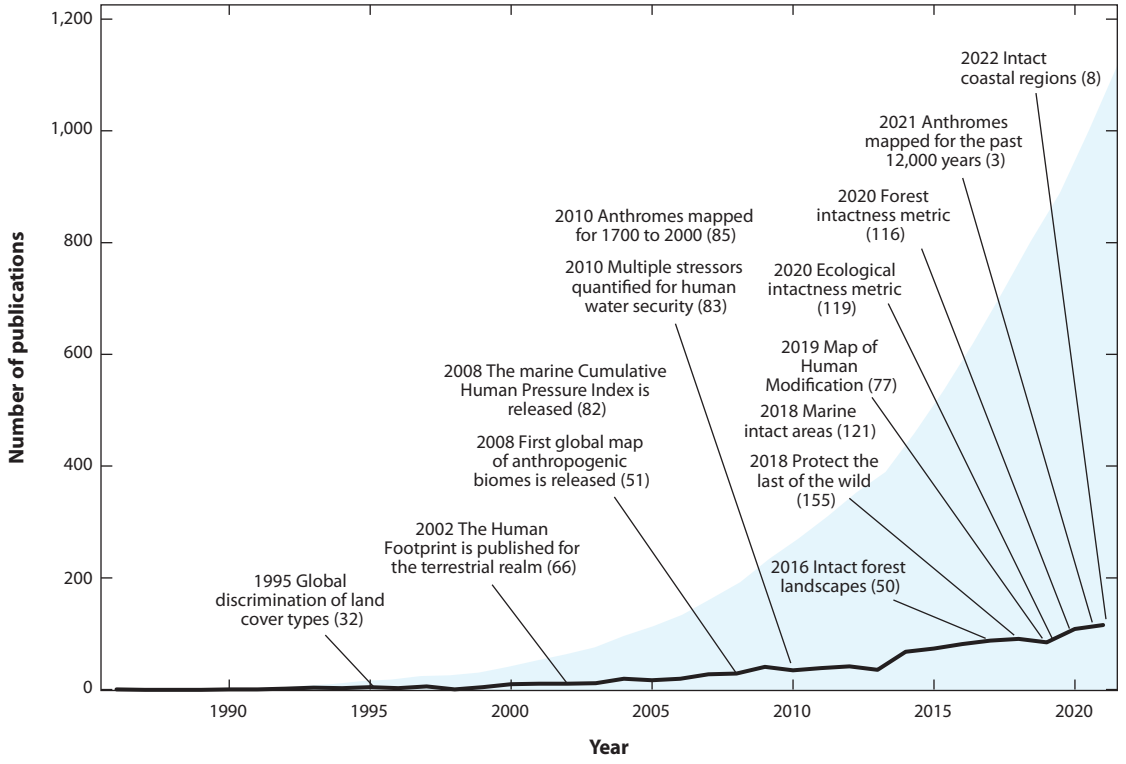

Figure 1

A search conducted within the ISI Web of Science database for terms relating to mapping industrial pressures (1986–2022). Search terms were "industrial human" OR "anthropogenic pressure" OR "human pressure" OR "human impact" OR "cumulative human" AND "map." Although not a systematic literature review, this figure represents the broader academic publishing trends. The black line represents the number of publications per year, and the blue shaded area represents the cumulative sum of publications over time. Examples are of major human industrial influence mapping milestones.

nature themselves (15). This results in different understandings and values about the role of human interactions with nature, including the classic natural science conception of humans as separate from nature and inherently destructive of nature where present (16). For the most part, policymakers have tended to ignore these multiple ways in which nature matters to people (17) and have instead prioritized a narrower set of nature's values, including conceptions of wilderness, naturalness, and intactness, and those that provide economic and other direct benefits or contributions to people (see also the sidebar titled Rethinking Terminology Used in Industrial Influence Mapping) (15, 18). Although such benefits and contributions are undoubtedly critical to human well-being, this article focuses primarily on recent advances in mapping the global spread and intensification of industrial land systems—rather than earlier traditional and Indigenous land systems—and their direct consequences for biodiversity and ecosystem functioning across the planet. A reason for our targeted focus on industrial land systems is that the data and science needed to map earlier human land-use changes at the global scale depends largely on models and reconstructions, rather than the direct observations available for more recent times (3, 19, 20). We discuss this issue further in the final section of this article, including recommendations for advancement in this important area of inquiry.

This review synthesizes major mapping efforts over the past four decades that have assessed the industrial transformation of land- and seascapes worldwide and how this knowledge has

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RETHINKING TERMINOLOGY USED IN INDUSTRIAL INFLUENCE MAPPING

A fundamental reason geographers and other researchers produce maps of human influences is to illustrate the unprecedented degree of biosphere transformation caused by industrial societies, and to allow for questions to be asked around where and what priorities are needed for concerted environmental actions and remediation (14). However, some of the terms used in past mapping efforts are perceived as inconsiderate and harmful by many communities owing to their apparent erasure of long-term sustainable interactions between many human societies and their traditional lands and waters (1, 17). Such terms as natural ecosystems, naturalness, intactness, wild, degraded, and footprint and the generalized attribution of negative impacts, modifications, or influences to humans, even those living sustainably on their lands and waters, have often been used without clear definitions of what the maps capture and what they ignore. Too often these terms appear to either erase or overgeneralize in characterizing all human inhabitation and use of ecosystems. Even when clearly defined, authors should recognize that some concepts like wilderness and pristine are contested and, for some, offensive (17). Throughout this review, we refer to some of these terms in the context of summarizing published scientific works. However, we urge researchers and practitioners involved in global mapping efforts to consider appropriate terminologies and semantics in the light of decoloniality and other critiques of Western grand narratives about humanity.

influenced our understanding of the biosphere and strategies for conservation and restoration of biodiversity and the environment at global and regional scales. We outline the various contemporary methodologies for data acquisition, their underlying theoretical and analytical underpinnings, and how they differ and have evolved in relation to the original goals that motivated their development. We then discuss the most recent research and its potential to inform current environmental commitments outlined in the Convention on Biological Diversity (CBD), the United Nation's Sustainable Development Goals (SDGs), and the United Nations Framework Convention for Climate Change (UNFCCC) around safeguarding ecosystems, and maintaining and, where possible, restoring ecological integrity. We conclude by outlining key theoretical and practical questions and concepts for advancing future mapping efforts, particularly those that better incorporate people, culture, and especially Indigenous and traditional land use, within global assessments and policies relating to human transformation, conservation, restoration, and sustainable use of ecosystems and biodiversity.

Convention on Biological Diversity (CBD): a multilateral commitment created in 1992 for biodiversity conservation and sustainable use and fair sharing of the benefits arising from it

United Nation's Sustainable Development Goals (SDGs): a set of global goals agreed upon by world leaders and representatives to build a more sustainable, equitable, better world by 2030

2. A BRIEF HISTORY OF EFFORTS TO MAP THE INDUSTRIAL TRANSFORMATION OF EARTH

The past four decades have seen a proliferation in the breadth of data describing ecosystems across the biosphere and how industrial societies have transformed them (**Figure 2**) (21). New academic disciplines, including conservation biogeography (22) and conservation biology (23, 24), have emerged together with scientific efforts to map the biosphere and human shaping of its patterns and processes, especially those of the industrial period of the past two to three hundred years. As understanding human transformation of terrestrial ecology requires a landscape approach (1, 25), this section summarizes the evolution of several distinct landscape-scale mapping approaches that have transformed our understanding of the spatial extent and ecological consequences of industrial transformation.

2.1. Earth Observation Systems Data

Spatial data from remote Earth Observation Systems (EOS) have been used by scientists to map global patterns of agricultural lands, buildings and other infrastructure, forest harvesting, and

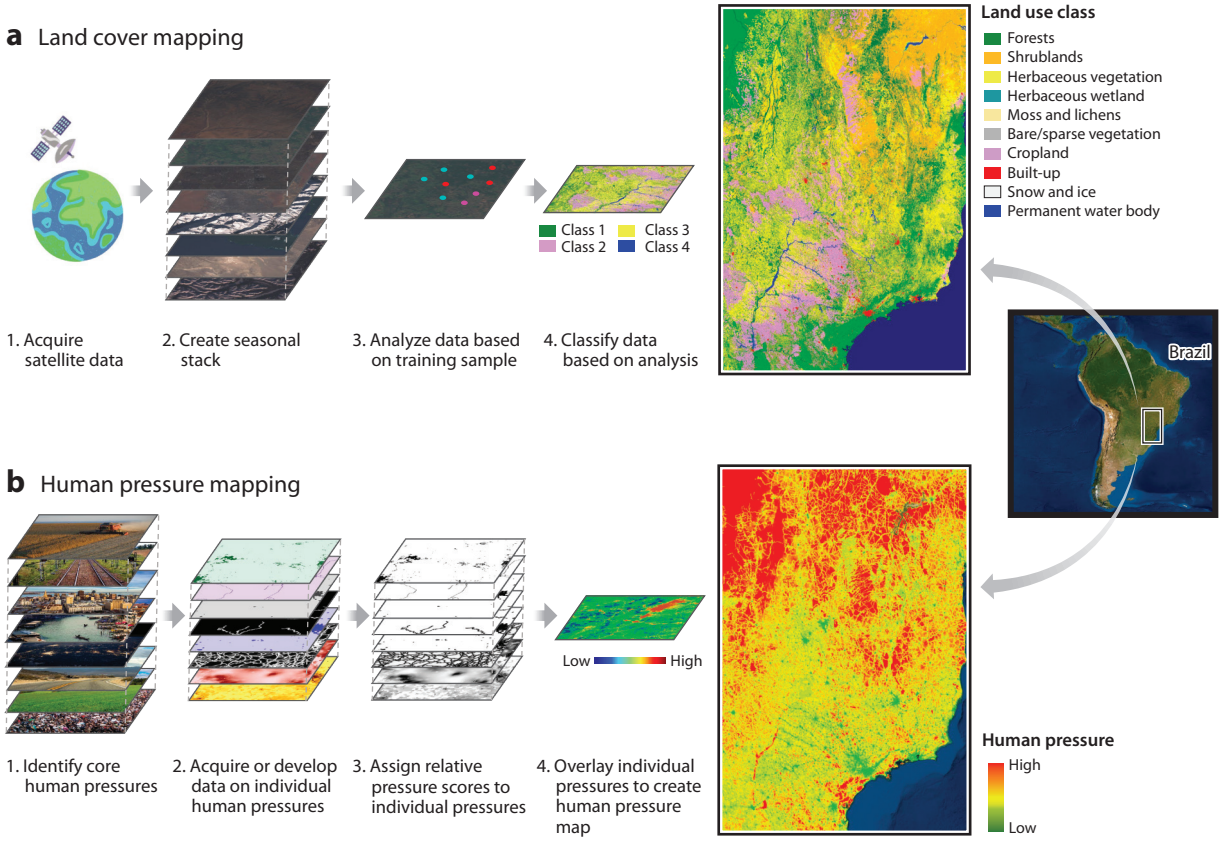

Figure 2

The basic methodological steps used in creating (*a*) land cover/land use maps (in this case, Copernicus Global Land Service) compared to a (*b*) map of cumulative human-industrial pressures (in this case, the Human Footprint Index). On the right-hand side is an illustration of how these mapping efforts differ when focused on the southeast region of Brazil. Land cover/land use maps give a categorical classification of Earth's surface, and human pressure maps provide a cumulative measure of relative industrial-level pressure. Both are crucial pieces of information for conservation and sustainable development planning but are used in different ways. For example, a land cover/land use map might help identify areas available for forest restoration, whereas a human pressure map might help identify ecosystems that are in crisis and in need of an urgent conservation response.

other patterns of human-altered vegetation cover for at least the past four decades (**Figure 2**). Landsat-1 and its Multi-Spectral Scanner, launched in the 1970s, were the start of an era of widely available EOS data (26). The early global land cover mapping efforts of the 1980s (27, 28) harnessed these developments and were critical to the advancement of our understanding of the expanding anthropogenic modification of Earth's terrestrial ecosystems. Although the data were collected by automated sensors, many of these early efforts were still highly labor-intensive. For instance, the first global vegetation and land-use maps were digitized by drawing on approximately 100 published sources complemented by a large collection of satellite imagery that was classified and integrated into a single land-cover database at a 1° latitude by 1° longitude resolution for studies of climate and climate change (28).

In the late 1990s, numerous improved EOS emerged as the first sources of data with global extent, frequent repeat coverage, and high-level processing (e.g., georectified, at-satellite reflectance) for land-use and land-cover mapping (26, 29). For example, the Terra/Aqua satellites

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United Nations Framework Convention for Climate Change (UNFCCC): sets out the legal framework and principles for international climate change cooperation with the aim of stabilizing atmospheric concentrations of greenhouse gases to avoid dangerous anthropogenic interference with the climate system

Earth Observation Systems (EOS): the gathering of information about planet Earth's physical, chemical, and biological systems via remote sensing technologies, usually involving satellites carrying imaging devices

were launched in 1999 carrying sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Measurements of Pollution in the Troposphere that had daily revisit and significant data preprocessing. This ushered in a monitoring revolution that allowed improved mapping of different industrial land uses, as well as their change over time (**Figure 2**). Numerous global land-cover products emerged, mostly based on Earth observation data (30–32), which served as foundations for important insights on anthropogenic influences on the planet. Early work by Ramankutty & Foley (33) combined data from EOS, agriculture and population census, and global vegetation modeling to assess global land-use changes and their transformation of ecosystems over the past 300 years. In 2005, Foley et al. (34) went further, using these integrative EOS products to show how croplands, pastures, and urban areas had expanded in previous decades, accompanied by losses of biodiversity. The authors argued that although these changes in land use enabled humans to appropriate an increasing share of the planet's resources, they also undermined the capacity of these very ecosystems to sustain food production, maintain freshwater and terrestrial ecosystem resources, regulate climate, and ameliorate infectious diseases.

Government agencies including the National Aeronautics and Space Administration (NASA), the European Space Agency, the China–Brazil Earth Resources Satellite program, and others, together with new commercial ventures made rapid advances in EOS through the 2000s, leading to widespread availability of verifiable, finer-scale global maps of land use and land cover. This coincided with a burgeoning land-cover and land-use change (LCLUC) researcher community calling for globally consistent yet locally relevant EOS data with the operational updates necessary for historical analyses, and both the spatial resolution needed for variable scale applications as well as the thematic detail relevant to Earth systems modeling applications (35). As a result, a suite of important thematic maps emerged that were far finer in resolution and comprehensive in capturing vegetation structure and dynamics at the product cell (pixel) scale. An important element of EOS has been the consistent increase in resolution of land cover products generated from them. Annual maps of global LCLUC have been developed by many groups, including NASA's MCD12Q1 500 m resolution dataset (36) (2001–2018) and Copernicus Global Land Service Land-Cover 100 m dataset (37) (2015–2019), and a global 10 m Dynamic World, land-use land-cover mapping via 10 m Sentinel-2 imagery (38). Many of these regularly updated global LCLUC datasets provide the foundation for understanding the influence of human activity on aspects such as the carbon and water cycles, as well as global biodiversity patterns (39–41).

Beyond the different EOS satellite products emerging since the early 2000s, advances in computing methods applied to EOS data allowed for more direct interpretations of land cover maps. One such example was the Vegetation Continuous Fields approach, which estimates per-pixel continuous fractional cover of major land-cover types, namely woody vegetation, herbaceous vegetation, and non-vegetated land cover. This approach has been applied at global and national scales using different EOS products, including MODIS (42) and Landsat data (43), and has become the foundation for efforts around global forest monitoring (44), forest structure mapping (45), cropland area and crop type mapping (46) and even non-vegetated lands (47), and surface water dynamic assessments (48) (see also the sidebar titled Mapping Forest Cover Change).

2.2. Integrating Global Spatial Data with Earth Observation Systems

Despite their many uses, a common criticism of even the most advanced EOS has been that the categories used for mapping are too superficial and simplistic (51), often using a small number of anthropogenic land cover classes [e.g., urban/built-up, cropland, and a few natural vegetation mosaics (see, for example, 52)] or more binary classifications such as forest/nonforest (44). Moreover, there remained concern that the methodologies miss many forms of industrial influences

MAPPING FOREST COVER CHANGE

Changes in forest cover over time can have profound consequences on ecosystem functions, biodiversity, and human well-being, including climate regulation, water supplies, and recreation (34). Although deforestation rates in tropical regions had long generated serious concern, the overall extent and regional patterns of forest cover changes across highly biodiverse humid tropical forest biomes were not well measured until the mid-2000s. Probability-based sampling approaches leveraging both low- and high-resolution satellite datasets enabled the first comprehensive estimates of forest cover change across the humid tropics in 2008 (49). In 2013, high-resolution (~30 m) maps of global forest cover change from 2000 to 2012 were produced with Landsat remote sensing data and shared widely online (44). This global analysis improved on prior efforts to map forest cover change by estimating forest loss and gain in a spatially explicit manner and quantifying trends in annual loss of forest cover. Over the 12-year period, it was estimated that 2.3 million km^2 of forest cover was lost worldwide. Important spatial trends were quantified for the first time, such as the reduction in deforestation in Brazil and the rise of higher deforestation rates in countries in tropical Asia and Africa (44). Further advances in Landsat remote sensing data have enabled the mapping of land cover and land-use change from 2000 to 2020, to capture trends in forest and land cover change over long timeframes at global scales (50).

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and some forms of low-intensity land use. For example, extensive road networks (53), power lines, water irrigation systems, fencing, grazing lands for livestock (54), low-density human settlements (55, 56), emerging settlements, and small-scale agriculture can often transform ecosystems as much as industrial conversion and intensive use for crops and urban settlements, yet can be challenging to detect with EOS. Substantial advances in geographic information systems (GIS) software and the storage of large datasets in conjunction with the emergence of international efforts to curate and share spatial data provided the tools necessary to better detect human influences missed by EOS (57, 58).

Global data acquired from a range of shared governmental, international, and other sources have been harnessed to better understand the spatial distribution of social, economic, and ecological patterns of industrialization. The foundation for using these data emerged through increasingly open data sharing initiatives established during the 1990s and early 2000s (**Figure 3**). Geopolitics changed globally with the end of the Cold War, and calls for efficiency in government across the developed world meant that other sources of global geographic data were released to the public by national agencies. For instance, the US National Imagery and Mapping Agency released the digital chart of the world and later Vector Map Level 0, providing worldwide coverage at a small scale (1:1,000,000) of major road, railroad, and utility networks as well as major airports and populated places, all of which are critical industrial infrastructures that can be challenging to map reliably with EOS.

In 1995, improved international curation of national population statistics enabled geographers to create global digital maps of human population density for the first time by coupling census tables with geographic boundaries (59). These maps represented a huge step forward in representing the density and distribution of people themselves, albeit with the census units used to collect these data generally being far coarser than the resolutions available from remotely sensed data products. To overcome this limitation, hybrid spatial disaggregation methods were developed that combined EOS spatial resolutions with the thematic resolutions provided by census and survey methods. In 2000, this approach was used to create the first high spatial resolution maps of human population density by disaggregating census unit mapping of population density using remotely sensed data on nighttime lights and other data (60). More recently, machine learning techniques have

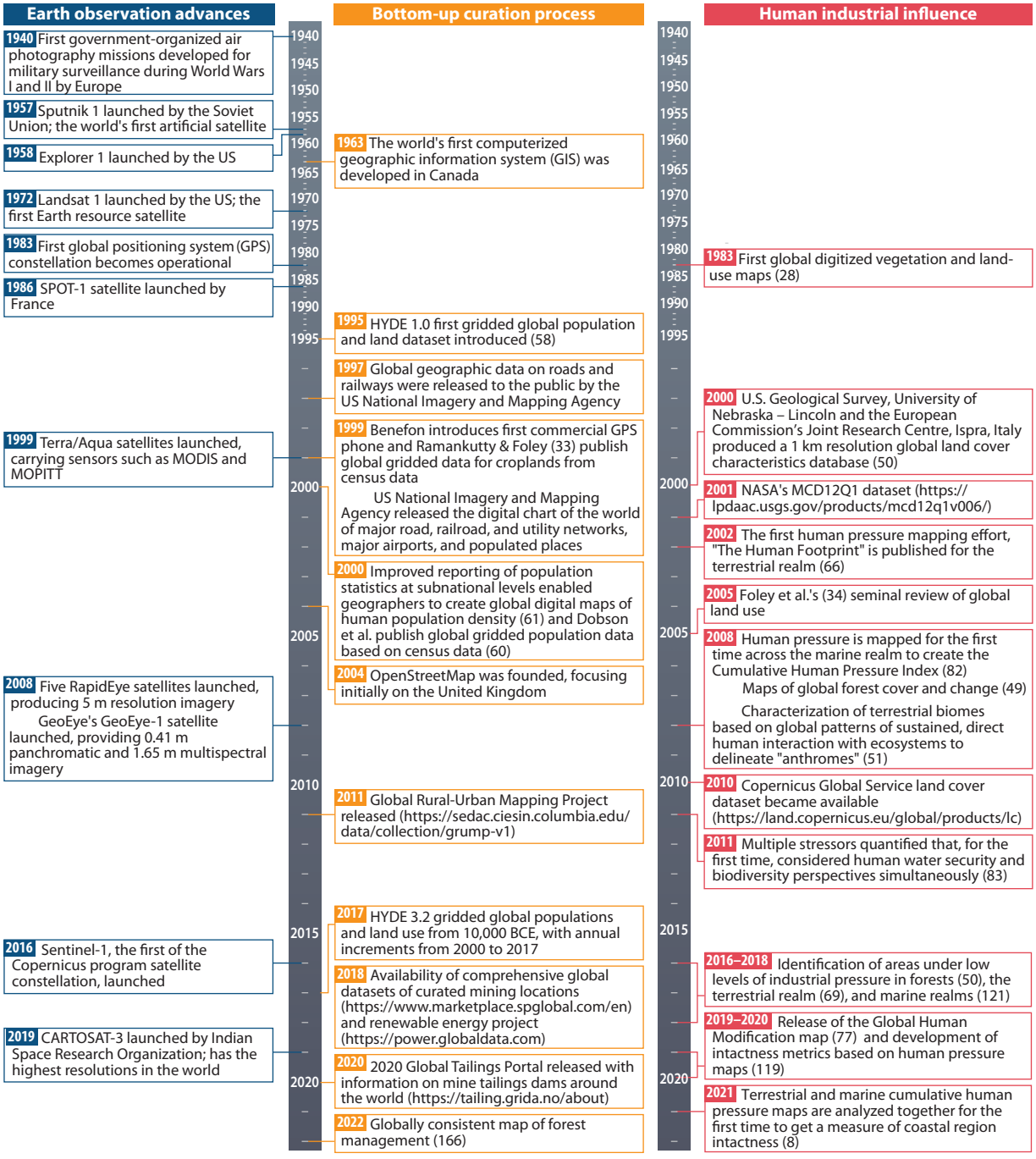

Figure 3

The major Earth observation, extensive bottom-up curation programs and bottom-up data collation that has led to different human industrial mapping advances beginning with the first artificial satellite in 1957. Abbreviations: MODIS, Moderate Resolution Imaging Spectroradiometer; MOPITT, Measurements of Pollution in the Troposphere.

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combined satellite imagery and census data to map individual buildings and create population maps at a striking ~30 m resolution (61), roughly equivalent to other high-resolution global data products derived from EOS. Another example of international curation of social data is efforts to combine agricultural census data with remotely sensed land cover maps to delineate global pasture lands (62), which have been chronically difficult to separate from natural grasslands by EOS alone (63).

A major advance in use of shared spatial data has been the emergence of platforms that harness crowdsourcing at an unprecedented scale. This is most evident in the mapping of transport networks. For instance, although its primary purpose is to enable more efficient navigation, OpenStreet Maps now represents the most complete open download of spatial data on roads and trails, with numerous applications to mapping industrial infrastructures. Data are derived from 900,000 data providers uploading their GPS traces and thematic encoding of actual trips taken. More recently, crowdsourcing has harnessed the proliferation of GPS enabled phones to map human recreational use of trails and other otherwise unmapped infrastructures (64, 65).

Remote sensing: the acquisition of information about an object or phenomenon without making physical contact with the object, in contrast to in situ or on-site observation

Invasibility: the level of vulnerability of a habitat to invasions from outside species

2.3. Efforts to Develop Global Maps and Measures of Anthropogenic Influences

Improvements in satellite remote sensing technology and the scale of their resolution, alongside the increased availability of shared datasets and GIS tool enhancements, have seen the development of several different anthropogenic influence mapping approaches. These are distinct from land-use mapping efforts that involve the a priori categorization of specific land-use activities. Using different formulations (**Figure 4**), these influence assessments allowed for maps quantifying spatially varying levels of industrial influences beyond the land-use and population mapping efforts outlined above. In this section, we describe two of the most well-known anthropogenic influence mapping approaches and some of the advances that have taken place since their development.

2.3.1. Industrial influence mapping. The first global-scale effort to combine the full suite of EOS and shared global data to map industrial influences was the Human Footprint (HFP) Index produced by integrating geographic proxies of anthropogenic influences, including human population density, built infrastructure, roads and other access points, and various land-cover categories (66). Nine such anthropogenic pressure datasets were combined by allocating each pressure a standardized score that reflected their estimated contribution to human influence on a scale of 0 to 10 (0 for low human influence, 10 for high). The combined sum of these scores were then normalized by biomes and to develop a single indicator varying from 0 to 100. This new method of cumulative human influence mapping (**Figure 2**) differed substantially from previous land-use maps that were categorizations as well as from regional human industrial influence assessments in that they incorporated more "pressure" datasets (67). The resulting global terrestrial HFP revealed that 83% of the Earth's non-Antarctic land surface was directly influenced by some form of human activities. The novel insight exceeded the estimates of human impacted land-cover using categorical land-use maps of the time. For example, around the same time, Foley et al. (34) determined that croplands and pastures had become two of the largest terrestrial biomes on the planet, collectively occupying 40% of the land surface. However, this classification did not include other indicators of industrial influences such as linear infrastructures and nighttime lights and their potential cumulative influences, that were captured by the early HFP map.

Since first published in 2002, a broad literature has used the HFP to quantify the loss and fragmentation of natural ecosystems (4, 68, 69), its subsequent effects on the species distributions, abundance and extinction risk (70–72), the invasibility of landscapes by non-native species (73)

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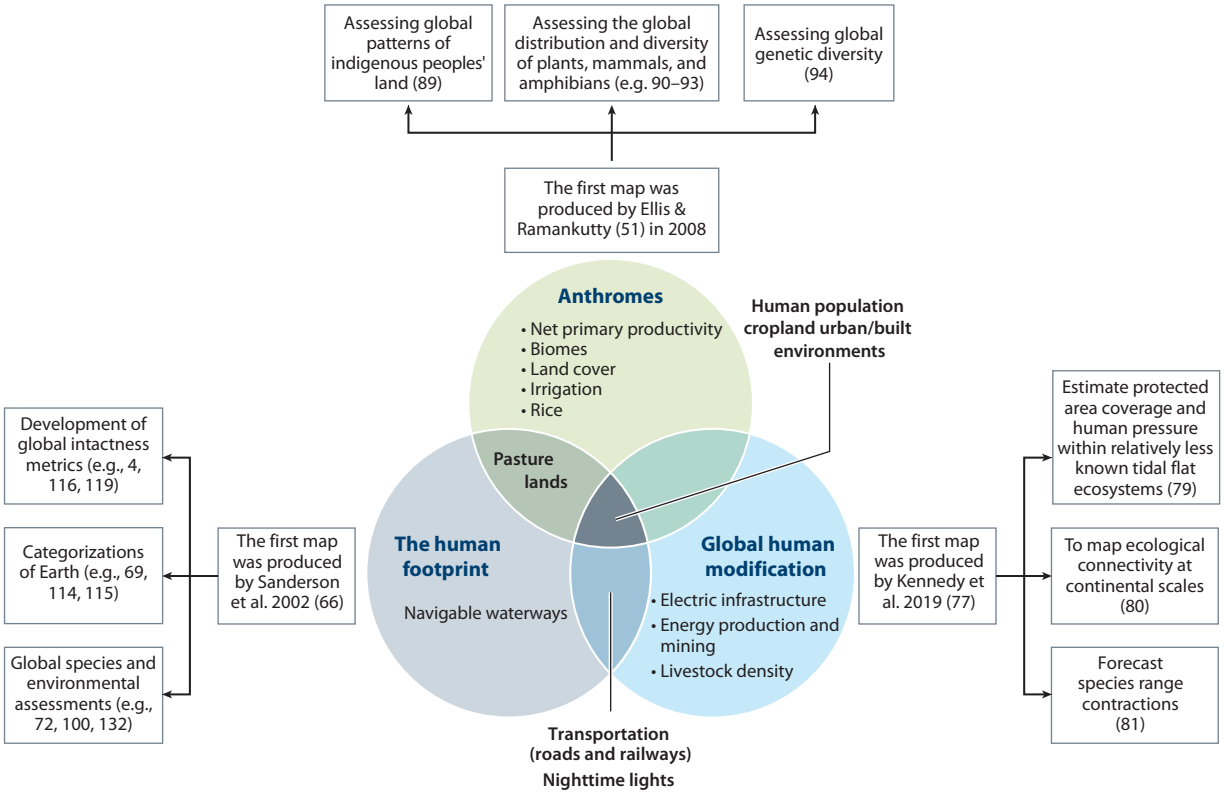

Figure 4

A Venn diagram depicting the types of overlapping datasets used in three well-known human industrial influence products: anthromes (51), global human modification (77), and human footprint (66). All three datasets have been used numerous times in various global assessments and subsequent products, with some cited in the figure.

and explaining disease patterns across different regions (74). The HFP has been updated several times using different datasets (4, 75, 76), and different variants have been produced. For example, the Global Human Modification (HM) map (77), first published in 2019, incorporates five additional anthropogenic pressures than the nine included in the HFP (**Figure 4**) (66). Despite issues with validation (78), the HM map has been utilized to estimate protected area coverage and human pressure within relatively less known tidal flat ecosystems (79), map ecological connectivity at continental scales (80), and forecast species range contractions (81). Overall, these diverse applications suggest that broadening out the number of influences measured in cumulative influence assessments is important and demonstrates the need for continued development and improvement of cumulative human influence maps to inform ecological monitoring and conservation planning.

The overall cumulative human influence methodology has also been modified to measure industrial influence on non-terrestrial ecosystems. In 2008, the first marine Cumulative Human Impact map quantified global industrial human pressure across the oceans. Synthesizing 17 global datasets for anthropogenic drivers of ecological change across four primary categories (fishing, climate change, ocean shipping, and land-based stressors) and then assessing these against 20 marine ecosystems revealed that no marine area was unaffected by human influence and that a large proportion (41%) was heavily impacted by multiple pressures (82). Beyond covering the marine realm, it advanced current cumulative influence mapping efforts by including climate change

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pressures and modeled land-based stressors (such as nutrient run-off). These important advances were quickly transferred to the freshwater environment, with a map of global human influence on human water security and river biodiversity released in 2010 (83). This map accounted for 23 threats to freshwater security and biodiversity, spanning the categories of catchment disturbance, pollution, water resource development, and biotic factors (such as non-native fishes). By linking the map to human populations, the study found that nearly 80% of the world's population is exposed to high levels of threat to water security.

2.3.2. Anthrome mapping. Anthrome (or anthropogenic biome) mapping was developed to provide a global biogeographic framework characterizing human reshaping of ecology in a form analogous to the classic "natural" biomes shaped by climate and terrain (51). The anthrome approach is distinct from HFP and HM approaches in that it emphasizes that human transformation of Earth's land is not reducible to a single dimension of impact or influence ranging from low to high, but rather represents a diverse spectrum of social-ecological landscape patterns shaped by sustained direct human interactions with ecosystems, including hunting and foraging, agriculture, urbanization, and other land uses (84). In this approach, the many different global patterns of human-shaped landscapes across the planet can be characterized, understood, and investigated, without ordering them along a single scale of human influence, disturbance, or "naturalness" ranging from low to high.

Anthromes represent the global patterns of human ecology by categorizing the different forms of heterogeneous multifunctional landscape mosaics that human populations produce through diverse land-use practices (**Figure 5**). The most recent maps recognize 18 anthrome classes grouped into intensive anthromes, with more than 20% of their area intensively used (dense settlements, villages, croplands, and rangelands) and cultured anthromes with lower levels of intensive use, with wildlands classified in landscapes without evidence of human populations or intensive land use (3). Although anthromes are classified in relation to intensive land use areas and human population densities, considerable areas and even entire anthrome landscapes may be shaped by less intensive land uses, including hunting, foraging, cultural burning, forestry, conservation, fallow, and remnant native habitats (84, 85).

The first anthrome map, for year 2000 CE, was produced by applying a statistical clustering algorithm to global gridded spatial data for vegetation cover, crops, pastures, urban areas, and human populations, yielding a global map with 18 anthrome classes covering ~75% of Earth's ice-free land surface (51). Landscapes without evidence of human populations or intensive land uses (e.g., urban areas, crops, pastures) were mapped as wildlands in the remainder (51). This was soon followed by efforts to map anthrome changes over time, from 1700 CE to 2000 CE, using a rule-based classification system designed to produce similar anthrome maps using comparable input data (85). These maps used a geographic grid cell system common in Earth system models, with grid cells varying from ~85 km^2 at the equator to ~11 km^2 at the poles.

Most recently, anthrome maps for selected time intervals over the past 12,000 years have been produced using a classification approach similar to the 2010 effort (85), but using a hexagonal equal area global grid system yielding global maps at a regional landscape scale (~100 km^2) (3, 25). These anthrome maps reveal that even 10,000 years ago, wildlands were nearly as rare as they are today (3). Moreover, their extent, both past and present, has likely been overestimated owing to the challenges of detecting low density and/or mobile populations (1, 19, 20). With wildlands always rare over the past 10,000 years, intensively used anthromes have largely developed not through the spread of people and land use into wildlands, but rather through processes of land-use intensification in the cultured anthromes long inhabited and used by Indigenous and other traditional land-using peoples, largely through the colonization, displacement, and appropriation

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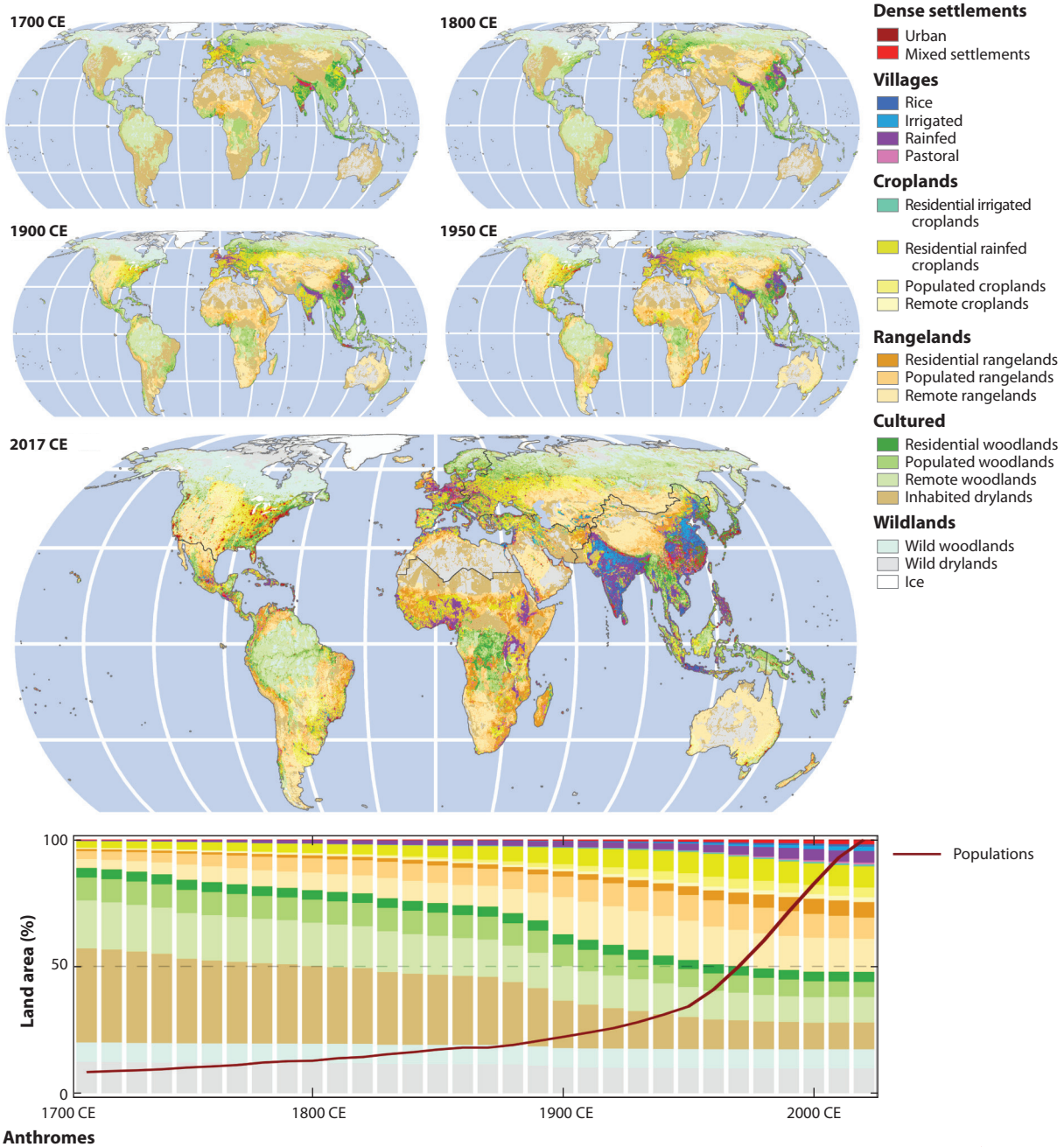

(*Caption appears on following page*)

Figure 5 (*Figure appears on preceding page*)

Anthromes represent the global patterns of human-shaped ecology by categorizing the diverse forms of heterogeneous regional landscape mosaics produced by human inhabitation and use of land. Global maps of anthromes and their changes, 1700 CE, 1800 CE, 1900 CE, 1950 CE, and 2017 CE, as classified by Ellis et al. (85). Wildlands are regional landscapes without evidence of permanent human populations or intensive use; Cultured anthromes are continuously inhabited, with <20% of their area intensively used; Croplands and Rangelands have ≥20% crop and pasture areas, respectively; and Dense settlements have population densities ≥100 persons km^{-2}. Cultured and Intensive anthromes are further stratified by population densities, in persons km^{-2}, as Remote (>0 to <1), Populated (1 to <10), Residential (10 to <100), Inhabited (>0 to <100), Villages and Mixed settlements (100 to <2,500), and Urban (≥2,500). Intensive anthromes are further stratified based on intensive land use area ≥20% in order of most intensive type of use (urban > rice > irrigated > cropped > pastured). Woodlands combine all forest and woodland biomes, and drylands comprise the remaining biomes, from savanna to tundra, excluding permanent ice. Maps in Eckert 4 projection. Abbreviation: CE, Common Era. Figure adapted with permission from Reference 1 (CC BY 4.0).

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of their lands by larger-scale colonial and industrial economies (20). After increasing gradually for millennia in most regions, the global extent of intensive anthromes exploded across the planet in the late nineteenth century (3). Remarkably, this rapid expansion appears to end by the middle of the twentieth century, even while population and other global changes continue to accelerate (86). Likely, this leveling off represents increasing agricultural productivity using green revolution technologies in lands already in agricultural use, a trend that continues today (87, 88).

Since it was first conceived, a wide range of scholars, conservationists, and educators have used anthrome maps in their work, in assessing the global patterns of Indigenous peoples' land (89), the distribution and diversity of plants, mammals, and amphibians (90–93), genetic diversity (94), fire regimes and in conservation (95, 96), including major policy frameworks (97, 98), textbooks, and atlases. Global mapping of anthrome history confirms that human transformation of ecology is neither new nor does it always have to be inevitably harmful, enabling a deeper and more general understanding of the human role in shaping nature at local, regional, and global scales over the long term (1). This deeper integration of people and nature is considered by some as essential to support broader strategies for conservation and sustainable use of ecosystems and species for the future in ways that embrace the pluralistic values of nature, including practices for biodiversity conservation in working landscapes (142).

3. HOW EFFORTS TO MAP HUMAN INDUSTRIAL TRANSFORMATION OF EARTH ARE INFORMING CURRENT GLOBAL ENVIRONMENTAL AGENDAS

Ever since the first global land cover map was generated through direct observations from remote sensing, such products have increasingly informed global environmental dialogues (34, 99). As mapping techniques evolved to incorporate human use of land, populations, and industrial influences across Earth (**Figure 3**), a myriad of interdisciplinary approaches have allowed scientists to show how human activities can shape biodiversity in a range of ways, including species population declines, invasions, and behavioral changes (72, 100, 101), facilitating infectious disease spread (102) and compromising crucial ecosystem services, such as water quality and carbon storage and sequestration (83, 103). These scientific efforts have been included throughout important environment assessments such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services Global Assessments (104), the latest Intergovernmental Panel on Climate Change (IPCC) reports (105), and the Global Biodiversity Outlook (106). Given their rising utility in describing the state of the natural environment, products like HFP and their derivates are increasingly being proposed as formal indicators to help monitor national and international efforts to track targets in various international environmental conventions (107).

Ecoregion: an ecologically and geographically defined area of land or water, which contains characteristic, geographically distinct assemblages of natural communities and species

In this section, we summarize recent research that has utilized industrial influence mapping to provide new insights into the state of the world's ecosystems, specifically how and where biodiversity is at risk, the location of priorities for conservation action, and how well different conservation interventions are performing when it comes to abating biodiversity loss. All three of the above scientific efforts are now critical components of current global environmental agendas focusing on overcoming the biodiversity crisis, abating climate change and achieving global sustainability.

3.1. Mapping Ecosystem Extent and Condition

Retaining and, where possible, restoring ecosystems and the essential services they provide have become central components to international agreements and frameworks that support and set policy agendas, including the UNFCCC, CBD, SDGs, and Convention to Combat Desertification in recent years (108, 109). It is now well established that the less an ecosystem is degraded by industrial activities, the more it can support globally significant environmental values, including endangered biodiversity, and critical ecosystem services such as carbon sequestration and storage, water provisioning, and the maintenance of human health (110, 111). For example, the climate mitigation potential of nondegraded ecosystems is formally recognized in Article 5 of the IPCC's Paris Agreement (103) and the biodiversity significance of these ecosystems are captured in the first target of the Kunming-Montreal Global Biodiversity Framework (112).

Mapping how degraded an ecosystem is due to industrial activity (and its relative "integrity") is inherently complex and can be value-laden (113), as it involves comparisons of measures of ecosystem structure, composition, and function against a baseline or reference state (109). There have been increasing calls for approaches to measure and interpret gradients of integrity consistently across ecosystem types and jurisdictional boundaries utilizing methods that are repeatable and simple to interpret (109, 114). Recent advances in human industrial influence mapping have enabled different methodologies to capture important elements of ecosystem integrity, many of which have been shown to be helpful in guiding ecosystem assessment and decision making (109, 115, 116). For example, across the global humid tropics, forests have recently been mapped using a combination of space-based lidar, multispectral imagery, and human pressure indices to delineate gradients of forest structural integrity (117, 118). These efforts have shown that tall forests with closed canopies and low levels of industrial influences comprise only half of the global humid or moist tropical forest estate, largely limited to the Amazon and Congo basins (117). They also show that most of these forests have no formal protection and, given recent rates of loss, there is an urgent need for their conservation and restoration (117).

Beyond forests, efforts have been made to assess differing levels of industrial influences across all terrestrial ecoregions, and how they have changed over time, using modifications to the HPF (119). The latest global assessment showed that most ecoregions have large areas with high HFP scores (74%) and just 6% of ecoregions are on improving trajectories. And although industrial influence mapping has been less advanced for marine and freshwater ecosystems, there have been efforts to map where large-scale human industrial influence has been limited across the marine realm (120, 121). In a global assessment of what they labeled marine wilderness, Jones et al. (121) identified marine areas that have both very little impact from 15 anthropogenic stressors and a very low combined cumulative influence from these stressors, discovering that just 13% of the ocean—mostly the high seas—meets their proposed definition of wilderness. For rivers, there are now several continuous indices that rate individual river reaches using criteria based on major industrial pressures and by assessing their natural flow (122, 123). The Connectivity Status Index (123), for example, utilizes five major pressure types to score individual river reaches, which then allows entire river networks to be defined as free-flowing rivers. A recent assessment showed that

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only 37% of rivers longer than 1,000 km globally remain free-flowing over their entire length and 23% flow uninterrupted to the ocean (123).

3.2. Informing Species Risk Assessments

Although the first efforts to map industrial human influence were focused on quantifying broader spatial patterns of land use at different scales, the field has moved rapidly around investigations of what these mean for biodiversity (3, 14). This has often been through efforts to spatially link the known main drivers of species and ecosystem function decline with activities that cause conversion of natural habitats for land uses such as crops, pasture, and infrastructure as well as the overexploitation of species through activities such as hunting and fishing (124, 125). As the many different industrial influence maps all show (**Figure 4**), the distribution of these activities varies across Earth's surface, as do the distributions of the species they threaten, and by integrating these data alongside knowledge of their traits, research efforts have shown where human industrial pressures overlap with sensitive species (126) and how much industrial pressures influence their overall persistence (72, 127). For instance, researchers evaluated the movement patterns of 803 radio-collared individuals across 57 species of mammals and discovered that individuals moved just one-half to one-third as much in areas with high HFP values, compared to individuals in areas of low HFP (100). This reduction in movement has huge potential to alter predator-prey interactions, nutrient cycling, reproductive success, and the ability to adapt to a changing climate and resource base. There has also been important work on how species behavior has been influenced by industrial activities, with work showing chimpanzee behavioral diversity severely reduced in areas with high HFP, reducing the basic ecological elements these species need to adapt to a changing world (128).

Other research has utilized HFP mapping to assess how entire taxonomic groups have fared, by utilizing known data on threats and the spatial occurrence of species. For example, working with terrestrial mammals, researchers recently found HFP values, and their changes over time, were significantly correlated to trends in mammal species extinction risk, with higher predictive importance than environmental or life-history variables (72). Using these relationships, a second study found up to 85% of terrestrial vertebrate species with more than half of their range exposed to high levels of HFP are likely going to be exposed to increased extinction risk. Furthermore, there are at least 2,478 species considered least concern that have considerable portions of their range overlapping with areas of high HF, indicating they may have higher risk of decline than anticipated (126). In the marine realm, similar efforts have been undertaken around mapping the spatial distribution of anthropogenic stressors and assessing them against at-risk marine species. For example, a recent assessment shows that between 2003 and 2013, 1,271 marine species assessed faced direct potential impacts across 57% of their ranges; these impacts expanded over time and intensified across 37% of their ranges (129).

Other efforts have started to combine fine-scale remote sensing technology and human influence mapping assessments to examine how changes in habitat extent and quality may impact the likelihood of extinctions. For example, an assessment involving 16,396 vertebrate species inhabiting tall, closed-canopy tropical rainforests worldwide established that species were far more likely to be threatened or have declining populations if their geographic ranges contained high proportions of degraded forest (defined by high HFP scores) than if their ranges contained lower proportions of forest cover and lower HFP scores (101). This suggests that forest structure alone may be insufficient to conserve tropical rainforest biodiversity without efforts to limit industrial influences such as selective logging. The researchers observed this pattern consistently across Neotropic, Afrotropic, Indomalayan, and Australasian biogeographic realms and argued that their

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findings support calls in the CBD to increase not just forest protection targets but also ones that are aimed at enhancing the integrity of these ecosystems.

3.3. Informing Conservation Interventions

One consequence of continued failings to abate the biodiversity crisis has been an increase in calls to assess which types of interventions work and why (130, 131). The broadening use of industrial influence maps and other global maps of human influences to inform species, biodiversity, and ecosystem risk assessments (see above) has led to their increasing adoption within conservation assessment frameworks, often utilizing a pressure-state-response (PSR) framework (14). The PSR framework in conservation science uses a theory of change highlighting linkages among and between the different types of industrial pressures, the change in state of environmental values, and the conservation response to these changes as society attempts to halt the pressure or to restore land that has been degraded.

The now numerous global evaluations of networks of protected areas and how effective they have been in abating biodiversity loss are clear examples of how industrial influence maps are a PSR framework (132). The primary objective of protected areas is to secure places where plants and animals can exist in near-natural conditions without the high levels of industrial pressure that plague most places and drive biodiversity toward extinction (133). As nations have continued to commit to bigger protected area estates over the past decade, it has become essential to assess the extent and intensity of human industrial influences across protected areas worldwide. Given advances in deforestation mapping, some studies were able to assess the amount of deforestation within and beyond protected areas to assess their ability to halt the threatening process via a counterfactual framework (134). Recently, utilizing the latest forest cover maps via the Global Forest Change initiative (44), scientists have started to uncover the actual drivers behind this forest loss globally within protected areas (135). For example, researchers working on deforestation rates in protected areas found pastures and other subsistence agriculture to be the dominant direct driver of deforestation in the Latin Americas, while forest management, oil palm, shifting cultivation, and other subsistence agriculture dominate in Asia (140). In Africa, shifting cultivation and other subsistence agriculture is the main driver of deforestation (135). Such land-use assessments around drivers of forest loss in and around protected areas have subsequently been used to predict where forest loss will occur in the near future within the protected area estate (136) and have also allowed assessments of what future deforestation scenarios mean in relation to ongoing climate change (137).

Furthermore, human footprint mapping has allowed for an assessment of industrial footprint within protected areas, with a recent assessment showing that almost three-quarters of countries have more than 50% of their protected land under intense pressure and only 42% of land safeguarded for conservation goals—comprising a mere 4,334 individual protected areas— which were completely free of measurable industrial pressure (132). Importantly, the authors did find that protected areas with strict management for biodiversity conservation (a strong response in the PSR framework) have significantly lower levels of human pressure compared to those permitting a wider range of human activities. There has also been a recent assessment matching bird species sensitivity to human footprint maps to show the clear mismatch between where sensitive species' habitat is and what is actually protected, allowing for the identification of areas where protection and management of habitats, complemented by restoration, is urgently needed (138). In addition, using human footprint maps, the functional connectivity of the world's terrestrial protected areas was mapped recently through the lens of moving mammals (139). The study found that most globally important areas of concentrated mammal movement remain unprotected, with 71% of these overlapping with global biodiversity priority areas and 6% occurring on land with moderate

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to high human modification. Follow on work has now shown that high HFP between species core habitat is a strong predictor of mammal extinction risk, indicating that heavily influenced matrix habitat may be preventing species movements or otherwise contributing to their decline (140).

There is also now an increasing focus on strategies for conservation and ecosystem restoration within inhabited landscapes (98, 141–143) that cover much of the terrestrial biosphere (144). There are increasing numbers of global assessments on biodiversity, habitat, and ecosystems that have been utilizing anthromes and other integrated assessments of anthropogenic ecosystem structure (89, 145–148), which assess opportunities of different forms of area-based conservation activity in these working landscapes.

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4. FUTURE RESEARCH ISSUES

The past 40 years have seen enormous advances in capacities to map industrial influences on the planet. We have moved from categorical mapping of land cover at coarse and then finer scales, to mapping more complex forms of human and industrial influences, and using interdisciplinary approaches to assess how anthropogenic changes to land- and seascapes are shaping the future of nature. Yet, it is important to recognize that the field of industrial and human influence mapping is still very much in its infancy and there are numerous areas for improvement in not only how scientists map this influence but also how it is described.

4.1. Temporal Maps for Longitudinal Studies

A major limitation of some of the work around mapping human industrial influence and assessing its effect on the wider environment is that the maps are often static in time, leading to the widespread use of space-for-time substitutions in studies seeking to link industrial influences to possible ecological changes (101). Although space-for-time substitution can be reliable in ecology (149), longitudinal analyses testing whether and how changes in industrial transformation of ecosystems over time lead to change in other values (such as biodiversity) as well as system relationships (such as biodiversity-ecosystem function) represent an important research gap (150). A key factor stymieing efforts to create longitudinal data is the incompatibility of underlying datasets such that it is challenging to quantify change. For example, when considering the human footprint datasets, the first map (66) was static, and the second (75) and third efforts (7) were only able to map changes over short timeframes (1993–2009 and thereafter 2000–2013). Nevertheless, these short time-series datasets have been used for efforts such as testing whether changes in HFP over time drive changes in species extinction risk (72) and showcase the utility of obtaining longitudinal datasets. Future efforts to map long-term changes in industrial influences and their consequences for ecosystems and biodiversity would therefore greatly inform conservation and climate change research aimed at understanding long-term trends in biodiversity, as well as climate variables and their underlying drivers. There is also potential to utilize anthrome maps in these efforts, as these have been produced using consistent inputs at annual increments since 2000 and decadally since 1700 CE (3).

4.2. Putting Indigenous Peoples and Local Communities in the Map

To date, most efforts to map anthropogenic influences on global ecology have aimed at assessing recent negative changes, including biodiversity losses and runaway climate change. However, a consequence of this focus is that these maps are generally blind to earlier histories of land use, especially by Indigenous societies (89). Recent work confirms the history of long-sustained interactions between human societies and ecosystems across most of Earth's land surface (3, 20). Failing

Indigenous peoples and local communities (IPLCs): typically, ethnic groups who are descended from and identify with the original inhabitants of a given region, in contrast to groups that have settled, occupied, or colonized the area more recently

to map and account for these historical and prehistoric interactions limits scientific understanding of sustainable ecosystem and biodiversity management that is critical to policy and practices relating to conservation, restoration, and sustainable use of land- and seascapes, including the critical role of Indigenous and traditional peoples in these efforts (1, 89). Moreover, the terminologies used in the global mapping of anthropogenic influences, like human footprint, can appear to disregard the beneficial role that Indigenous peoples and local communities (IPLCs) have played in shaping, conserving, and sustaining the ecology of their traditional lands and waters over hundreds to thousands of years.

Although low-intensity land- and seascape use likely contributed to some species extinctions and reshaped ecological form and functioning in the past (151–154), areas under Indigenous and traditional low-intensity use today are recognized as some of the most biodiverse areas remaining on the planet, especially when compared with those used intensively by industrial societies (89). As a result, recent dramatic declines in biodiversity are best explained not by humans or land use per se, or even by recent conversions of uninhabited wildlands, but rather by the appropriation, colonization, and intensifying use of the biodiverse cultured landscapes shaped and sustained by earlier societies (3). Future approaches to mapping anthropogenic changes in land- and seascapes for environmental assessment and planning need to use methods that account for the full suite of costs and benefits of historic and contemporary human use.

A starting point for further understanding long-term human inhabitation and use of landscapes is changing mapping terminology. Although human footprint, human modification, and measurements of what is "intact" when it comes to the natural environment have generally focused on industrial forms of ecosystem transformation and use, these terms are easily interpreted as insensitive to the long sustained and ecologically sustainable use of species, ecosystems, and landscapes by Indigenous and traditional peoples. Reconsidering existing terminology and clearly defining what is being mapped could help overcome these issues (155).

One approach that has been different in this respect has been the mapping of anthromes. The deep integration of people and nature that is inherent in anthrome mapping is aimed at helping to support strategies for conservation and sustainable land use that embrace pluralistic values of nature (156). Efforts to map anthrome histories confirm that human transformation of ecology is not new, enabling a deeper understanding of the human role in shaping nature at local, regional, and global scales over the long term (3, 157). Efforts to map ecosystem transformation and integrity, now so important for current international agreements such as the UNFCCC and CBD, must embrace efforts to account for long histories of sustainable human inhabitation and use of ecosystems by Indigenous peoples and local communities across the planet.

4.3. Predicting Human and Industrial Influences into the Future

A major area for future work is toward spatially explicit forecasts and scenarios of future changes in human transformation of ecology and biodiversity across all realms. Integrative global land-use models that incorporate dynamic adaptations in human–environment relationships have been generated over the past two decades and have helped to advance our understanding of potential future land-use changes (158). Yet they are still too simplistic in the spatializing of these future land use patterns and have yet to incorporate many forms of human influences, positive and negative, on ecosystems and biodiversity across the planet. Given the increased utility that comes from combining different forms of global data through integrative (e.g., anthromes, land systems) and cumulative (HFP, HM) strategies for human influence mapping methodologies, and the emergence of very fine scale global EOS data (38), an urgent research priority is to generate predictive maps of industrial influences, and integrate these with climate change predictions as part of global

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scenarios of population and socioeconomic growth (159). This is particularly important given predictions of accelerating infrastructure development in the near future (160).

Industrial influence projections could be used in assessing hotspots of risks to biodiversity, habitats and ecosystems. These would be significant for implementing current and future policy goals, especially those relating to ambitious area-based targets for conservation and nature-based solutions to abate climate change (131). For the success of any new "global deal for nature" (161) being discussed by nations and industry, there is an urgent need not only to identify priority areas to protect but also for a clearer understanding of how much time we have to act and the most socially and ecologically appropriate methods to secure them. As all threats to biodiversity and ecosystems are inherently intertwined with social and economic forces, interdisciplinary integrative and cumulative approaches to identifying, mapping, and addressing risks of future industrial transformations of land- and sea use will be critical for policy and planning across Earth in the Anthropocene.

Artificial intelligence (AI): the theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages

4.4. Utilizing Technological Advances

Advances in technology hold the potential to vastly increase our ability to understand and address critical environmental challenges (162, 163). In recent years, there have been significant advances in hardware, software platforms, computing resources, and algorithms that can aid researchers in better understanding patterns of human industrial influence across the planet (164–166). The proliferation of affordable and cheap transmission units has allowed monitoring environmental change in near real time. For example, automated vessel tracking and monitoring systems (which use a constellation of satellites and vessel mounted transmitters) can be used to inform models, which predict illegal fishing activity in real time (167). Identifying patterns of suspicious behavior has allowed governments to conduct targeted investigations of vessels that may be undertaking illegal activity in their waters (168) and to deploy timely and directed conservation actions.

In an era of global change, new technologies will be increasingly vital for responding to even bigger conservation challenges such as climate change (169). A critical advance is the near real-time observations of climatic events and natural disasters stemming from the proliferation of private and high temporal and spatial resolution satellite networks. For instance, imagery from Planet Labs is now available daily at 0.5 m resolution and was recently used to track a major Himalayan landslide's impacts and to guide first responders (170). Moreover, our ability to map an ice sheet's changing volume, flow, and gravitational attraction and then to model its surface mass balance has also fundamentally changed over the past five years due to increased computational power, meaning scientists have greater levels of confidence in the estimated volume of Antarctic lost ice and its impact on sea-level rise (171, 172).

Perhaps the largest area of untapped potential is technologies that can rapidly detect environmental change via the combined use of fine-scale remote sensing data and artificial intelligence (AI). These applications are already being harnessed by researchers, governments, and the private sector for early applications such as monitoring of restoration projects (173) and disaster response (174–176). AI enables a vast improvement in the accuracy and speed of processing remotely sensed images (177). For example, a new machine-learning approach to generate the human footprint was recently developed to capture changes in global terrestrial ecosystems over a 20-year timeframe (2000–2019) (75). In this new approach, a convolutional neural network machine learning algorithm was trained to ingest satellite imagery of Earth and predict the human footprint. The method does not require harmonization of multiple datasets representing different human pressures and can be regularly and rapidly updated with only remotely sensed imagery.

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Thus, the new machine learning human footprint overcomes the challenge of previous versions lagging behind the present day by seven or more years (4, 76).

Yet, wholesale advancements in the use of big data and the use of AI algorithms are still in their infancy when mapping human industrial influence on Earth (21). Research around the use of different platforms, in particular the use of AI, is needed to enable a closer coupling of big data analytics and human industrial influence mapping. As such algorithms gain ground, it is important that the data on which they are trained be free from biases that often affect human decisions and do not reflect historical or social inequities.

Big data: extremely large datasets that may be analyzed computationally to reveal patterns, trends, and associations, especially relating to human behavior and interactions

5. CONCLUSIONS

All maps, by simplifying and abstracting the real world, embody perspectives on interpreting pattern and orientation of the world around us. As concern has increased around anthropogenic transformation of Earth's ecology, a range of different mapping approaches have been developed to assess anthropogenic transformation of the biosphere through changes in land- and seascapes over the industrial period. This in turn is leading to a far more nuanced understanding of how humans are fundamentally changing biological communities and their function, as well as insights into how to better manage these changes in the future. This body of work has enabled an increasing amount of interdisciplinary research and is starting to allow practitioners, scientists, and policymakers to recognize, understand, adopt, and apply concepts from other disciplines to meet societal grand challenges. Yet this work remains in its early days, and our hope is that the coming decade will include a broadening of our understanding of human-nature interactions, and a tighter integration of this information within global sustainable development agendas.

SUMMARY POINTS

1. The impetus and foundation for mapping the biosphere itself, as well as human shaping of its patterns and processes, has been a burgeoning data revolution over the past 40 years, especially for the industrial period.
2. Rapid advances in Earth Observation Systems over the past two decades have led to enormous advances in global land cover and land use mapping.
3. The increased availability of shared global data and geographic information systems tool improvements have led to the development of numerous distinct cumulative industrial influence and integrative anthrome and land system mapping approaches that have enabled more nuanced assessments of industrial transformation of the planet.
4. A myriad of interdisciplinary approaches have generated a vast literature, demonstrating the utility of these mapping products, including for understanding the transformation and loss of habitats, biodiversity, and ecosystems.
5. Industrial influence mapping products are increasingly utilized in important global environment assessments and are viewed as foundational products for assessing species extinction risk, measuring ecosystem integrity, and rapidly assessing the effectiveness of conservations interventions.
6. Advancements in big data and the use of artificial intelligence may be increasingly useful for mapping industrial influence across Earth's environment as recently demonstrated by a machine learning algorithm that can generate maps of change in the human footprint over a 20-year timeframe based on satellite imagery alone.

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7. Most human influence mapping efforts to date have been oriented toward helping explain humanity's modern day negative influence on Earth's environment and are blind to prior histories and contemporary patterns of sustainable land and sea use, especially by many Indigenous societies and traditional land users.

FUTURE ISSUES

1. Future mapping efforts must rethink and revise their terminologies and semantics in the light of decoloniality and other critiques of the grand narratives of humanity inherent in terms like human impact, human pressure, human footprint, and human influence and also to terms implying human absence, such as nature/natural, pristine, and wilderness.
2. Greater research investment and collaboration with Indigenous and local experts is needed to improve spatial assessments on the global extent, timing, and ecological consequences of inhabitation and land use by Indigenous peoples and other traditional land users.
3. Global maps of human populations need to correct for past failures to incorporate low density and mobile populations, leading to erroneous assessments of human inhabitation and use, especially in lands traditionally used by Indigenous people.
4. There is a clear need for real-time high-temporal-resolution human industrial influence maps to help inform policymakers as to how to abate the impacts of anthropogenic environmental change.
5. The use of artificial intelligence (AI) and big data remains limited in our efforts to map human industrial influence across the planet. Further research on software platforms, computing resources, and algorithms is needed while ensuring that AI algorithms are free from the biases to which human researchers are often susceptible.
6. Forecasting human influences and integrating these with climate change data will be critically important for assessing the locations and types of appropriate environmental actions.
7. The positive role of Indigenous, traditional, and other cultures and societies in shaping and sustaining biodiverse and productive landscapes and seascapes must be better understood and recognized by ecologists and conservationists and incorporated into global assessments of anthropogenic transformation of the biosphere.
8. Indigenous and local knowledge systems and the people who share them need to be integrated into global efforts to characterize and map social-ecological systems.
9. Human influence mapping efforts have yet to be standardized across realms and ecosystems. There is an acute need for comprehensive global maps of human influences that account for connectivity and dynamic feedbacks between social-ecological systems.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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