Challenges in producing policy-relevant global scenarios of biodiversity and ecosystem services

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Mapping the Continuum of Humanity's Footprint on Land

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The past three decades have seen a proliferation in the breadth of data documenting the natural world around us. In concert with this, the new field of cumulative human-pressure mapping has emerged to integrate these data forms and allow practitioners in different disciplines to utilize and apply concepts from others. These mapping efforts provide a new view of the terrestrial biosphere and humanity's role in shaping its patterns and processes. Here, we present an overview of this field and its major advances by exploring how these maps have found diverse uses in environmental management and in informing international policy and debate around how best to achieve sustainability, reach biodiversity conservation goals, and avert dangerous climate change. The field is still in its infancy, and we conclude with our views of what could be the next set of interdisciplinary advances for mapping human pressure to inform the global environmental agenda.

The Need for an Integrated View

Humanity has been reshaping Earth's ecosystems for millennia. We engage in large-scale conversion of natural habitats to agricultural crops and urban areas to feed and house our burgeoning population. In more subtle ways, we change the state of natural systems through activities such as hunting, logging, recreation, and fire management. A multitude of impacts on the terrestrial biosphere have now been recorded, including significantly altered global patterns of species composition and abundance, loss and appropriation of primary productivity, changes in land-surface hydrology and albedo, and alterations to the biogeochemical cycles of carbon, nitrogen, and phosphorus. Many natural scientists argue that we have now entered a human-dominated geological era termed the Anthropocene and are increasingly transgressing catastrophic environmental boundaries.

While humanity is now altering natural systems at the planetary scale, the extent and intensity of these alterations vary across space. Yet until very recently—that is, the last 20 years—broad spatial descriptions of the extent of anthropogenic impact across Earth's terrestrial ecosystems were grossly incomplete. Most mapping efforts either completely ignored human influence on natural systems or described it using broad classes of land use (i.e., dividing landscapes into urban and other built-up areas and one or two crop-land and natural vegetation mosaics). At the beginning of this century, many biogeographers lamented the fact that available mapping efforts missed many lower-intensity forms of human pressure, such as our extensive networks of roads, power lines, and water irrigation (known as linear infrastructures), along with grazing lands for cattle and sheep and low-density human settlements, some of which are more insidious than outright habitat conversion.

There was good reason for these omissions: many of these anthropogenic pressures that degrade but do not outright convert natural ecosystems are difficult or even impossible to detect across large areas with space-borne satellites. The consequences were substantial, and in only the recent past our efforts to measure humanity's impact on the planet simply overlooked many important degrading processes, such as grazing pressure, and remained completely ignorant to the fact that many pressures co-occur and interact in ways that have profound consequences for the natural environment (for example, a road created to go to a new mine could lead to entirely new agricultural frontiers and new human settlements, a phenomena witnessed all over the world).

In the last two decades, our ability to map humanity's influence across the terrestrial planet has fundamentally evolved thanks to increasingly powerful computing working to make sense of the deluge of data now available from an expanding network of improved satellites combined with new bottom-up census and crowd-sourced data forms. We can now quantify and locate even sparse human settlements, low-intensity agricultural farming, and road construction, among other forms of human pressure previously overlooked. As a consequence, we now live in a special time where we have the opportunity to better understand how human pressures vary across space and time and, increasingly, assess what this means for the state of natural systems and the interventions we are conducting.

A Brief History

A number of factors during the 1990s and early 2000s laid the foundation for subsequent cumulative human-pressure mapping. First, there were rapid advances in earth observation using satellite technology pioneered by space agencies such as NASA and the European Space Agency, which meant that verifiable global maps of land use and land cover were available to the wider scientific community. What was considered very high resolution back in the 1990s—for example, NASA satellite data from Landsat with its 60 m per pixel—has become low by today's

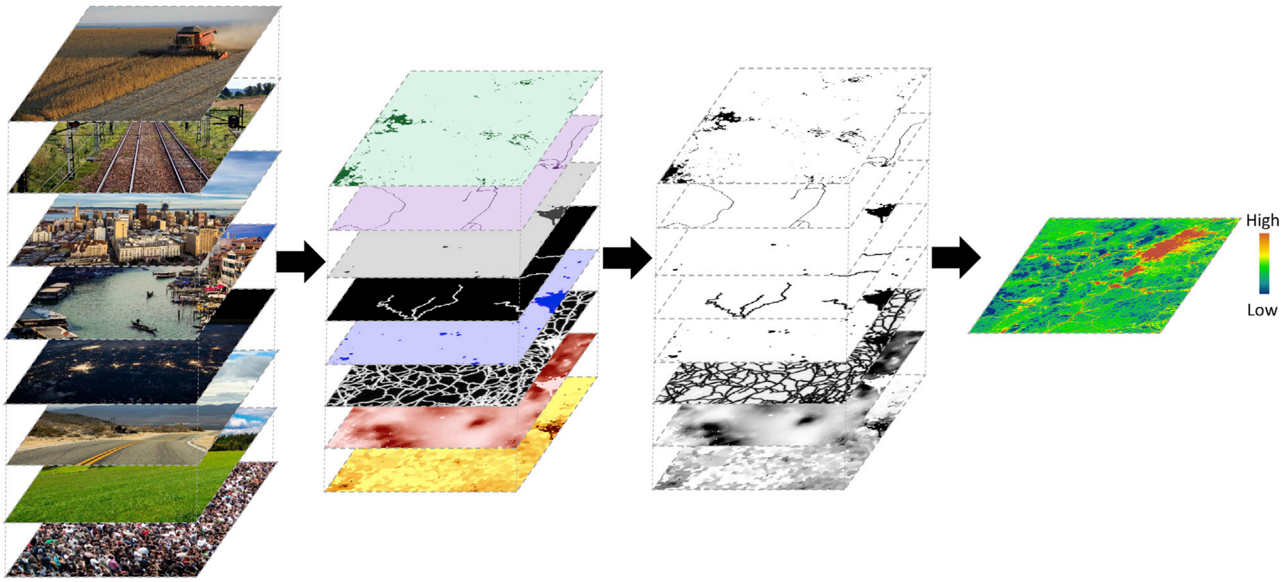

Figure 1. The Broad Methodological Framework Used to Create a Map of Cumulative Human Pressure

standards. The finest resolution is now 30 cm provided by very high-resolution commercial satellites. In addition, geo-politics 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, for example, on roads and railways, were released to the public by national agencies. At the same time, improved reporting of population statistics across the planet enabled geographers to create global digital maps of human population density for the first time. Finally, advances in geographic information system (GIS) software and our ability to store large datasets, in conjunction with improved methodologies around integrating different spatial layers, have provided the integration technology necessary to combine these data in an efficient and reproducible manner.

The first global-scale effort to seize upon the full suite of these newly available data and vastly improving GIS technologies and computational power was that of Eric Sanderson and colleagues. By generating a new method of cumulative pressure mapping (Figure 1), they produced the global terrestrial "human footprint," and from this a global map of Earth's last wild places in 2002. Their efforts changed the way many saw humanity's influence on the planet. The human footprint clearly showed the spatial extent of humanity's environmental footprint, with 83% of the land's surface directly influenced by humans. This far exceeded the estimates of affected land from past efforts using categorical land-cover methods. In particular, human pressures that fall short of outright habitat conversion were much better reflected in the human footprint than through categorical land-cover maps (Figure 2). Erle Ellis and his colleagues then went on to build off Sanderson's work by integrating proxies of human pressure with measures of ecological conditions to define and map the global distribution of "Anthromes." Ellis's work verified Sanderson's findings but went on to reveal that only a small fraction (11%) of terrestrial net primary productivity was occurring in Earth's remaining wildlands, which means that most of this primary ecological function is taking place on and being utilized for human-dominated Anthromes.

Continued advancement in the availability of fine-scale data from remote sensing satellites has facilitated our unprecedented capacity to visualize and measure human impacts on the planet, and there are now a myriad of recently published "human footprint" maps that broadly use the same cumulative human-pressure methods outlined in Figure 1 but take advantage of different, more up-to-date datasets as they become available. These efforts show that regardless of the data used, a profound pattern is emerging: Earth has very few places that can now be considered wild (i.e., devoid of industrial-level human activity), and the only places where one can find large expanses of ecosystems that have not been touched with an industrial footprint are in central Africa, the Amazon, the boreal and tundra forests of the north, and deserts, woodlands, and savannah systems of Australia.

Only in the last 5 years have comparable datasets from satellite images, roads, and population censuses become available across multiple time periods. This has created the first opportunities to generate time-series assessment of cumulative pressures, providing the first insights into how our footprint is changing through time and across space. The first effort to seize on this opportunity was published by ourselves and our colleagues in 2016, when we assessed the total change in the human footprint from 1993 to 2009. During the 16-year period, the human footprint was found to have increased by 9%, during which time the human population increased by 23% and the global economy increased by 153%. We found that 26 countries managed to significantly grow the size of their economies while actually shrinking their environmental impact on land use and infrastructure. These countries, including, for example, Mexico and Sweden, tended to have good governance structures and higher rates of urbanization, which have led some to interpret this as clear evidence that it is possible

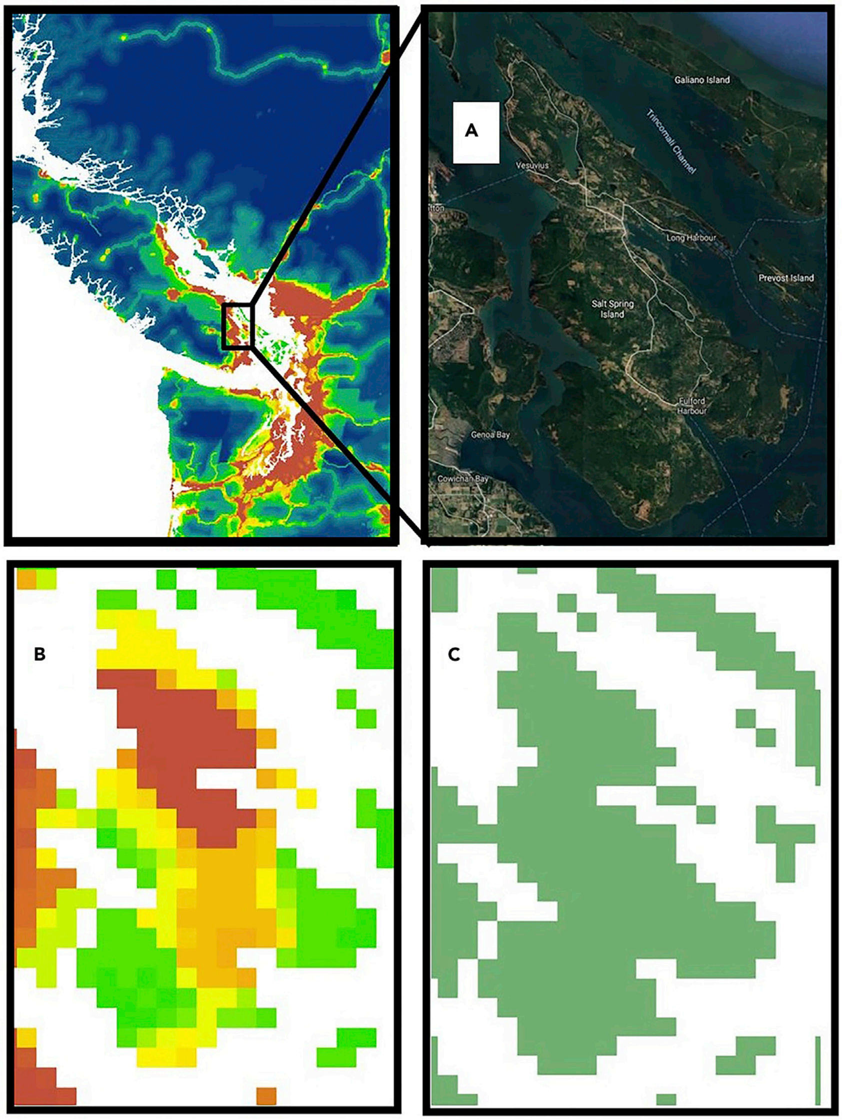

Figure 2. How Cumulative Human-Pressure Maps Compare with More Generic Landcover Mapping Efforts
Illustration of the more nuanced information provided by (B) a human-footprint map (2009 Human Footprint) relative to (C) a map of anthropogenic land covers from a leading categorical map (according to the European Space Agency GlobCover Project for 2009) and (A) observable and mapped human pressures.

to decouple economic growth from environmental impacts, and as such emerge from humanity's current trajectory of disastrous environmental impacts. However, further analyses of the same temporal human-footprint dataset revealed that 3.3 million km^2 (equivalent in area to half of the continent of Australia or twice the size of Alaska) of Earth's terrestrial wilderness estate was lost in the 16-year period, clearly showing a rapid spread of human influence into areas previously untouched by humanity's industrial footprint. Hardest hit was South America, which has experienced a 30% wilderness loss, and Africa, which has experienced a 14% loss in just under two decades. As such, these temporal analyses that use human cumulative pressure methodologies need further exploration, and there are clearly complex development and sustainability trajectories to be unpicked.

Informing Sustainability and Conservation

While the first efforts to map the continuum of human pressure have focused on quantifying the spatial pattern of human influence on natural systems, the field has recently grown through investigations of what these pressures mean for sustainability and biodiversity. There has been a boon of recent work that has utilized human-pressure mapping to better understand global patterns of biodiversity loss. For example, Moreno di Marco and colleagues assessed a 16-year trend in the global human footprint alongside extinction-risk changes of ~4,500 terrestrial mammal species. They found that the extent of the human footprint within a species' geographic range and the change in this extent over time are the strongest predictors of extinction risk, even more so than the biology of the species, such as its trophic level or body size. What was most surprising, however, was that the extent of low pressure values (at the global scale, a human-footprint score of <3 out of 50) was the most statistically significant predictor of change in extinction risk. This means that to predict extinction risk, it is necessary to map a level of degradation far below that of the outright habitat conservation. These findings serve to highlight the utility of human-pressure mapping over mapping broad classes of land cover for informing the conservation.

Subsequent work has found that the ecological impacts of the expanding human footprint can be also more subtle than outright species loss. For instance, a consortium of wildlife researchers led by Marlee Tucker recently evaluated the impacts of the human footprint on the movement patterns of 803 radio-collared individuals across 57 species of mammals. They discovered that individuals in areas with a high human footprint moved just one-half to one-third as much as individuals in areas with a low human footprint. 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. Moreover, the study revealed a concave relationship between increasing human footprint and decreased mammal movement, indicating that again the incremental impacts were strongest at the low end of human pressure (i.e., those areas that could be classified as either wilderness versus those just slightly degraded). In a similar analysis, Kühl and colleagues found that chimpanzee behavioral diversity decreased by almost 90% in areas with a high human footprint. This work, among others, clearly highlights a threshold where humanity activity is driving species and ecological declines around the world and the need for continuous and refined measures of these pressures to track and predict these changes.

Beyond species-based assessments, there are now efforts to utilize human-pressure maps in critical ecosystem service assessments. For example, cumulative human-pressure maps have been used for assessing the quality of the world's surface water; the first such assessment was conducted in 2010 by Charles Vörösmarty, who found that nearly 80% of the water used by the world's population had degrees of human influence. These findings have led to calls for not only huge investments in water technology to enable nations to mitigate and offset water-quality levels but also more assessments aimed at remedying their underlying causes and the vulnerability of the poor. Another example has been the use of human-pressure maps to understand and even predict patterns of infectious diseases. In 2014, Mica Hahn and colleagues, for example, used a human-pressure methodology to identify key drivers of zoonotic malaria outbreaks in Sabah, Malaysian Borneo. At a global scale, components of human pressure (human population density and growth) have been used to explain past outbreaks of emerging infectious diseases and to identify "hotspots" where future diseases are most likely to merge. This predictive effort serves as a basis to not only detect current patterns of risk but also identify likely future changes to these patterns and allow pre-emptive responses to minimize future risk to human health.

Pressure-State-Response Assessments

The broadening of the evidence base for the utility of human-pressure maps has led to their increasing adoption for adaptive planning efforts that utilize the pressure-state-response (PSR) framework. The PSR framework uses a theory of change that highlights the linkages among and between the pressures exerted on the land by human activities, the change in state of the environmental or socioeconomic values, and the response to these changes as society attempts to mitigate the pressure or restore land that has been degraded. The interchanges that take place in the PSR framework form, at least in theory, a continuous feedback mechanism that can be monitored and used for assessment of land quality and management effectiveness.

An example of human-footprint maps informing the PSR framework is through evaluations of networks of protected areas. The primary objective of protected areas is to secure places where plants and animals can live in near-natural conditions without the high levels of human pressure that plague most places and drive biodiversity toward extinction. While some protected areas are clearly effective at keeping human pressures out (Figure 3), this is not always the case. A number of studies are highlighting the extent and intensity of human pressure across protected areas worldwide, with the first global assessment (lead by Kendall Jones) showing an alarming story: almost three-quarters of countries have more than 50% of their protected land under intense human pressure. Only 42% of land safeguarded for conservation goals—comprising a mere 4,334 individual protected areas—is completely free of measurable human pressure. Importantly, we 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 than those permitting a wider range of human activities.

At least a quarter of Earth's land area is owned by or directly managed by indigenous peoples, and recent assessments are revealing the increasing importance of these indigenous managed lands for conservation and sustainable development. A recent effort led by Stephen Garnett assessed the degree of human influence on indigenous lands and showed that the extent of lands with strong indigenous connections are little changed by development such that two-thirds of indigenous land have very low human-pressure scores. This research therefore shows that governance responses focused on restoring indigenous land rights and titles could yield major benefits for conservation of ecologically valuable landscapes, ecosystems, and genes for future generations.

Future Directions

In just 20 years, we have moved from mere categorical mapping of land cover at the global scale to mapping the continuum of human pressure and, using interdisciplinary approaches, determining how these pressures interact to drive species declines and behavioral changes, facilitate infectious disease spread, and compromise some crucial ecosystem services such as water quality. Yet, there are still many unanswered questions, particularly with regard to how cumulating pressures affect the broad array of ecosystem services that underpin natural and anthropogenic systems. While there is widespread evidence for declines in critical ecosystem services, such as pollination, our ability to map these services with the precision needed to link human pressures to changes in these services across broad scales has been limited. This is an essential shortfall for local decision-making processes that aim to avoid the erosion of natural capital and biodiversity from current and future development and also for reporting national progress toward core international agreements, such as the Sustainable Development Goals, and implementing the United Nations Convention on Biological Diversity and Framework Convention on Climate Change.

Arguably the most critical persistent research gap is how carbon sequestration and storage changes along the continuum of human pressures. Natural climate solutions, such as slowing forest-based carbon emissions, could account for 30% of the emission reductions needed to keep global warming within safe levels. While many of these solutions are based on reducing emissions associated with the degradation and not full-scale conversion of carbon stocks, mitigation and research efforts to date have largely relied on only broad concepts of land use associated with satellite imagery, such as total extent of forest or cover. A critical need for future work is to better understand how industrial-scale logging, fragmentation and edge effects, farms and urbanization, and less visible pressures, such as defaunation and altered fire regimes, compromise carbon stores and undermine the process of carbon sequestration. Cumulative pressure maps have huge potential as a platform for understanding spatial pattern and emission intensity for this work.

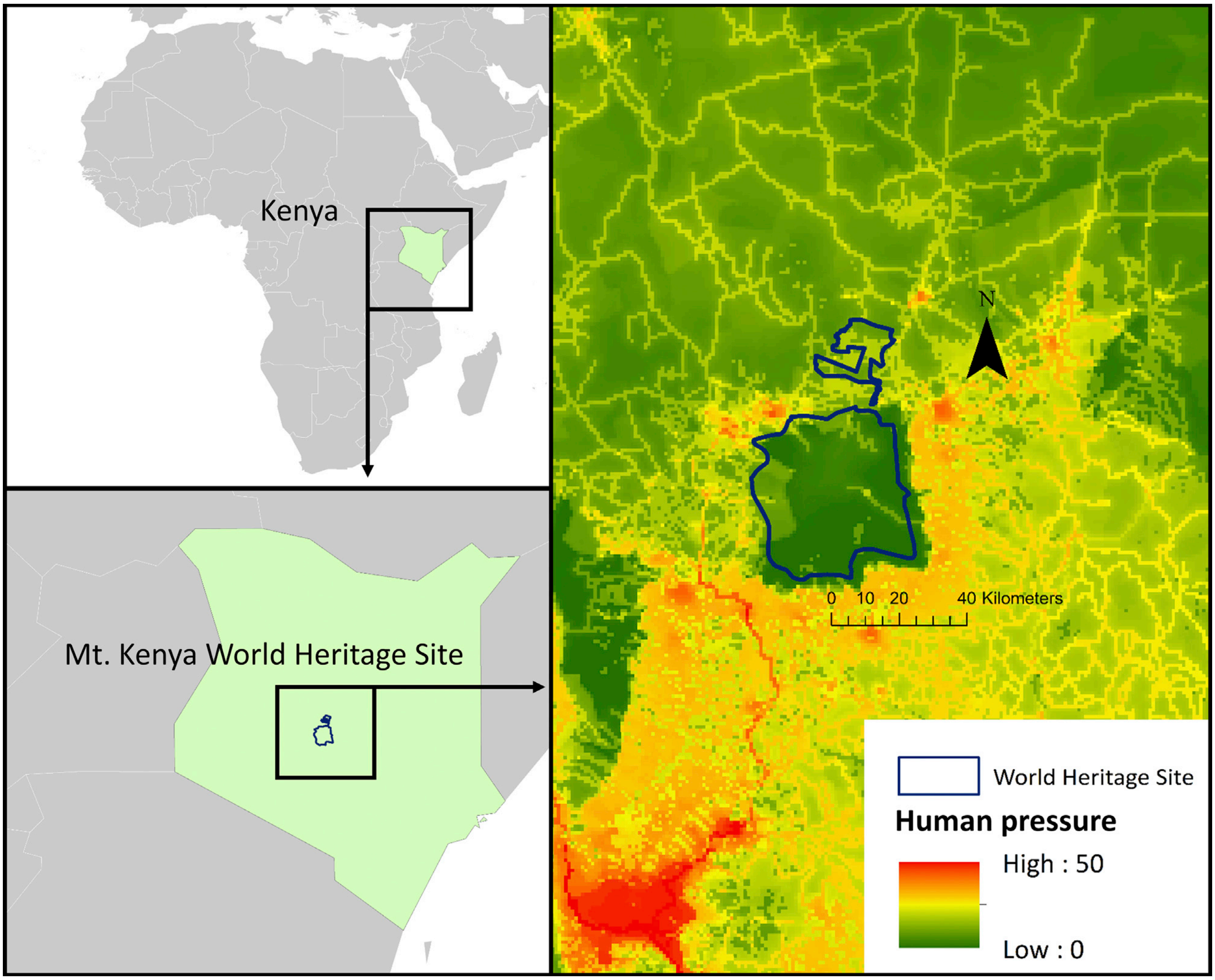

Figure 3. An Example of the Use of a Human Cumulative Pressure Map in an Assessment of World Heritage Effectiveness, in This Case Mount Kenya

There has long been an interest in mapping ecological integrity as a means of prioritizing novel areas for conservation or for evaluating management effectiveness. Ecological integrity is defined as a situation whereby the structural condition of habitat, its ecological function, and biodiversity composition are within the range of natural values for an ecosystem. However, mapping ecological function and biodiversity composition directly across broad scales has remained elusive. The emerging evidence base for cumulative human pressures as a proxy for ecological function and biodiversity supports the applications that combine maps of the human footprint with direct measures of habitat structure from satellite or aircraft-based instrumentation to develop the first broad-scale maps of ecological integrity.

Finally, a major area for future work is to develop the capacity to spatially predict future changes across the full continuum of human pressures. Although land-use processes are now shifting rapidly from historical patterns in both type and scale, integrative global land-use models that incorporate dynamic adaptations in human-environment relationships help to advance our understanding of both past and future land-use changes, including their sustainability and potential global effects. These projections, which must include climate-change scenarios, are crucial for estimating future land-based carbon emissions, changes to biological diversity, and other ecosystem services. However, the spatializing of these patterns is currently only done with categorical maps of land cover. Given the increased information that comes from cumulative pressure maps and the emergence of fine-scale climate-change projections across Earth, a priority should be to integrate maps such as the human footprint and climate change with global scenarios of socioeconomic growth.

Conclusions

All maps simplify and scale down the real world to provide us perspective, pattern, and orientation. As concern has arisen around the erosion of the natural environment and its consequences for the sustainability of the human experiment, the use of cumulative human-pressure maps has played an increasingly important role in identifying loss and degradation of ecosystems and mapping those values that are at risk. By integrating top-down satellite imagery that provides consistent and reproducible information of vegetation cover and land surface structure with bottom-up, spatially explicit data on human population, roads, and other linear infrastructure, human cumulative maps are offering us increasing clarity regarding the scale and intensity of human influence across our planet. This, in turn, is leading to a far more nuanced understanding of how we are fundamentally changing biological communities and how they function, as well as early insights into how we can better manage these changes. This work has enabled an increasing amount of interdisciplinary research and is now starting to allow practitioners, scientists, and policy makers in one discipline to recognize, understand, adopt, and apply concepts from others to meet societal grand challenges. However, this work is still in its infancy, and our hope is that the coming decade will include a broadening of our understanding of these human-nature interactions and a tighter integration of this information within the global sustainable development agenda.

RECOMMENDED READING

Di Marco, M., Venter, O., Possingham, H.P., and Watson, J.E.M. (2018). Changes in human footprint drive changes in species extinction risk. Nat. Commun. *9*, 4621.

Ibisch, P.L., Hoffmann, M.T., Kreft, S., Pe'er, G., Kati, V., Biber-Freudenberger, L., DellaSala, D.A., Vale, M.M., Hobson, P.R., and Selva, N. (2016). A global map of roadless areas and their conservation status. Science *354*, 1423–1427.

Ellis, E.C., Goldewijk, K.K., Siebert, S., Lightman, D., and Ramankutty, N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000. Glob. Ecol. Biogeogr. *19*, 589–606.

Tucker, M.A., Böhning-Gaese, K., Fagan, W.F., Fryxell, J.M., Van Moorter, B., Alberts, S.C., Ali, A.H., Allen, A.M., Attias, N., Avgar, T., et al. (2018). Moving in the Anthropocene: global reductions in terrestrial mammalian movements. Science *359*, 466–469.

Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, A., Molnár, Z., Robinson, C.J., Watson, J.E.M., Zander, K.K., Austin, B., Brondizio, E.S., et al. (2018). A spatial overview of the global importance of Indigenous land for conservation. Nat. Sustain. *1*, 369–374.

Hahn, M.B., Gangnon, R.E., Barcellos, C., Asner, G.P., and Patz, J.A. (2014). Influence of deforestation, logging, and fire on malaria in the Brazilian Amazon. PLoS One *9*, e85725.

Kühl, H.S., Boesch, C., Kulik, L., Haas, F., Arandjelovic, M., Dieguez, P., Bocksberger, G., McElreath, M.B., Agbor, A., Angedakin, S., et al. (2019). Human impact erodes chimpanzee behavioral diversity. Science *363*, 1453–1455.

Geldmann, J., Joppa, L.N., and Burgess, N.D. (2014). Mapping change in human pressure globally on land and within protected areas. Conserv. Biol. *28*, 1604–1616.

Jones, K.R., Venter, O., Fuller, R.A., Allan, J.R., Maxwell, S.L., Negret, P.J., and Watson, J.E.M. (2018). One-third of global protected land is under intense human pressure. Science *360*, 788–791.

Kennedy, C.M., Oakleaf, J.R., Theobald, D.M., Baruch-Mordo, S., and Kiesecker, J. (2019). Managing the middle: a shift in conservation priorities based on the global human modification gradient. Glob. Chang. Biol. *25*, 811–826.

Sanderson, E.W., Jaiteh, M., Levy, M.A., Redford, K.H., Wannebo, A.V., and Woolmer, G. (2002). The human footprint and the last of the wild. Bioscience *52*, 891–904.

Theobald, D.M. (2013). A general model to quantify ecological integrity for landscape assessments and US application. Landsc. Ecol. *28*, 1859–1874.

Watson, J.E., Shanahan, D.F., Di Marco, M., Allan, J., Laurance, W.F., Sanderson, E.W., Mackey, B., and Venter, O. (2016). Catastrophic declines in wilderness areas undermine global environment targets. Curr. Biol. *26*, 2929–2934.

Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., et al. (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nat. Commun. *7*, 12558.

Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., et al. (2016). Global terrestrial human footprint maps for 1993 and 2009. Sci. Data *3*, 160067.