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Viewpoint

Pandemics and the future of human-landscape interactions

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ABSTRACT

Pandemics have accelerated in frequency in recent decades, with COVID-19 the latest to join the list. Emerging in late 2019 in Wuhan, China, the virus has spread quickly through the world, affecting billions of people through quarantine, and at the same time claiming more than 800,000 lives worldwide. While early reflections from the academic community have tended to target the microbiology, medicine, and animal science communities, this article articulates a viewpoint from a perspective of human interactions with Earth systems. We highlight the link between rising pandemics and accelerating global human impacts on Earth, thereby suggesting that pandemics may be an emerging element of the "Anthropocene." Examples from Denver, Colorado, USA, show how policy responses to the COVID-19 pandemic changed human-environment interactions and created anomalous landscapes at the local scale, in relation to the quality of air and patterns of acquiring and consuming food. In recognizing the significance of novel infectious diseases as part of understanding human-landscape interactions in the Anthropocene, as well as the multi-scale interconnectedness between environment and health, this viewpoint converges toward an urgent need for new paradigms for research and teaching. The program required extends well beyond the already broad interdisciplinary scholarship essential for addressing human-landscape interactions, by integrating the work of health scientists, disease specialists, immunologists, virologists, veterinarians, behavioral scientists, and health policy experts.

1. Introduction

The COVID-19 pandemic originated in Wuhan, China, in late 2019 and spread quickly through the rest of the world. By late August 2020, the virus is responsible for nearly 24 million known cases and has claimed over 800,000 lives globally (Johns Hopkins University, 2020). The pandemic has affected billions more people through shuttered economic activity and widespread quarantine. The all-encompassing nature of the COVID-19 pandemic has prompted much reflection (e.g., Chin et al., 2020), as scholars gather their thoughts to decipher lessons for the future. Many such articles focus on the microbiology, medicine, and animal science communities (e.g., Bonilla-Aldana et al., 2020; Frutos et al., 2020). This contribution articulates a viewpoint from a perspective of human interactions with Earth systems, targeting an interdisciplinary community of human-environment scholars. As humanity is at a crossroads, with a pandemic raging amidst unprecedented environmental change, the current situation offers opportunity to gain clarity about human-landscape interactions at the origin of pandemics, as well as their effects and possible human responses and adaptations.

Below, we first examine the trend of rising pandemics against the backdrop of the global-scale emergence of the "Anthropocene," an era of ever intensifying human interactions with Earth systems, which poses risks for increasingly frequent pandemics. Next, we present two examples from the city of Denver, Colorado (USA), showing how policy responses to the spread of the virus triggered exchanges that altered human-environment interactions and created emergent new landscapes—in relation to the quality of air and ways of obtaining and eating foods—with implications for managing the effects of pandemics at a local scale. Lastly, we highlight the significance of an Anthropocene lens in going forward from the COVID-19 pandemic, linking the origin and effects of pandemics across scales. Such a perspective leads toward an

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urgent need for broader collaborations than ever before in a new paradigm for research and teaching.

2. The anthropocene and rise in pandemics

Parasitic organisms have afflicted human beings throughout history. The establishment of networks of villages and towns, in particular, provided conditions to sustain a variety of pathogenic lifeforms (Dobson and Carper, 1996). The earliest communicable diseases included measles, smallpox, rubella, typhoid, dysentery, and influenza. We are familiar with these diseases because, over time, with continual exposure to their outbreaks, human societies develop resistance and achieve herd immunity, controlling outbreaks well enough to prevent transition into pandemics. When people have no immunological resistance to new pathogens, however, novel emerging infectious diseases (EID) can devastate human health on a global scale.

While EIDs have occurred throughout human history, they have increased dramatically in recent decades. Jones et al. (2008), for example, catalogued the emergence of 335 infectious diseases between 1940 and 2004. Compounding the problem of EIDs, increasing globalized trade and travel can quickly transform novel outbreaks into epidemics or pandemics. Twenty-first century pandemics include SARS (2002), the Avian Flu (2003), Swine Flu (2009), MERS (2012), Ebola (2014), and Zika (2015). COVID-19 now joins this inauspicious list.

The exponential trend in increasing frequency of pandemics since the mid-20th century is eerily similar to other trends that signify accelerating human impacts on Earth (Fig. 1). What is now known as the "Great Acceleration" documents a sharply rising intensity of human activity since about 1950 (Steffen et al., 2015). The many socio-economic indicators documenting the accelerating human imprint include urban and ex-urban populations, economic development, transportation, energy use, and international tourism. At the same time, the growing human impacts on the structure and functioning of the Earth system during the same period are apparent in many key metrics. They include the loss of tropical forests, terrestrial biosphere degradation, increases in domesticated lands, ocean acidification, and increased emissions of greenhouse gases. The scale and pace of these human-induced changes on Earth are so vast and comprehensive that they are among the basis for a proposed new epoch in Earth's history, the Anthropocene (Waters et al., 2016), with the Great Acceleration period a possible beginning (Zalasiewicz et al., 2017). A careful look at pandemics during the time of the Great Acceleration indicates that pandemics are also apparently an element of the "Anthropocene."

The concurrent trend of accelerating pandemics and anthropogenic change on Earth is perhaps not surprising, given what is known about the origin of such diseases and their subsequent spread (Supplemental Table 1). Nearly all novel EIDs originate in animal populations. A "spillover event" occurs when a zoonotic infection passes to human populations. HIV/AIDS in the 1980s had simian origins, for example, and transferred to humans through the bushmeat trade in Africa (Sharp and Hahn, 2011). COVID-19 likely originated in bats (Zhou et al., 2020), with pangolins as a possible intermediate host and reservoir (Zhang et al., 2020).

The risks that a spillover event transforms into a pandemic increase with accelerated contact between human and animals. Deforestation and agricultural intensification are key activities through which people encroach into wildlife habitats and increase risks of disease transmission (Chaves et al., 2020). Agricultural development and urbanization also simplify ecosystems by changing habitats, often leading to a loss in predator species and enabling disease-carrying reservoirs and vector species to thrive (Keesing et al., 2010). Processes such as rapid urban growth create new habitats for attracting a range of species (e.g., bats, mice) that are common origins and hosts of infectious diseases

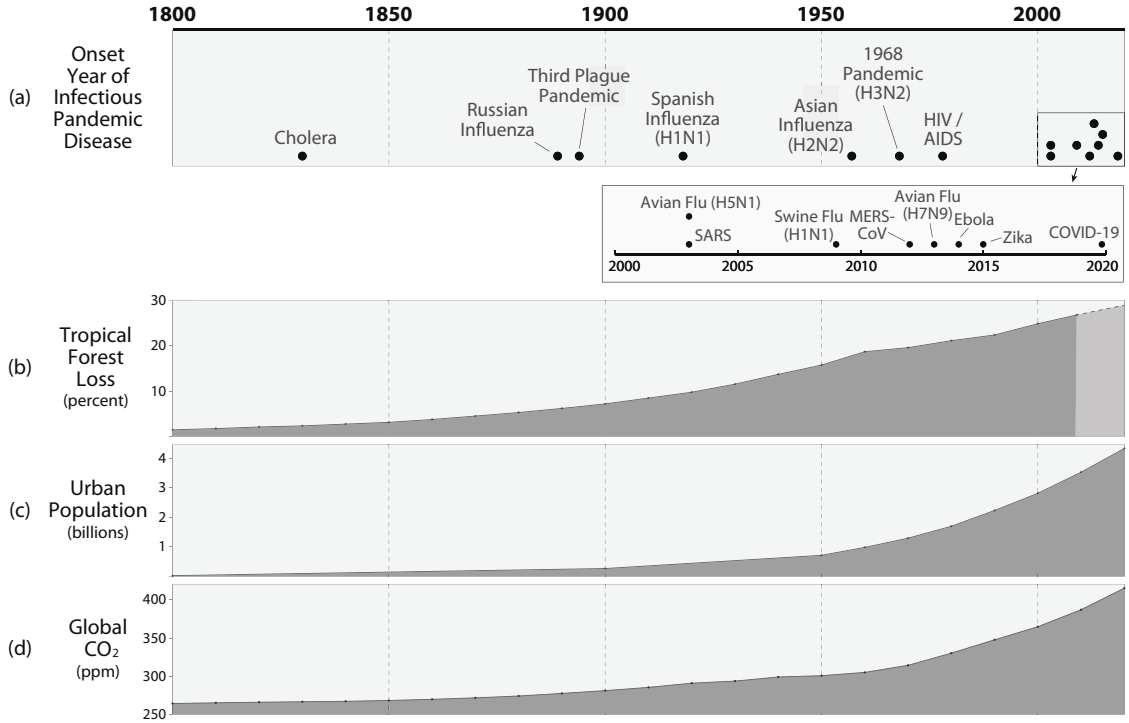

Fig. 1. Trends from 1800 relating pandemics to selected characteristics representing the human imprint during the "Great Acceleration" period. The authors constructed the figure using the following sources: (a) Frequency of pandemics (data from Bramanti et al., 2019; Kempińska-Mirosławska and Woźniak-Kosek, 2013; Kilbourne, 2006; Snowden, 2008; (b) percent loss of tropical rainforest relative to 1700 (after Steffen et al., 2015); (c) urban population (data for 1800 and 1900 from Klein Goldewijk et al., 2010; data for 1950-2020 from United Nations, 2018); (d) atmospheric carbon dioxide (CO_2) (Historical data from CO2-earth, 2020; data since 1960 from National Oceanic and Atmospheric Administration (NOAA, 2020).

(Afelt et al., 2018). Further, the processes of globalization through trade and travel can quickly turn outbreaks into pandemics (Saunders-Hastings and Krewski, 2016), though pathogens disproportionately impact underprivileged communities less connected to these global transactions (Dorn et al., 2020).

The relation between the origin of EIDs and anthropogenic environmental change is quantifiable at a global scale. Allen et al. (2017) empirically linked the occurrences of zoonotic diseases and many indicators representing human activity interacting with environment, including human population, proportional cover and change of pasture and cropland area, and change in urban cover extent. These quantitative results are particularly important because the Anthropocene is characterized by the acceleration of many of these same human interactions with the Earth system (Fig. 1). The results also provide compelling evidence that the association between the accelerating rate of pandemics and the key metrics of the Anthropocene is not by chance. Current data indicate that these interactions are still intensifying. Some of the greatest rates of loss of tropical forests, for example, have occurred within the last few decades, driven by agricultural expansion (Curtis et al., 2018). These trends suggest that the human-environmental processes responsible for the Anthropocene will continue to be significant for the health of humans and animals globally into the future.

3. Interacting responses and changing landscapes: examples from Denver

Though the origins of pandemics are rooted in global-scale human impacts on environment, i.e., the Anthropocene, the COVID-19 case shows how their riveting effects can also alter human-landscape interactions locally, with consequent cross-scale feedbacks. Historically, one can look to the Bubonic Plague in Europe in the sixth century and the Smallpox epidemic/pandemic (particularly in the Americas) between 1500 and 1800 CE for examples of such human-landscape interactions. According to Ruddiman (2005), the dramatic declines in human population following the pandemics may have caused a drop in atmospheric CO_2 concentrations through abandonment of farms and decrease in deforestation. This reduction in CO_2 may have been large enough to cool global temperature by up to 0.1 °C. So far, the current COVID-19 pandemic has not resulted in changes of this magnitude, but it nevertheless offers examples of how pandemics can contribute to the increasingly complex and altered human-landscape systems that characterize the Anthropocene (Harden et al., 2014). From Denver, Colorado, we outline two examples of ways in which the response to the COVID-19 pandemic has already produced, even if temporarily, anomalous human-environmental outcomes. As a representative growing city (with a population nearly 3 million) in the USA, located in the eastern foothills of the Rocky Mountains, the human-environmental responses documented in Denver enable broader generalizations that coincide with increasing observations reported elsewhere.

3.1. The COVID-19 pandemic in Denver

COVID-19 emerged in Colorado on 5 March 2020, about two months after China reported its first cases. After 13 presumptive cases five days later, with exponentially increasing illnesses and deaths, the governor declared a state of emergency. This action precipitated several policy responses in rapid succession that would affect business and travel and force changes in human behavior. On 18 March, the state of Colorado ordered the closure of schools and prohibited gatherings of more than 10 people. A stay-at-home order in Denver began on 25 March and remained through 8 May 2020, even though state-level restrictions began relaxing earlier, after the number of daily reported new cases in the state peaked on 26 April (at 993; Colorado Department of Public Health and the Environment (CDPHE, 2020). Although these closures disrupted society and economy, with consequences that included loss of employment, these policy responses also triggered interacting effects and feedbacks between people and environment, giving unique circumstances for observing changing human-environmental interactions. We focus on two examples that arose from the same circumstances: policy responses to the impacts of the COVID-19 virus that significantly limited movement and altered human behavior in the region.

3.2. The anomalous landscape of clean air

In early March, data show that people began to alter their daily routines to travel less (Streetlight Data, 2020). The stay-at-home order, however, drastically changed daily lives, including work patterns, employment habits, modes of teaching and learning, and social and recreational activities. The end result was an abrupt and dramatic drop in mobility in Denver County (Fig. 2a).

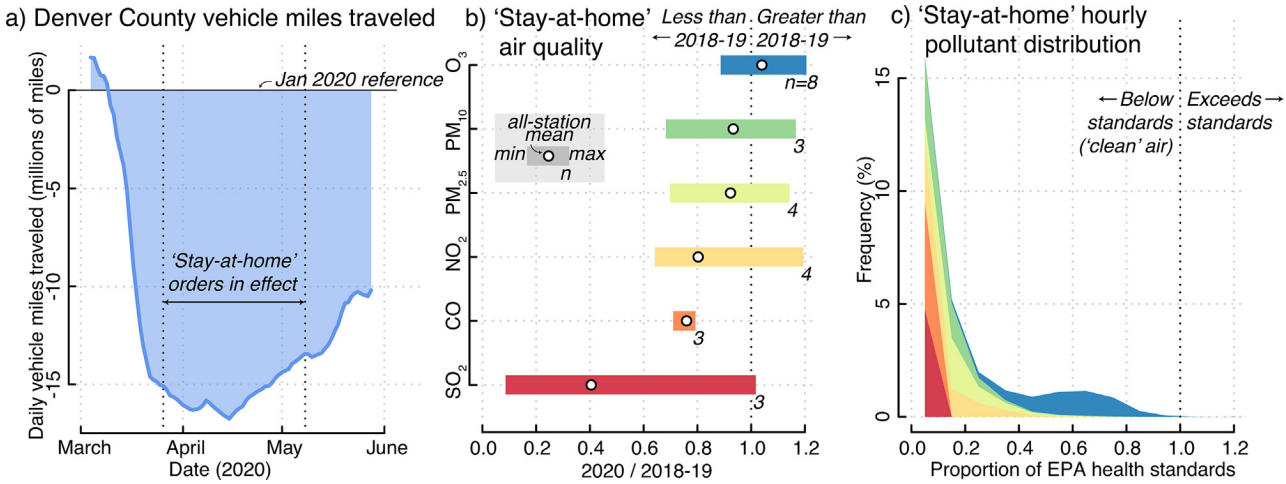

Fig. 2. Changes in mobility and air quality during Denver's "stay-at-home" period (26 March – 8 May 2020). (a) Data representing vehicular travel relative to a reference period of January 2020 (Streetlight Data, 2020). (b) Relative air quality compared to the same dates during 2018-19 for sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter ($PM_{2.5}$ and PM_{10}), and ozone (O_3); n = number of stations (CDPHE, 2020). (c) Frequency distribution of hourly measurements during the stay-at-home period, scaled relative to each pollutant's primary health standard as defined by the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standards (EPA, 2020).

Whereas Denver has historically struggled with poor air quality (e.g., Flocke et al., 2020), the widespread reduction in human activity during the "stay at home" period led to noticeable improvements. During this period, concentrations of the pollutants sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2) and airborne particulate matter (PM) were 40–93% lower than values for the same dates during 2018 and 2019 (not controlling for variable year-to-year weather conditions) (Fig. 2b). The only measured component of air quality that did not improve was ozone (O_3) concentration. Consistent with other cities (e.g. Sharma et al., 2020; Nakada and Urban, 2020), this lack of change is likely attributable to sources un-related to human activity, such as inter-annual variability in local weather conditions, reduction of nocturnal ozone chemical decomposition (Jhun et al., 2015), or natural gas extraction outside Denver. Improvements in Denver's air quality during April 2020 brought pollution below the National Ambient Air Quality Standards of the U.S. Environmental Protection Agency (Fig. 2c).

The data from Denver are representative of trends documented in cities worldwide after installation of pandemic-related social controls. Examples of dramatic improvements in air quality and visibility have come from urban areas in India (−43 % $PM_{2.5}$, Sharma et al., 2020), China (−60 % NO_2, Adams and Johnson, 2020), Brazil (−54 % NO_2, Nakada and Urban, 2020), and Europe (-62 % NO_2, Baldasano, 2020). In the USA, urban counties experienced a 26 % reduction in NO_2 on average, as well as declines in $PM_{2.5}$ (PM with diameter < 2.5 μm; Berman and Ebisu, 2020). Worldwide decreased mobility had also reduced daily CO_2 emissions by −17 % globally in early April (Le Quéré et al., 2020). In this way, Denver's improvement in air quality represents a broader anomalous landscape of clean air, generated as a byproduct of the pandemic response, conceivably akin to novel ecosystems in the Anthropocene (Morse et al., 2014).

While it was the declining health of individuals that prompted the policy measures of quarantine, the resulting improvements in air quality nevertheless may return health benefits. Although this analysis did not quantify human health, the benefits of good air quality are well documented. Both short- and long-term exposure to $PM_{2.5}$, O_3, and especially NO_2 are known to contribute to asthma (Anenberg et al., 2018). In China, a 10 % decrease in PM_{10} (PM with diameter < 10 μm) concentrations during the 2008 Beijing Olympic games correlated with an 8 % reduction in mortality (He et al., 2016). Fine PM is the leading risk factor for disease worldwide and contributes to 2.9 million premature deaths annually (Brauer et al., 2016). The rippling effects of the pandemic, therefore, had unintended consequences of creating an anomalous landscape of clean air, while providing a glimpse of a positive human-environmental trajectory.

3.3. Toward local foods

The policy response of the stay-at-home order in Denver also changed peoples' activities abruptly with respect to acquiring, cooking, and eating foods. The closure of restaurants required people to prepare and eat meals at home, leading Denver residents to purchase large quantities of groceries. This behavior, in turn, led to a shortage in grocery supplies in supermarkets, particularly meats, eggs, and vegetables. Consequently, demand for locally produced foods skyrocketed around the greater Denver area (Fig. 3a).

What drove Denver's increased demand for local foods differs from typical factors influencing demand. Changing demographics (Zepeda and Li, 2006) and cultural norms (Kumar and Smith, 2018), greater affluence (Holt-Giménez and Wang, 2011), and changing supplies and marketing (Blake et al., 2010) commonly drive demand for local food. The agricultural response during the "Special Period" in Cuba, however, gives a close analogy to the pandemic context in Denver (Díaz-Briquets and Pérez-López, 1995). When the dissolution of the Soviet Union stopped both food imports and chemical inputs required for Cuba's industrialized sugar exports, the country moved suddenly to local and more sustainable production.

Similar to the case with air quality (Section 3.2), the societal changes exhibited in the shifting local food scene altered human-environment interactions and created unintended and anomalous conditions in Denver. With a heightened need to cook at home, along with a shortage of groceries in stores, growing food in backyards has become popular, turning them into "edible landscapes" (Fig. 3b). People also bought more baby chicks to raise for egg production, so that chicks in backyards and home garages have also become a common landscape feature in Denver during the COVID-19 pandemic. Though sample sizes are small, the sharp increase in sales and demand for agricultural products within nurseries and home improvement stores illustrates the surge in local domestic farming activities (Fig. 3a).

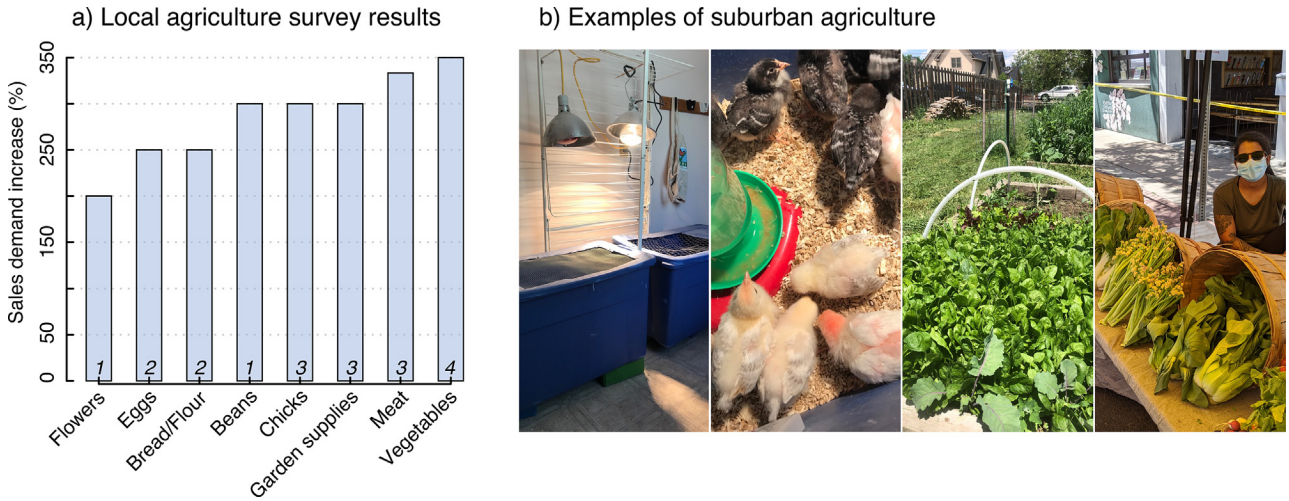

Fig. 3. Shifting demands in food and resulting landscapes during the COVID-19 pandemic in Denver. (a) Responses to semi-structured surveys (conducted by authors during week of 1 June 2020) of 10 representative Denver-based sellers of local food, garden, and farm supplies. Numbers within bars indicate responses received; % increase represents an average if n > 1. Changes in demand refer to the period 26 March – 30 April 2020. Eight of these businesses also reported that demand could not be met as products were depleted. (b) From left to right: Raising chicks in a suburban Denver garage, view of chicks inside the blue-colored bins in garage, an "edible landscape" of spinach and lettuces in one's backyard, selling home-grown produce at a Farmer's Market.

Changes in the supply and demand in food during the COVID-19 pandemic are not isolated to Denver (Hobbs, 2020). A recent study in Wales, for example, revealed a significant growth in demand for fruits and vegetables immediately following the onset of the pandemic (Pitt et al., 2020). To ensure future resilience in the urban food system around the world, experts from diverse regions have suggested greater allocation of resources for urban agriculture (Pulighe and Lupia, 2020), home gardening (Lal, 2020), and local food networks (Kolodinsky et al., 2020).

This recent engagement in eating locally, making food at home, or engaging in "personal" agriculture (e.g., gardening, raising backyard chickens) has implications for long-term human-environmental sustainability. Generally speaking, producing and eating local foods promotes a shorter and more resilient supply chain (Reisch et al., 2013) and more environmentally sustainable practices and community-based distribution methods (e.g., farmer's markets, local restaurant sales) (Fig. 3b; Halweil, 2002), and increases the likelihood of eating fresh healthy foods (Kortright and Wakefield, 2010). Local food production also avoids many risks that industrialized agriculture poses for the emergence of novel infectious disease, including "rendering" animal waste products into livestock feed (Walters, 2014) and use of antibiotics (Khachatourians, 1998). Yet, local food production also brings additional ripple effects at both broad and fine scales that are not well understood. These potential effects include increases in prices for certain food staples (de Paulo Farias and de Araújo, 2020), soil and water contamination due to home gardening (Lal, 2020), the spread of pathogens (Davis and Kendall, 2012), and inadequate access for those without available resources (Bublitz et al., 2020).

4. Going forward

Examination of the COVID-19 pandemic from a perspective of human-landscape interactions reveals the critical importance of such interactions at both the global scale, in inducing and transmitting the disease, as well as the local scale in managing its effects. The analysis has shown that the accelerating problem of pandemics closely relates to the rapid rise of anthropogenic environmental change and globalization. At the same time, the case examples from Denver highlight the fact that pandemics—in part through our policy responses—also alter the relationship between people and environment, with ripple effects still poorly understood and even unknown. The complex and changing interactions are creating emergent landscapes that may be analogous to novel ecosystems of the Anthropocene. As such, pandemics may be a currently under-recognized and emergent facet of the "Anthropocene."

Such realization suggests that the work of human-environment scholars is as consequential and urgent as ever. Addressing the roots of pandemics requires clarifying the complexities of human-landscape interactions and making their global-scale management a high priority. Controlling the effects of novel infectious diseases also requires revealing their rippling impacts and feedbacks, and understanding human-environment interactions at local scales.

Additionally, COVID-19 has illuminated the tight, rapid, and far-reaching pathways connecting the broad-scale origin and local-scale responses that affect social wellbeing. This connectedness contrasts with other global-scale human-environmental crises, such as climate change, that operate across decades or even centuries. The OneHealth perspective promoted by the World Health Organization, in fact, advocates such a view of interconnectedness of health, people, animals, and environment with respect to pandemics (Bonilla-Aldana et al., 2020). As difficult as some of the impacts are, we suggest that the COVID-19 pandemic offers a "teachable moment" to broadly communicate just how closely the drivers and impacts of environmental health relate to human health.

Finally, the lessons derived from a perspective of human-landscape interactions point toward an urgent need to develop new paradigms for research and teaching. Building upon the recognition of the importance of environment in addressing zoonotic diseases, an outstanding need remains to explicitly integrate a predictive understanding of human-landscape dynamics with the emergence and spread of diseases. We suggest that new scientific questions, theories and frameworks are needed to merge these critical strands within an Anthropocene context, as well as to address the complex rippling effects. New "anthropocenic" methods and approaches, too, will be necessary to bridge the cross-scale responses and feedbacks involved. The program required extends well beyond the already broadly interdisciplinary science essential for addressing human-landscape interactions in the Anthropocene (Harden et al., 2014), because it must integrate the work of health scientists, disease specialists, immunologists, virologists, veterinarians, behavioral scientists, and health policy experts. Though challenging, such collaborations could stimulate powerful support for policies driving more sustainable human-environmental interactions in the future, with the aim of flattening the upward trajectory of both pandemics and underlying processes that have led to an Anthropocene.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2020.100256.

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