ENVIRONMENTAL STUDIES

Lessons from a pandemic for systems-oriented sustainability research

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This review examines research on environmental impacts of coronavirus disease 2019 (COVID-19) from a systems-oriented sustainability perspective, focusing on three areas: air quality and human health, climate change, and production and consumption. The review assesses whether and how this COVID-19–focused research (i) examines components of an integrated system; (ii) accounts for interactions including complex, adaptive dynamics; and (iii) is oriented to informing action. It finds that this research to date has not comprehensively accounted for complex, coupled interactions, especially involving societal factors, potentially leading to erroneous conclusions and hampering efforts to draw broader insights across sustainability-relevant domains. Lack of systems perspective in COVID-19 research reflects a broader challenge in environmental research, which often neglects societal feedbacks. Practical steps through which researchers can better incorporate systems perspectives include using analytical frameworks to identify important components and interactions, connecting frameworks to models and methods, and advancing sustainability science theory and methodology.

INTRODUCTION

The COVID-19 (coronavirus disease 2019) pandemic has caused tremendous devastation to people across the world through illness and death. The pandemic's impacts and associated responses have affected economies, tested institutions, prompted new technological developments, changed people's behavior, and altered the environment. COVID-19 can thus be viewed in the context of broader challenges to the lives and livelihoods of people on Earth. Equitably maintaining and enhancing human well-being, today and in the future, are often defined as the challenge of sustainability (*1*). In 1987, the World Commission on Environment and Development (known as the Brundtland Commission) defined sustainable development as that which "meets the needs of the present without compromising the ability of future generations to meet their own needs" (*2*). COVID-19 is, by this definition, one of many threats to sustainability. The pandemic has immediate impacts today, in ways that involve people's health, livelihoods, and communities. Both the long-term ramifications of COVID-19 and actions to address the pandemic will affect the ability of future generations to survive and thrive on a finite planet.

Addressing sustainability challenges like COVID-19 in their full complexity requires systems thinking. The SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2) virus that causes COVID-19 does not act in isolation: Its impacts are determined by the context in which it operates. The virus itself is deadly. The disease is characterized by respiratory symptoms, pneumonia, and multiple organ failures, and in 2020, it claimed nearly 2 million lives globally. The basic reproduction number, R_o, for an infectious agent is affected by numerous factors (*3*), which may be biological, behavioral, technological, economic, and environmental. People of certain ages and those with other medical problems can be more severely harmed by COVID-19. The frequency and type of people's interactions with each other, in combination with the properties of the virus, influence the growth rate of infections. The availability of

technology—ranging from basic personal protective equipment (PPE) to advanced respirators—influences the medical care that those with the disease receive and thus their survival rates. The communicability of disease depends on the environment, for example, the characteristics of air flow in any given location. The spread of the disease and the ability to control it—including access to vaccines—are influenced by institutions that set rules, norms, and expectations for behavior, as well as the capacity of people and societies to maintain and alter them.

The pandemic and the actions taken to address it have influenced multiple environmental variables; like the virus itself, however, these environmental changes cannot be fully understood without considering them as part of a complex, adaptive system. For example, greenhouse gas (GHG) and other air pollutant emissions fell as societies closed down and increased again when national and local lockdowns were lifted. Some early analyses and commentaries suggested that COVID-19 had a positive effect on the environment, or on "environmental" aspects of sustainability (*4*, *5*). Rutz *et al.* (*6*) suggest the term "anthropause" to characterize the decrease in human mobility during the pandemic, with substantial impacts on human-wildlife interactions. It has been suggested that lockdowns offered an opportunity to calibrate baseline pre-industrial values (*7*). Lockdowns, however, do not mirror a pre-industrial state, as they occurred in a tightly coupled system in which modern human impacts and feedbacks are inseparable. No ecosystem on Earth is without human influence (*8*). For large changes, such as those occurring during COVID-19, studying environmental variables in isolation is insufficient: Interactions with and feedbacks that include people, technologies, institutions, and knowledge become critically important.

The shocks that human societies throughout the world experienced as a result of COVID-19 provide unique data for conducting empirical analysis of systems relevant to sustainability and for understanding system connections, time scales, and interactions. McNutt (*9*) proposes that the COVID-19 pandemic offers an opportunity for "irreplaceable science"; that is, research taking advantage of unusual conditions. These conditions—sudden, large changes on very short time scales—can be viewed as shocks. In some analyses of

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complex adaptive systems, shocks are considered external to the system studied and result in changes in the direction or rate of change of a state variable (*10*, *11*). Responses to shocks can be used to diagnose system structure and functioning. For example, the response of a system to a change in a key variable can be considered a measure of stability—will the system return, with some time constant, to its previous state, or will it transition to a new state? Diffenbaugh *et al.* (*12*) hypothesize that pandemic-related systemic disruptions will occur as a result of interactions associated with two pathways: involving energy, emissions, climate, and air quality; and poverty, globalization, food, and biodiversity. Research on sociotechnical transitions observes that many historical societal transitions have occurred following large shocks or forcing events (*13*). A major challenge for decision-makers addressing COVID-19 is to better understand the impacts of potential interventions and to identify those that can effectively address present challenges without compromising the ability to meet future needs. This is also the case for many other major societal challenges, and analyses of COVID-19 impacts may provide useful lessons.

This review examines published literature up to early 2021 on COVID-related environmental changes and assesses it from a systems perspective focused on sustainability. The analysis focuses on whether COVID-19–related research has captured systemic dimensions of environmental impacts and whether it has considered COVID-19 as an occasion to better understand system functions and behavior. Its major finding is that few analyses of COVID-related environmental changes have addressed their full complexity, and most have not leveraged data on system shocks to build theories and knowledge relevant to inform sustainability transitions. The next section identifies characteristics of systems-oriented research that captures relevant components and dynamics and can lead to broader insights about sustainability, highlighting key elements of methods and approaches that can help researchers better understand problems that have environmental and societal dimensions. The 'Pandemic shocks and sustainability' section examines COVID-19–related research in three domains where systemic interactions are important—air quality and human health, climate change, and production and consumption—and examines whether and how researchers have accounted for sustainability-relevant components, interactions, and interventions. The 'Sustainability impacts of COVID-19 and research needs' section discusses lessons from the three domains, highlighting the need for further developments and improvements in methods and approaches. The review concludes in the 'Steps forward and barriers' section by identifying practical steps by which researchers can better take into account the full complexity of sustainability-relevant systems, in ways that can inform decision-making.

SYSTEMS-ORIENTED SUSTAINABILITY RESEARCH: METHODS AND APPROACHES

The overwhelming impact of humans on Earth has been recognized by analysts who suggest that Earth has entered a new geological epoch, termed the Anthropocene (*14*). Researchers who aim to understand processes and dynamics occurring in the environment increasingly stress the need to examine Earth as a system with integrated biophysical processes and human dynamics (*15*). The connectivity between human activities and environmental phenomena means that there are few variables that can be considered

exogenous in analyses (*16*). Like other research addressing a human-dominated Earth system, research on COVID-19 and its implications on environmental phenomena benefits from a systems-oriented perspective, for two main reasons. First, analyses that do not account for systems behavior risk mischaracterizing the pandemic's impacts, implications, and related causal mechanisms. Second, pandemic-related impacts offer a chance to examine systemic responses to this large-scale shock, informing efforts to build knowledge and theory about interactions of importance to broader sustainability challenges.

Conducting analyses of systems where virtually everything is connected poses a challenge to researchers, however, who must decide what to include, and what to exclude, in their system description and analysis. Previous work in systems analysis and sustainability science, however, has identified some of the characteristics and dynamics that are critical to identify and include in research. Below, I review this previous work and build upon it to identify three characteristics of systems-oriented sustainability research. These characteristics are presented in Box 1 and further described below. First, systems-oriented research identifies and examines societal and environmental components in an integrated way. Second, it considers interactions among these components, considering the complex, adaptive nature of the integrated system and its dynamics. Third, it is use-inspired, providing information that can inform interventions to advance human well-being in the present and future.

Components: Examining an integrated system
Sustainability-relevant systems have components that are societal as well as environmental, and they are integrated. Researchers based in different disciplines apply different and overlapping names for systems and their components, and these names highlight the perspectives taken by different research communities. They include coupled human-natural systems, sociotechnical systems, engineering systems, social-ecological systems, production-consumption systems, and human-technical-environmental (HTE) systems, among others (*17*–*20*). Coupled human-natural systems perspectives envision two subsystems, human and natural, which interact with each other, and which can be analyzed together by bridging ecological science and social science perspectives (*18*). The engineering systems literature focuses on design and performance of sociotechnical systems that are related to human challenges of present and future generations (*20*). Economic-based perspectives often focus on production-consumption systems. As parts of production-consumption systems, supply chains have been evaluated as complex engineered systems, including both physical and societal elements (*21*). The HTE systems perspective attempts to bridge many of these disparate communities without prioritizing a specific discipline or approach, and its initial application focused on technologically mediated material interactions (*17*). Here, the term "sustainability-relevant systems" is

Components: Examining an integrated system	Interactions: Accounting for complex, adaptive dynamics	Interventions: Oriented towards informing action
☐ Humans	☐ Couplings and connections	☐ Actors (interveners)
☐ Technologies	☐ Dynamic behaviors	☐ Agency
☐ Environment	☐ Feedbacks, nonlinearities, thresholds	☐ Goals
☐ Institutions	☐ Adaptation	☐ Power
☐ Knowledge	☐ Innovation	☐ Leverage points

Box 1. Characteristics of sustainability-relevant systems research.

used to encompass a broad range of perspectives. This more general term is chosen to avoid confusion with any one of the disciplines or literatures mentioned above.

Consistent with these various perspectives, research on phenomena characteristic of the Anthropocene such as COVID-19 and the environment is likely missing key elements if it does not include human, technological, institutional, and knowledge components as part of an integrated system together with environmental variables. The definition of the problem of COVID-19 and the environment involves drivers that are societal (e.g., changes in human behavior and institutional decisions associated with the pandemic) as well as those in nature (e.g., atmospheric and climatic processes). These changes have also taken place in what are acknowledged in the Anthropocene to be integrated systems with societal and environmental components.

Interactions: Accounting for complex, adaptive dynamics

Many (perhaps most) sustainability-relevant systems are complex and adaptive (22). These systems are characterized by couplings and connections across domains, and dynamic behavior, and systems-oriented research should address both of these aspects (Box 1). Dynamics can include feedbacks, nonlinearities, and thresholds, as well as adaptation and innovation processes. Because almost nothing is exogenous, unintended and unobserved reactions might appear as a result of linkages that researchers have not accounted for. A classic example of the perils of ignoring these links comes from the case of corn-based biofuels as an alternative to fossil fuel, where substantial impacts occurred in agricultural prices as a result of changing demand (23). Relevant dynamics result from characteristics of individual components acting individually and in combination. Systems also can have emergent properties—behavior determined not solely by individual components but that emerge in part as a result of interactions between these elements. Adaptation refers to actions that are taken in response to risks to maintain pathways of development. A large number of studies on social-ecological systems, many of which deal with ecosystem services and resource issues, have highlighted "resilience" perspectives—which address the capacity of a system to absorb a disturbance and reorganize when undergoing change while retaining essential attributes like functions and structure (24). Associated with coupled human-natural systems research, the perspective of telecoupling examines flows of information, energy, materials, and other products around the globe in these systems (25). Innovation is a key way in which societies make progress toward sustainability, and the dynamics of innovation systems involve multiple feedbacks and nonlinearities (26).

COVID-19–related research that accounts for complex, adaptive behavior needs to capture couplings and connections as well as dynamic behavior. The larger the magnitude of changes or shocks in a system, the more likely it is that these changes trigger feedbacks and responses beyond the immediate variables examined. While some system dynamics can be assumed to be negligible when addressing marginal changes, COVID-19 prompted major discontinuities. Related to environmental impacts, a pandemic-related shock to transportation might not only affect emissions but also affect the agricultural sector, in turn altering atmospheric composition. Societal attempts to adapt to pandemic-related risks, such as changes in purchasing behavior, could counteract or overwhelm other pressures—for example, shortages in production-consumption systems can be caused both by supply chain disruptions and demand responses. Particularly important to capture are interactions that cross spatial scales, and slow and fast temporal dynamics, with time scales of infection and quarantine interacting with time scales of production-consumption and processes in the environment. Ideally, studies will also acknowledge the potential for innovation to affect dynamics, which for COVID-19 may include new modes of operation as well as treatments and vaccines. For example, COVID-19 has prompted innovators to design new ways to provide resources to populations with reduced probabilities of transmitting disease.

Interventions: Oriented toward informing action

Much research on sustainability aims to informing and facilitating a transition that enhances human well-being—this is a central aspect of work in the area of sustainability science. Science focused on sustainability has been described as "use-inspired basic research" (27), simultaneously motivated by a search for fundamental understanding and considerations for eventual use (28). Several indicators can illustrate whether research is use-oriented or potentially actionable in the context of sustainability. It should ideally identify interveners, assess their agency to take actions to modify the system (including their goals and power) toward greater sustainability, and characterize leverage points they have the potential to influence (Box 1). In that regard, attention to dynamics of power and the politics of knowledge is critical (23). Effectively learning to manage interacting systems requires addressing individual and organizational barriers that prevent understanding system dynamics and responding to feedbacks (29).

Several research traditions within sustainability science focus on change processes and on designing interventions. Sustainability transitions research examines the pathways by which change occurs through sociotechnical, socio-institutional, and socioecological perspectives, with particular strengths in social science and applications (30). Research on transitions and transformations (the latter of which some analysts distinguish as more radical departures from the status quo) acknowledges that deliberate change is necessary for society to move toward a more sustainable trajectory. Governance scholars have focused on institutions, networks, and rules that can manage sustainability-relevant systems (31). Governance systems can themselves be complex, and prior work has emphasized the importance of institutions that operate across different scales (32).

Like research on broader sustainability issues, research on COVID-19 focuses on understanding the impacts of the disease on people and society to inform efforts to mitigate risk and damage. Research that addresses COVID-19 and its environmental dimensions could inform action to promote human well-being in a variety of ways and on different time scales. Information provided could assist in mitigating the direct effects of COVID-19 or associated environmental or societal burdens. Such research can also help better understand the basic functioning of systems that promote human well-being, providing information on leverage points. Research that uses the pandemic-related shock to examine causal mechanisms, for example, can identify leverage points by capturing both proximate causes and underlying structural factors that affect well-being and could potentially be altered by interventions.

PANDEMIC SHOCKS AND SUSTAINABILITY

A growing body of research aims to diagnose and explain pandemic-related impacts on the environment and on related processes and

dynamics that influence people's well-being. The pandemic itself and associated economic disruption have had major impacts on societies, and data and analysis have documented and attempted to explain these changes. Three concrete examples are described below of topics important to sustainability that illustrate the challenges and opportunities of research on COVID-19, and which have been the topic of much pandemic-related inquiry: air quality and health, climate change, and production and consumption. For each of these areas, this review examines whether the three characteristics of systems-oriented sustainability research described above are captured in COVID-19–related literature: (i) examines components of an integrated system; (ii) accounts for interactions including complex, adaptive dynamics; and (iii) is oriented to informing actions toward advancing sustainability. These aspects are evaluated for each area below, and results are summarized in Table 1.

Air quality and human health

Outdoor air pollution, largely as atmospheric particulate matter with a diameter smaller than 2.5 μm ($PM_{2.5}$) and tropospheric ozone (O_3), leads to millions of deaths worldwide annually (33), through raising risks for cardiovascular and respiratory diseases. Changes in emissions as a result of the pandemic have influenced air quality worldwide. Hundreds of peer-reviewed publications attempting to link air quality changes and COVID-19 were published in 2020 (34). It has been widely reported that pandemic-related shutdowns resulted in improvements in air quality due to reductions in anthropogenic emissions. However, diagnosing the impact of COVID-19 on air quality and related health damages is not straightforward. Research on the air pollution response to the COVID-19 pandemic would fulfill the three characteristics of systems-oriented sustainability research described above to the extent that it (i) captures the physical and societal components that influence both pollution concentrations and impacts, (ii) accounts for dynamic nonlinearities and feedbacks that occur both in the chemistry of the atmosphere and in individual and institutional responses, and (iii) addresses causality of air pollution changes and their multiple potential physical and societal drivers in ways that can inform effective action.

System components related to the COVID-19 and air pollution system involve not only the environmental properties of the atmosphere but also knowledge and technologies that create emissions, and human and institutional factors that affect exposure and impacts. Air pollution responds most directly to local emission-producing activity, which was affected during COVID-19 by reduced mobility and social distancing and government-imposed shutdowns. These changes are larger than those typically examined in air pollution studies. Le et al. (35) note that, in China during lockdowns, changes in nitrogen oxides (NO_x), an emitted pollutant that is a precursor to $PM_{2.5}$ and O_3, far exceeded those that occurred during previous "natural experiments" associated with policies during the 2008 Beijing Olympics and the 2014 Asia-Pacific Economic Cooperation summit. Emission changes also reflect changes in local and global demand for industrial goods (36), for which the response of pandemic-related economic changes remains uncertain. Long-range and even global transport of air pollutants can also affect local pollution (37). Air pollution is furthermore shaped by institutions, which interact across different locations and levels of governance, for example, in coordinating regulatory approaches (38). The negative human health impacts of air pollution are affected not only by exposure but also by socioeconomic factors that affect health outcomes. People who live in areas where air quality is poor are more likely to suffer from respiratory ailments, including infections. Disparities in pollution exposure are further enhanced when accounting for the goods and services that people consume (39).

Individual studies on COVID-19 and air pollution research have largely focused on characterizing environmental changes. Many papers from atmospheric science have quantified short-term changes in NO_x concentrations; only few account explicitly for institutional and regulatory factors that drive underlying trends, which are largely long-term reductions (34). The most thorough studies in this area, however, have conducted extensive analysis of pandemic-related changes in the context of underlying variability, including both long-term regulatory trends and meteorology [e.g., (40–42)]. Some research building from techniques in economics has examined societal and institutional factors in detail. For example, Liu et al. (43) use a difference-in-difference approach to assess the impact of lockdowns on air quality in China, including variables that address changes in mobility and social connections, but with air quality simplified to an aggregate index. Studies have also attempted to calculate changes in mortality from COVID-related declines in air pollution using typical methods from air pollution impact literature, largely without accounting for additional COVID-19–related factors. For example, Chen et al. (44) attempted to calculate reduced mortality from NO_2 and $PM_{2.5}$ from early pandemic-induced lockdowns in China using standard concentration-response relationships from the literature and estimated larger avoided deaths than confirmed COVID-19 mortality at that time.

With respect to examining an integrated system, the large majority of COVID-19–related air pollution studies have examined

Table 1. Evaluation of COVID-focused environmental research from a systems perspective.

	Components	Interactions	Interventions
Air pollution	Focus on environmental components; limited treatment of societal factors	Nonlinearities unaccounted for in many studies; societal feedbacks rarely endogenized	Structural and institutional factors overlooked in causal attribution
Climate change	Technologies and environment well captured; less specificity on policies and institutions	Short-term interactions characterized, especially for energy; longer-term trajectories unknown	Largely aspirational rather than evidence-based
Production-consumption	Addresses comprehensive range of components, but largely for single products or areas	Complex feedbacks and dynamics included, but most studies address short-term effects	Focused on continuity of existing systems rather than sustainability

only a limited set of components, mostly environmental. Even in the most comprehensive analyses of observed pollutant changes, COVID-19–related societal actions are generally treated in less detail than more traditional environmental indicators, often simplified to be defined by a period of time or a stay-at-home order date. In contrast, in economic analysis, air quality has been simplified. With respect to studies of health impacts, while calculating avoided air pollution–related deaths can provide a useful proxy for the relative impact of shutdowns in different regions across the globe, the conditions under which concentration-response relationships were derived are not representative of pandemic-influenced systems in which people have changed their behavior and their access to health care is different. Associations between elevated mortality, COVID-19 prevalence, and socioeconomic characteristics may emerge in part not only from underlying physical or biological factors but also from structural and institutional patterns that predate the pandemic.

Interactions in the complex system involving COVID-19 and air pollution are characterized by nonlinear dynamics and feedbacks, both in the atmosphere itself and involving societal and institutional factors. The formation of atmospheric pollutants is nonlinear, and the underlying drivers of pollution and its health and societal impacts interact locally to globally in both the short and long term. Even where emission reductions during the COVID-19 pandemic are clearly identifiable, they can have differential impacts on resulting concentrations of $PM_{2.5}$ and O_3, which are produced in chemical reactions that exhibit nonlinear behavior. For O_3, under certain atmospheric conditions, decreases in emissions of NO_x (O_3 precursors) do not lead to decreases in O_3 but instead cause O_3 to increase because of nonlinearities in chemical reactions (45). Health responses are also nonlinear; this may have the counterintuitive effect that reductions of pollution are more beneficial to health in places that are already cleaner (46). Changes in air pollution can have differential effects on populations not only due to exposure but also due to economic interactions (47, 48). Elevated air pollution and its associated health impacts can influence the economy; people's reduced ability to work and health care costs to treat them can lower economic productivity, and this can, in turn, affect emissions (48, 49).

Papers on COVID-19 and air pollution have addressed a limited set of these relevant interactions. Some studies have addressed nonlinearities in atmospheric chemical behavior. Sicard et al. (50) report higher ozone concentrations in four European cities as well as in Wuhan, China during COVID-19 lockdowns; they calculate a 2 to 27% increase in O_3 relative to the same period in 2017–2019 in Europe and 36% in Wuhan, despite >50% reductions in NO_x concentrations. Le et al. (35) showed that declines in NO_x coincident with COVID-19 lockdowns led to O_3 enhancement in China due to the nonlinear chemical behavior described above. With respect to COVID-19 and air pollution–related mortalities, a growing number of papers use epidemiological approaches to attempt to connect increases in COVID-19 morbidity and mortality with ambient air pollution concentrations (51–53), controlling for a variety of factors.

Related to complex, adaptive dynamics, many COVID-19–related studies have not accounted for either the dynamics of atmospheric processes or those of individual and institutional responses. A review of studies of air pollution impacts as a result of COVID-19 stay-at-home policies noted that many failed even to account for well-known nonlinear chemical behavior within the physical system

(34). Furthermore, while there are well-known links between air pollution and respiratory diseases, much of the research that has been published on COVID-19 mortalities and air pollution has also had substantive flaws, including in both specifications of air quality and epidemiological relationships (54). A deeper critique of even the most well-conducted studies focuses on the difficulty of accounting for the dynamics of social factors involving policies and institutional measures that can affect both viral spread and air pollution (55).

Relevant to interventions, the goal of much air pollution–related research is to inform efforts to mitigate its damages, and thus, a key challenge is determining causality. Identifying what types of variables are considered potential causal factors, and what are not, has methodological and practical applications. Many analyses aim to identify where, when, and from which sources the specific emissions of precursors such as NO_x occurred that ultimately led to the production of O_3 and $PM_{2.5}$ (56). Such analysis has been extended to attribute air pollution–related mortalities to the location and source of atmospheric emissions (57). In contrast, attributing mortality to end-use activities, such as consumption of the goods produced, implies that final purchasers are ultimately responsible, providing a distinctly different picture of root causes of pollution inequality with different policy implications (39). There are further challenges in attributing emission declines from sources to policies and regulations. With respect to air pollution health outcomes, standard epidemiological methods seek explanations related to changes in particulate matter concentrations. In contrast, some environmental justice activists frame air pollution as primarily social, emphasizing, for example, racial discrimination in funding of cleaner transportation alternatives as an underlying cause of elevated asthma rates in minority communities (58).

COVID-19–related air pollution addresses a range of potentially causative factors, some of which are directly relevant to decision-making. Liu et al. (59) report that declines in NO_2 after the announcement of the first COVID-19 cases in Chinese provinces were about as large as the declines that occurred after provincial lockdowns. Zhao et al. (60) show that meteorology contributed substantially to changes in air pollutants after the initiation of COVID-19 responses. Some COVID-19–related research has addressed selected causal factors in detail, using data from COVID-19 impacts to assess decision-relevant parameters. Tanzer-Gruener et al. (42) use a network of low-cost sensors deployed in Pittsburgh, Pennsylvania, USA to explore the impact of "modifiable factors" on ambient air pollution, focusing specifically on linking activity level changes due to shutdowns with measured pollutant concentrations. They suggest that a 50% reduction in vehicle emissions could essentially eliminate the morning rush-hour peak in $PM_{2.5}$, CO, and NO_2.

In assessing whether COVID-19 and air pollution research is oriented toward informing action, casual attribution of air quality changes during the pandemic reflects a larger challenge in air pollution literature regarding assigning causality to complex, interacting phenomena. Emission changes that co-occurred with lockdowns may be a direct result of government action or societally mediated responses in the absence of top-down policies (or both). Comparisons of atmospheric concentrations between lockdown and reference periods ideally should take into account differences in seasonality, meteorological variability and change, and baseline pre–COVID-19 trends. Research that directly addresses decision-relevant parameters is most consistent with the perspective of informing action.

In summary (see Table 1), while many studies have examined air pollution in the context of COVID-19, most have been limited in scope. A focus on environmental components, and limited treatment of societal factors, has led to numerous papers mischaracterizing air pollution phenomena that vary with time and space and failing to link underlying causal variables to observable outcomes in ways that could inform policies and decision-making. Nonlinearities are unaccounted for in many studies, and societal feedbacks are rarely endogenized in air pollution analysis methods or models, a limitation that carries through to COVID-19 research. Much existing research, on COVID-19 and atmospheric composition more generally, privileges certain explanations of air pollution and its impacts (e.g., straightforward attributions to industrial activity). In contrast, structural and institutional factors are often overlooked in causal attribution.

Climate change

The COVID-19 pandemic is occurring on a planet that is already seeing the impacts of the climate crisis. The causes and impacts of climate change are fundamentally linked to nearly every aspect of human activities, and thus, it is no surprise that COVID-19 affects activities that contribute to human-induced climate change, such as energy and transportation. Climatic factors such as temperature, humidity, and ultraviolet (UV) radiation can, in turn, influence how diseases spread and also affect human behavior and activity patterns. Research on climate-related aspects of the COVID-19 pandemic would fulfill the three characteristics of systems-oriented sustainability research described above to the extent that it (i) addresses components that illustrate both the proximate and underlying structural factors related to emission changes and climate-related pandemic effects; (ii) evaluates short- and long-term interactions in the climate system, including societal implications and potential feedbacks and responses; and (iii) acknowledges the potential for different types of interveners and interventions to address climate problems.

Assessing the influence of COVID-19 on climate, and vice versa, from a systems perspective, involves considering environmental factors such as changes in GHG emissions and concentrations in the context of policies, institutions, and technologies. Pandemic-related lockdowns have resulted in decreases in certain activities associated with CO_2 emissions, including heavy industry and transportation. However, the connections between COVID-19 and climate change are broader—both can affect nearly every aspect of society and human well-being in both the short and longer term. Climate-related disasters such as wildfires and floods have already occurred during the COVID-19 pandemic; these influence vulnerability to disease and humanitarian responses that involve governmental and nongovernmental organizations (61). Seasonal variations exist in the prevalence of a broad range of viruses for temperate regions, which may be a result of meteorology, behavior, or changed susceptibility (62). Factors such as temperature affect disease transmission in the context of institutions and knowledge that also vary over time and space.

Research on climate and COVID-19 has integrated data on environmental, economic, and technological factors. Le Quéré et al. (63) found that average daily CO_2 emissions in early April 2020 were 17% below 2019 levels, comparable to emissions in 2006. They devise an aggregate index that captures policy and combine it with data on activities in six different economic sectors. Liu et al. (64) use data on power production, vehicle and aircraft traffic, industrial production, and energy consumption to conclude that CO_2 emissions were 8.8% lower in the first half of 2020 compared to the same period in 2019. Integrating data from electricity markets, health outcomes, and mobility, Ruan et al. (65) show that reductions in electricity consumption in the United States are strongly correlated with COVID-19 cases, social distancing, and levels of commercial activity. With respect to the influence of climate on COVID-19, a comprehensive analysis by Carleton et al. (66) that controlled for many confounding variables and nonenvironmental factors found that the influence of social distancing policies on COVID-19 transmission rates was 3 to 6 times larger than the influence of UV radiation outside the tropics and 35 to 85 times larger in the tropics.

While research on climate and COVID is notable in accounting for a variety of data sources, the influence of and variation in specific policy actions, for example, to impose lockdowns, are not addressed in great detail. Research on GHG emissions and COVID addresses environmental, human, and technological components thoroughly but has less specific focus on (often less quantifiable) institutions and policies. Like COVID-19 and air quality research that addresses health impacts, much published research that links weather and climatic factors with changes in COVID-19 transmission also does not fully account for relevant confounding variables, especially in the case of nonenvironmental factors (67).

Research that captures COVID-19 and climate change as a complex, adaptive system needs to account for short-term and long-term dynamics. The pandemic's effects have manifested in the last year, with dynamics varying week to week as infection rates changed and policy responses adjusted; meteorological variability occurs on daily and seasonal time scales, and climatic variations extend much longer. The influence of COVID-19 on climate forcings, at least on the GHG emissions side, occurred over the course of weeks, but emissions increased again as lockdowns eased. The amount that GHG emissions decreased in 2020, however, is not large enough to have a longer-term impact on the global climate. Le Quéré et al. (63) estimated that the annualized decrease in CO_2 due to the short-term reductions during the pandemic would be in the range of a 4.2 to 7.5% decrease, comparable to the annual decreases required to limit global average warming to 1.5°C. The pandemic has also changed institutional and political responses, including those associated with climate change, leading to adaptations and feedbacks that will, in turn, affect emissions and climate.

Research on climate and COVID-19 has addressed complex, adaptive dynamics in some relevant domains, particularly energy. For example, Chen et al. (68) examined energy use together with data on social-psychological factors during COVID-19 in New York, showing that differences in risk perception relate to willingness to pay for home energy management features. Gillingham et al. (69) calculate that a 1-year delay in renewable electricity investments would outweigh the emission reductions from spring 2020 and stress that the policy response will determine the future path of emissions. Hepburn et al. (70) conduct a survey of economic experts to assess the consequences of COVID-19 for climate policies and use their results to identify response policies with potential for both economic and climate benefits. Steffen et al. (71) note that large economic shocks, similar to those that are occurring as a result of COVID-19, will occur numerous times during a transition to clean energy and that efforts to make policies "shock-proof" should be incorporated into their design. Kuzemko et al. (72) evaluate the potential for

energy system transitions as a result of the pandemic, focusing on political factors and continuities and discontinuities with prepandemic trends.

While several climate-related COVID-19 studies have accounted for some complex, adaptive dynamics by integrating interactions of social and environmental factors, particularly on the dynamics of energy, these studies remain limited in number and scope, and more are needed especially in other domains. Many focus on quantifying shorter-term effects. Few data exist quantifying societal responses, and most analyses are prospective. This may be a result of these feedbacks occurring on longer time scales than have elapsed since the beginning of the pandemic. There is, therefore, much potential for longer-term data collection and analyses as the pandemic and its impacts continue.

Related to interventions, COVID-19 and climate change share the characteristic that both are worldwide societal challenges, and thus, related research has the potential to inform action. There is much debate in climate literature about the impact of individual relative to institutional actions. Previous studies have highlighted the personal actions that individuals can take to reduce their carbon footprint (73). While both individual and structural actions are required for progress, the pandemic has drawn increased public attention to and provided an empirical test of the potential for and the limits of individual behavioral change in the absence of overarching reforms. Pandemic-influenced lifestyle changes coupled with economic disruptions have not resulted in sustained emission declines of the magnitude of those required to achieve a trajectory consistent with a 1.5° or 2° temperature goal. However, the pandemic has provided a concrete, widely appreciated example of the degree and rapidity by which social norms and collective behavior can change (and will prove a test of which changes can be maintained and which changes are temporary). Interactions between climate change and COVID-19 also illustrate the ways in which agency and power play out in issues of sustainability and societal efforts to make collective decisions across space and time, especially for global challenges such as climate change.

From a policy perspective, some have suggested that institutional responses to pandemic risk have parallels to or could pose lessons for policy-makers addressing the climate challenge (74). Others have argued that responses to the pandemic provide an opportunity for action that simultaneously addresses COVID-19 recovery and climate change (13). A number of different organizations such as the United Nations and World Bank, and some governments and commentators, have referred to the COVID-19 pandemic as a "window of opportunity" for climate action (75–78). Some have used the occasion of COVID-19 to put forward policy proposals such as using large-scale investments to fuel the low-carbon transition (79).

With respect to its action orientation, published work on climate and COVID-19 has primarily been aspirational, rather than practically oriented: Most has not grappled with detailed mechanisms of change. Policies could simultaneously address post–COVID-19 response and climate change. However, many suggestions in the literature advance relatively straightforward arguments with well-known potential for benefits even without the pandemic. Much research has previously characterized the societal and institutional challenges for implementing climate action locally, nationally, and internationally; many of these involve variables and interactions that have not changed as a result of the pandemic. Last, there are both parallels and differences between policy responses to COVID-19 and

climate change, with policy-makers often reluctant to take decisive action early enough to forestall future consequences.

In summary (see Table 1), research on climate and COVID-19 has characterized emissions-related impacts using a variety of data sources, begun to characterize dynamics that link environmental and societal responses, and identified opportunities for implementing changes toward meeting climate goals. Technologies and the environment are components that are well captured in existing research, but there has been less specificity in treatment of policies and institutions. Short-term interactions have been documented, especially for energy, but longer-term trajectories that will determine the trajectory of GHG emissions and ultimately the climate post–COVID-19 remain unknown. Understanding the system in its full complexity will also allow analysts to more realistically assess challenges for implementation of climate policies while the world is recovering from the pandemic; to date, analysis of interventions has been largely aspirational rather than evidence-based.

Production and consumption

Production-consumption systems that facilitate access to resources supporting human well-being (including food, energy, and materials) are the focus of much sustainability-related research. Many of these systems, especially those that involve manufacturing and international transport of goods and people, have been disrupted as a result of COVID-19. Consumption of goods and services is a major driver of environmental damages that can undermine planetary life-support systems (80). In particular, research has drawn attention to the overconsumption by the world's most affluent (81). At the same time, consumption remains a key contributor to well-being, especially for the world's poorest who achieve the greatest well-being benefit from marginal consumption increases (82). Governments, firms, and nongovernmental organizations have implemented a range of different approaches to transition production-consumption systems toward sustainability, with varying degrees of success (83). Research on production-consumption impacts associated with the COVID-19 pandemic would fulfill the characteristics of systems-oriented sustainability research described above to the extent that it (i) addresses how linked physical and societal factors operate together to alter demand and supply; (ii) accounts for feedback effects, including vulnerability and resilience, across supply routes and markets on local to global scales; and (iii) assesses the potential for transformation with attention to value in the context of human well-being.

Pandemic-introduced disruptions have highlighted components of production-consumption systems that are both physical and societal. Numerous COVID-19–related supply chain disruptions have made visible to the average consumer how everyday consumption relies on resources from far away. Things that people consume in one place are often grown, captured, mined, or manufactured in other places that are geographically, politically, and culturally distinct (84). For example, the United States imports 15% of its food supply (85), and reliance on imports is larger for certain food categories. Frameworks that address supply chain systems have drawn attention to interactions between system architecture, system behavior, and system policy and control (21). Research focused on the integration of sustainable consumption and production systems often takes a high-level approach focused on policy initiatives, implementation, and strategies; a recent review found fewer integrated perspectives in papers applying modeling techniques (86).

Organizations and markets that facilitate the provision of resources operate in contexts that range from very local to global.

COVID-19 research on production-consumption systems have addressed multiple types of components. Shortages of PPE in the United States have been attributed to increased local demand, but also reductions in supply abroad, such as stoppages in the production of masks in China during their earlier outbreak of COVID-19 (*87*); similar shortages have occurred in other regions of the world. Disruptions to food systems have been prompted by both supply- and demand-side changes, with labor shortages and disruptions to transportation and trade networks combining with consumer behavior shifting to prepare more meals at home (*88*). Producers of French cheese saw sales drop 60% as a result of the pandemic, prompting an industry campaign to encourage consumption (*89*). Some studies address an even larger range of components beyond those specifically associated with supply and demand: Laborde *et al.* (*90*) assessed risks to food security from COVID-19, examining availability, access, and utilization from individual, societal, and institutional perspectives.

While published articles on production-consumption systems relevant to COVID-19 address physical as well as societal and institutional factors, many studies cover only one domain or sector. Within sectors, especially for food systems, a few COVID-19 studies have taken a broader perspective that addresses the range of components that address human well-being. Characterizing pandemic-imposed disruptions requires assessing a range of factors, both physical and societal, affecting supply and demand; these factors are commonly addressed in related literature. However, because of the large degree of disruption imposed by the COVID-19 pandemic, and links involving products, transportation, and labor, single sector–focused studies may be omitting some components necessary to fully understand impacts.

With respect to interactions, disruptions to production-consumption systems illustrate emergent system properties of vulnerability and resilience, for example, of international supply chains. Research has shown that highly interconnected networks, such as in the financial sector, can be resilient to small shocks but particularly vulnerable to large or repeated shocks (*91*). There is much potential for analysis that accounts for systems behavior to improve the resilience of systems to meet human needs, as illustrated by research on humanitarian response (*92*). During the COVID-19 pandemic, both producers and consumers struggled to adapt quickly to the impacts of large-scale disruptions, but in behavior typical of systems with strong feedbacks, adaptations that did occur—such as stockpiling toilet paper—often magnified other problems.

Papers on COVID-19 have noted the presence and implications of complex dynamics. Zhu *et al.* (*93*) review the impact of COVID-19 on businesses, identifying examples of supply and demand shocks as well as feedbacks. Guan *et al.* (*94*) model the effects of COVID-19 control measures on global supply chains, finding that the complexity of global supply chains will serve to magnify economic losses. Similarly, Ivanov (*95*) simulates COVID-19 impacts using a supply chain model, identifying the timing and scale of disruption to production as important factors that differentiate epidemics from other types of disruptions. Gordon (*96*) argues that the pandemic draws attention to the need to rebuild the resilience of a homogeneous and highly connected global food system characterized by weakened internal feedbacks. Golan *et al.* (*97*) use the occasion of COVID-19 disruptions to review the supply chain resilience literature, and note

that specific disruption scenarios are used to develop and test models.

Feedbacks, nonlinearities, and complex systemic dynamics are generally well characterized in literature on production and consumption related to COVID-19. One identified gap involves simulating and responding to interactions associated with network effects coming from disruptions not limited to a particular region or confined to one time period (*98*). In addition, many of the studies that address feedbacks focus on shorter-term behavior, rather than the longer-term dynamics more relevant to sustainability.

Production-consumption research links to action on sustainability through drawing attention to the contributions of different commodities and services to human well-being over time. The disruption posed by COVID-19 draws attention to the difficulty of attributing appropriate value to these products and services and to the limitations of market-based mechanisms for determining this value. Economic impacts of the pandemic have led to declines in human well-being, but the experiences of people during pandemic-related lockdowns have underscored the fact that economic flows are an imperfect measure of human well-being. Where populations have experienced large numbers of cases and associated lockdowns, it is increasingly appreciated that physical and mental health, and social ties and connections, are both critical to well-being and difficult to fully substitute for with monetary resources. Research focused on circular economy perspectives has advanced thinking about the ways in which materials are tracked in production-consumption systems with reference to sustainability (*99*); however, focusing on material efficiency does not fully grapple with the ways in which societies can promote production that provides greater value to human well-being. A commonly used definition of sustainable consumption and production, resulting from the 1994 Oslo Symposium, cites "the use of services and related products, which respond to basic needs and bring a better quality of life" (*100*). The concept of essential services during pandemics draws attention to the changing and constructed nature of these "basic needs," as well as the structures and functions that provide for them.

With respect to informing action on challenges to production and consumption, some sustainability researchers have argued that the COVID-19 pandemic could provide an opportunity to reduce harmful consumption in the longer-term through lifestyle changes (*101*) or to catalyze longer-term transitions that could include degrowth (*102*). Issues of equity have also been the focus of some studies related to essential services. Gans (*103*) suggests that wartime approaches, such as price controls or direct allocations, can improve resource allocation in crisis situations, for example, ensuring that the poorest members of a community during a pandemic receive resources such as hand sanitizer.

In research on COVID-19 impacts, however, similar to much work on production and consumption in general, action-oriented research is focused on maintaining functioning of existing systems. Standard economic value measures remain preeminent. Little evidence exists so far to support assertions that COVID-19 will lead to reductions in consumption or associated harms. One example of this is the case of plastics: The demand for single-use plastic products, for example, for PPE, has increased during the pandemic, with resulting potential impacts on disposal (*104*). These items suddenly became particularly valuable because of their direct impact on ensuring human well-being; however, they still are associated with liabilities due to their dependence on GHGs for production and their

single-use nature. The shortages and oversupplies that occurred during pandemic-induced disruptions also draw attention to the difficulty in coordinating a dispersed system governed by a heterogeneous set of norms and a very large number of independent actors.

In summary (see Table 1), research addressing production-consumption systems draws from a broad range of domains and theoretical approaches; this is reflected in the various treatments of this topic and how it is affected by COVID-19. This work addresses a comprehensive range of components but has largely focused on single products or areas. Much of this work takes a systemic view and includes complex feedbacks and dynamics; however, most studies address short-term effects. Evaluations that are targeted toward informing interventions are largely focused on maintaining the continuity of existing systems from the perspective of business and profit, rather than sustainability.

SUSTAINABILITY IMPACTS OF COVID-19 AND RESEARCH NEEDS

COVID-19 illustrates the empirical phenomenon of linked systems of relevance to sustainability and provides an example of how examining complex, adaptive systems and their components, interactions, and interventions could provide deeper understanding of how different variables affect outcomes of interest to sustainability. As discussed in the three example areas above, and summarized in Table 1, many studies and commentaries that focus on evaluating environment and sustainability-related impacts of COVID-19 do not fully capture the pandemic's impacts from a systems perspective. This leads to incomplete identification of causal factors, shortcomings in accounting for relevant feedbacks and dynamics (often, but not exclusively, involving interactions with institutions and knowledge factors), and inattention to underlying dynamics of power that reinforce inequities. The resulting analyses risk coming to erroneous conclusions. One implication of this lack of a systems perspective is that, in both popular discourse and academic journals, the effect of COVID-19 and associated pandemic-related policies on "the environment" has too often been presented as separate from its impacts on people and institutions and from its systemic feedbacks or longer-term impacts. This has led, for example, to arguments that COVID-19 has been good for Earth (even on a temporary basis) on the basis of a few select indicators of transient reductions in anthropogenic pressures, and to conclusions that posit that "restoring" the global environment from the ill effects of anthropogenic activities is potentially possible through temporary shutdown measures (4).

Existing studies of COVID-19 and its environmental impact also largely miss a further opportunity to use shocks resulting from the pandemic to analyze underlying complex systems of great societal importance—despite many commentaries identifying the potential for such insight. While some of the studies reviewed above related to the three topical areas have addressed system interactions and dynamics, few have done so in ways that aim to advance broader understanding of sustainability-relevant systems. There is thus a gap between the growing number of prospective and aspirational papers urging systems approaches and concrete studies that mobilize empirical material. In addition to the review presented above, one additional piece of evidence for this is the relative dearth of literature on COVID-19 that applies conceptual and theoretical perspectives typically considered within the domain of sustainability science. An online search for COVID-19–related publications in

Web of Science that also use search terms identified in a recent review as capturing the broad field of sustainability science (105) resulted in only 43 papers published up to late 2020, many of which mention COVID only incidentally. Given the much larger number of published studies that address COVID in the context of empirical analyses of sustainability-relevant systems (hundreds on air pollution alone), this represents a substantial gap and a potential opportunity.

Why have COVID-19 studies largely not addressed pandemic-related environmental impacts from a systems perspective? This can partially be explained by the proliferation of a large amount of quickly conducted (and perhaps cursorily peer-reviewed) research relying on limited, incomplete, and uncertain data. Another factor may be that few underlying structural shifts have thus far been observed as a result of COVID-19, despite marked changes in near-term behavior. However, even before the pandemic, in all three of the areas of literature examined, and others related to sustainability-relevant systems, relatively few studies comprehensively account for system dynamics. Much research still proceeds as if these interactions either do not occur or are able to be abstracted away as constant boundary conditions—even in studies that address multiple domains. Albrecht *et al.* (106) find, on the basis of a systematic review of 245 journal articles and book chapters on the water-energy-food nexus, that such research frequently falls short of capturing relevant interactions and that new approaches are needed that incorporate social and political dimensions. Messerli *et al.* (107) argue that, to address the United Nations' Sustainable Development Goals, more research is needed to improve understanding of how complex human-environment system dynamics can lead to synergies or trade-offs among stated targets. Di Marco *et al.* (108) argued before the emergence of COVID-19 that researchers and policy-makers could better explore synergies and trade-offs among sustainable development goals in the area of pandemic risks and the environment by considering the drivers of disease emergence and wider societal impacts. Siddiqi and Collins (109) argue that sociotechnical systems research has limited engagement with distributional aspects of societal well-being and propose applying inclusive development and inclusive wealth perspectives, emphasizing equity, to this field.

There remains much potential for existing research on COVID-19 to draw broader lessons and to inform action on sustainability by applying systems perspectives. Renewed attention to institutional and policy factors in quantitative analysis and modeling efforts related to air pollution, leveraging major changes occurring as a result of lockdowns, could help researchers identify factors and interactions they may have overlooked, develop approaches to account for societal feedbacks, and advance methods for accounting for complex causality. With respect to climate, a systems perspective informed by COVID-19 can help in identifying strategies that address root causes of unequal impacts and vulnerability to shocks and stresses, informing the design of climate policies that also enhance near-term human well-being, and assessing challenges for their postpandemic implementation. Research on production and consumption prompted by COVID-19 could leverage new ways of thinking about supply chain resilience and apply better measures of value in the context of human well-being. Research in all three areas could, in turn, build knowledge that could help inform broader sustainability goals. For example, transitions research and associated theories could benefit from engagement of scholars addressing crises and shocks caused by COVID-19 (30). Causal inference research

related to COVID-19 could emphasize structural and institutional factors as potential leverage points that might be overlooked by using standard methods. Insights from COVID-19 could prompt new understandings about value across space and time and how power manifests in individual and structural ways.

STEPS FORWARD AND BARRIERS

There is a pressing need for further developing theory and studying new empirical cases to explore connections among societies and the environment, model them, and use resulting knowledge to promote equitable improvements in human well-being in the shorter and longer term. As the pandemic continues to affect societies, and longer-term data emerge to better characterize its impacts, researchers examining COVID-19 and the environment could avoid mischaracterizations and take advantage of the potential for understanding sustainability-relevant systems by better applying systems thinking. Researchers could further apply improved methods and insights developed for addressing pandemic-related impacts to address emerging future sustainability-relevant systems challenges from other human-induced disruptions that are increasing in scope in a rapidly changing world. For investigators who are motivated by solving particular domain-specific problems, applying systems approaches can help avoid inaccurate and empirically limited portrayals of systems that fail to address broader sustainability-relevant contexts in which they operate. For researchers who aim to contribute to fundamental understanding of sustainability challenges, increased engagement with systems-oriented perspectives can help develop and advance new theories about how systems operate. Practical steps that researchers could take toward these ends include (i) using analytical frameworks to identify important components and interactions, (ii) developing and using new approaches that connect analytical frameworks to models and methods, and (iii) advancing theory and methodology within the field of sustainability science.

First, researchers who aim to explain dynamics and processes in sustainability-relevant systems, including on COVID-19, can apply systems thinking by using existing analytical frameworks. Frameworks can help analysts identify key variables to include, define questions that they are asking, and guide development of theories relevant to similar phenomena (110). Common components of sustainability frameworks could provide a "checklist" by which researchers can help contextualize the full range of factors that could link actions to their consequences (111). A simplified version of such a checklist drawn from previous literature is provided in Box 1 and used to evaluate the three areas of COVID-19–related research here, but researchers may find others more fit for purpose; a comprehensive list of frameworks is provided in a recent review of sustainability science (111). A large number of empirical analyses have built upon existing conceptual frameworks to examine concrete problems and used insights to build theories. However, a growing number of studies conducted by investigators outside the disciplinary communities that developed these frameworks aim to build knowledge about sustainability-relevant systems. The lack of a common language that includes these domain-focused researchers limits the impact of further theory-building across these disparate communities, toward sustainability transitions.

A major challenge of systems-oriented research involves identifying which components and interactions to include or leave out. Researchers (as well as peer reviewers and journal editors) can refer to frameworks as a guide to identify missing components and interactions that might affect research conclusions or increase the impact of analyses. An important consideration relates to whether the phenomena being examined involves only marginal change or whether impacts are large enough to involve interactions across domains, trigger thresholds or discontinuities, or result in feedbacks of a magnitude that could affect results. COVID-19 provides a clear example of the type of problem for which researchers should, at minimum, assess the potential for a comprehensive set of components and interactions to affect their conclusions—it involves a large change affecting human well-being in multiple ways. Applying systems approaches does not require that every analysis comprehensively account for all possible components and interactions. However, frameworks can help ensure that key factors are not a priori excluded from consideration simply because they do not fall within set disciplinary boundaries.

Second, new approaches are needed that connect analytical frameworks—and the components, interactions, and interventions that they include—to models and methods typically used in disciplinary investigations. There remains a large gap between analytical frameworks created by those focused on sustainability science and the ability and willingness of researchers who address domains where systemic interactions are important to use them. This is the case both for examining particular problems like those related to COVID-19 and in attempts to use these cases to draw broader conclusions about sustainability-relevant systems. If readily available approaches were available, then rapid-response research responding to shocks like COVID-19 might be more likely to encompass systems perspectives and draw broader lessons. For example, many quantitative models related to all three domains examined here increasingly integrate across different disciplines, but largely without explicit reference to existing analytical frameworks from sustainability science communities—and may thus still omit important components and interactions. This gap suggests that existing frameworks may not match up with methods or models that are useful "off-the-shelf" to those who are not already embedded in an existing community. To address these barriers, existing frameworks could be modified to facilitate their uptake beyond the communities that already typically apply them. Advances in frameworks and methods could, for example, better guide researchers who seek to integrate quantitative and qualitative analyses using data and modeling. Identifying a common set of elements and common language for translating among the insights gleaned from different approaches may also allow for learning across communities (111).

The newly developed HTE systems framework and its matrix-based approach provide a road map both for assuring that the three aspects of systems-oriented research are covered and as a way to map these elements to disciplinary methods, similar to the approach of Box 1 (17). The HTE framework provides a four-step analytical approach to assessing sustainability-relevant systems; the first three steps map directly to the three criteria in Box 1. The first step covers identifying components of systems, in five main categories: human, technological, environmental, institutional, and knowledge. The second step uses a matrix-based approach to identify connections between the material components in the context of identified institutional and knowledge components. The third step identifies interveners (actors with agency to affect the system) and classifies their interventions relative to the components or interactions that they target. The first three steps in the framework ensure that

sustainability-relevant systems are accurately captured in research; a fourth step addresses the challenge of drawing broader insights from these systems, relevant to building midrange theory. This type of framework could be applied to help researchers addressing issues such as COVID-19 identify which components and interactions are most important to account for. Furthermore, the HTE framework's matrix-based approach can be applied together with a broad range of both qualitative and quantitative methods, linking broader sustainability-oriented frameworks and detailed disciplinary models and techniques.

Third, COVID-19 research may provide an occasion to advance novel and state-of-the-art analytical methods, which could additionally benefit sustainability science researchers. Advances in causal inference and in understanding the use (and misuse) of statistics are vitally important to the progress of science; causal inference methods used in sustainability analyses could benefit from applying new approaches to identify pandemic-related impacts, and the challenges of dealing with often sparse and uncertain sustainability-relevant data could contribute to advancing cutting-edge methods. The marked expansion of "big data" has changed methods and analyses in a large number of fields, and much worldwide attention is focused on data collection and curation related to COVID-19. Sustainability science can both better harness the opportunities COVID-19 poses with respect to data and also provide tools and techniques to data scientists interested in incorporating institutions, power, and equity into their work. The pandemic provides an opportunity for research communities to collaborate on a common problem, and this could be encouraged by targeting grant funding for interdisciplinary work. Last, the sustainability science community could make better use of open science tools to enhance reproducibility and sharing (*112*), learning from open data efforts related to COVID-19.

COVID-19, caused by a so-called "novel" coronavirus, represents a worldwide shock beyond the prior experience of most humans alive today. However, COVID-19 interacts with an environment that reacts to this shock in ways that reflect systemic connections, behaviors, and responses, many of which are not novel at all. Methods and approaches to analyzing sustainability-relevant systems exist, but their lack of uptake challenges efforts to better characterize the context in which COVID-19 poses a threat to human well-being. To meet this challenge, researchers investigating the impacts of COVID-19 should take advantage of the evidence from this shock to examine fundamental system behavior, engaging with aspects that involve people, technologies, the environment, institutions, and knowledge. Researchers can further contribute to knowledge by advancing frameworks and theories that cross disciplines and by enhancing capacity for linking knowledge to action. Improved understanding is critical to promoting human well-being across communities throughout the world, today and in the future, relevant to COVID-19 and well beyond.

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Lessons from a pandemic for systems-oriented sustainability research

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