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Perspective

A systems lens to evaluate the compound human health impacts of anthropogenic activities

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SUMMARY

Diverse anthropogenic activities are changing our natural environment, with important implications for human health. Successfully managing their impacts requires an understanding of the compounding hazards resulting from multi-faceted environmental changes. Here, we propose a human-environment systems lens comprising public health, climate, air quality, and agricultural land-use land management to characterize the combined health risks of anthropogenic environmental changes. Interactions within this system can amplify, diminish, or generate additional hazards associated with changes in any individual element. Using South Asia as an example—where rapid industrialization and the Green Revolution aided economic development and food production but inadvertently compromised multiple human health dimensions—we synthesize the influence of human-environment system interactions on environment-sensitive health outcomes. We further demonstrate the utility of this lens for evaluating the health outcomes of existing and planned regional policies and interventions to identify unintended negative consequences and solutions that realize co-benefits and minimize trade-offs.

INTRODUCTION

Anthropogenic activities are affecting human health via changes in climate conditions, air quality, and reliable availability of sufficient nutritious food from the agricultural land. Globally, demographic and economic growth, the increase of food and energy demand, the intensification of land-use pressures from agricultural activities, and increased fossil fuel and biomass burning have profoundly altered the natural environment we depend upon.[1–3] Such anthropogenic activities affect land-surface conditions,[4] modify climate patterns,[1–3,5,6] and contribute to air pollution.[7–12] Exposures to these environmental changes—in particular extreme weather events, poor air quality, and food production and nutrient losses—are linked to a suite of climate-, air pollution-, and nutrition-related human health impacts, including cardiovascular and respiratory illnesses, heat stroke, anemia, malnutrition, and premature mortality, across the planet.[2,13] However, vulnerability to these hazards vary substantially based on several factors including socio-economic, demographic and livelihood profiles, behaviors, institutional access, governance, and infrastructure conditions.

A comprehensive understanding of the human health hazards of anthropogenically driven environmental changes can inform adaptation planning and regional policy development to minimize vulnerability. Although the influence of various anthropogenic activities on climate change, air pollution, and food production and nutrient content have been examined extensively in various regions, there are several interactions within the human-environment system that are rarely considered in assessing human health risks. Existing environment-related health impact studies are mostly limited to examining the impact of changes in individual elements of the system on specific human health outcomes (air pollution-related exposure;[14,15] heatwave-related mortality;[16] and crop yields and nutrient content).[17–19] A few recent regional and global studies have started to examine the interactions between climate, agricultural practices, and air pollution and the simultaneous health risks of more than one environment system component.[20–23] However, the understanding of compounding health risks posed by changes in multiple elements resulting from interactions within the environment system is rather limited. Such interactions (such as climate impacts from air quality changes or agricultural land use and land management) can amplify or diminish the health impacts of individual components or generate additional human health risks, which can worsen the vulnerability of the regional population. Neglecting interactions within this environment system can,

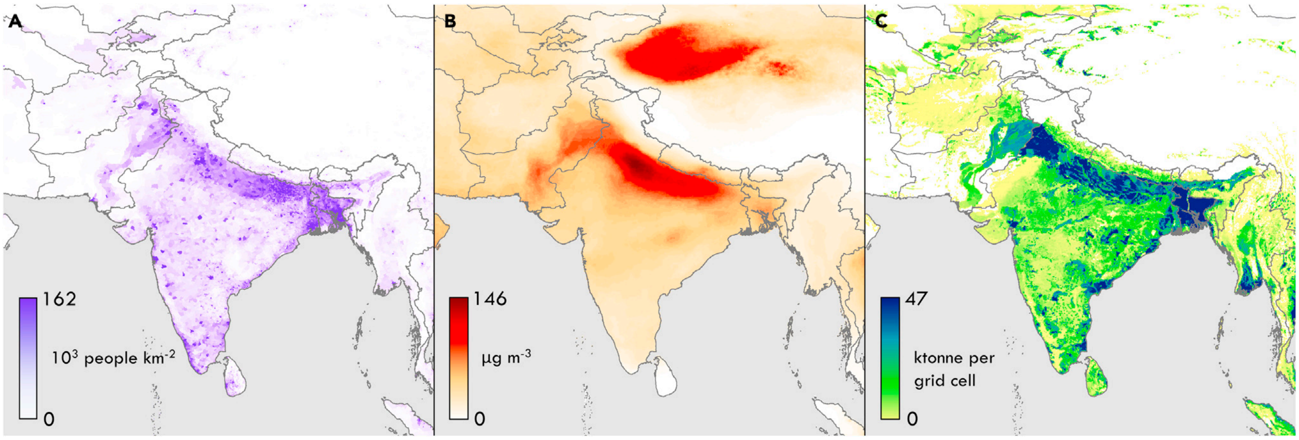

Figure 1. Population, air pollution, and agricultural distributions
Recent distribution of population (2015; GPWv4[51]), satellite-derived surface fine particulate matter ($PM_{2.5}$) (2016; van Donkelaar et al.[12]), and cereal production (2005; GAEZv3[52]).

therefore, potentially under- or overestimate the health impacts of changes in anthropogenic drivers.

South Asia is a region where anthropogenic activities and their associated environmental changes are acute and are likely to continue to intensify.[24,25] In addition to multiple environmental hazards that affect the region, the region's unique demographic factors and socio-economic characteristics make it one of the most vulnerable globally to environment-related health hazards.[26] Fossil fuel and biomass burning and intense agricultural activities have contributed to high aerosol concentrations over South Asia,[11,12] extremely poor air quality in the region,[27] and stress on limited available land resources,[3,28–30] modified the timing and strength of the predominant source of the region's rainfall—South Asian Summer Monsoon,[31–36] and contributed to severe health risks for nearly one-quarter of the world's population. The population's vulnerability to environment-related health risks is particularly high because of the region's high population density, high poverty rates, severe food insecurity, high rates of malnourishment, and substantial dependence on the agricultural sector.[37] The unprecedented scale of human health and environmental challenges underscore the urgent need for policies and interventions that will yield co-benefits across multiple environmental hazards.

Here, we propose a human-environment systems lens that incorporates climate, air quality, agriculture land use and land management (abbreviated as agricultural LULM) interactions, and environment-related health risks to characterize the compounding human health risks from anthropogenically driven environmental changes and demonstrate how it can be used to evaluate the implications of policies and interventions, drawing on examples from South Asia. We bridge multiple spheres of research to discuss interactions within the climate-air quality-agricultural LULM system, the associated health outcomes of individual components of the system, and the amplifying or confounding influence of various system interactions on climate-, air pollution-, and nutrition-related human health outcomes. Using specific examples of policies and interventions, we illustrate that the compound human health outcomes included potential unintended consequences resulting from human-environment system interactions in the region. Finally, we synthesize the research gaps and challenges in understanding these system dynamics and propose research foci for supporting the development of this human-environment system to support decision making. This ability to quantify the co-benefits and trade-offs of interventions is central to supporting sustainable development policy. Although we focus on South Asia, this lens is relevant in other regions with similar interactions and challenges, including sub-Saharan Africa, South America, and East Asia.

HUMAN ACTIVITIES AND CLIMATE TRENDS IN SOUTH ASIA

Anthropogenic activities have increased dramatically across South Asia over the past 60 years, with mounting impacts on climate, air quality, and the land surface. South Asia's population grew from 468 million to 1.8 billion between 1950 and 2017[38] (Figure 1A) along with increases in anthropogenic greenhouse gases (GHGs) and aerosols emissions. GHG emissions from the region increased from 1.48 Gtonne CO_2 equivalent (CO_2eq) to 3.85 Gtonne CO_2eq (+260%) between 1990 and 2014, due in large part to growth in the energy sectors.[39] Emissions from residential and agricultural biomass burning,[40,41] vehicular emissions,[42,43] and coal-powered plants[44] have led to increasing aerosol concentrations of sulfate and black carbon,[5,45] contributed to fine particulate matter ($PM_{2.5}$), and enhanced the formation of secondary pollutants such as ozone (O_3). Concentrations of these aerosols and other pollutants are highest over the Indo-Gangetic Basin[46–48] (Figure 1B). In addition, the widespread introduction of high-yielding, input-dependent crop varieties and near tripling of the irrigated areas[49] over the past half-century (i.e., the Green Revolution) has rapidly increased food supply (Figure 1C) while placing mounting pressure on agricultural inputs and resources[30,50] and altering land-atmosphere interactions. Much of the cereal production and agricultural intensification is concentrated in the Indo-Gangetic Basin (Figure 1C).

The evolution of these anthropogenic drivers has been accompanied by historical climate trends (Figure 2). The region has experienced an overall warming trend with increases in

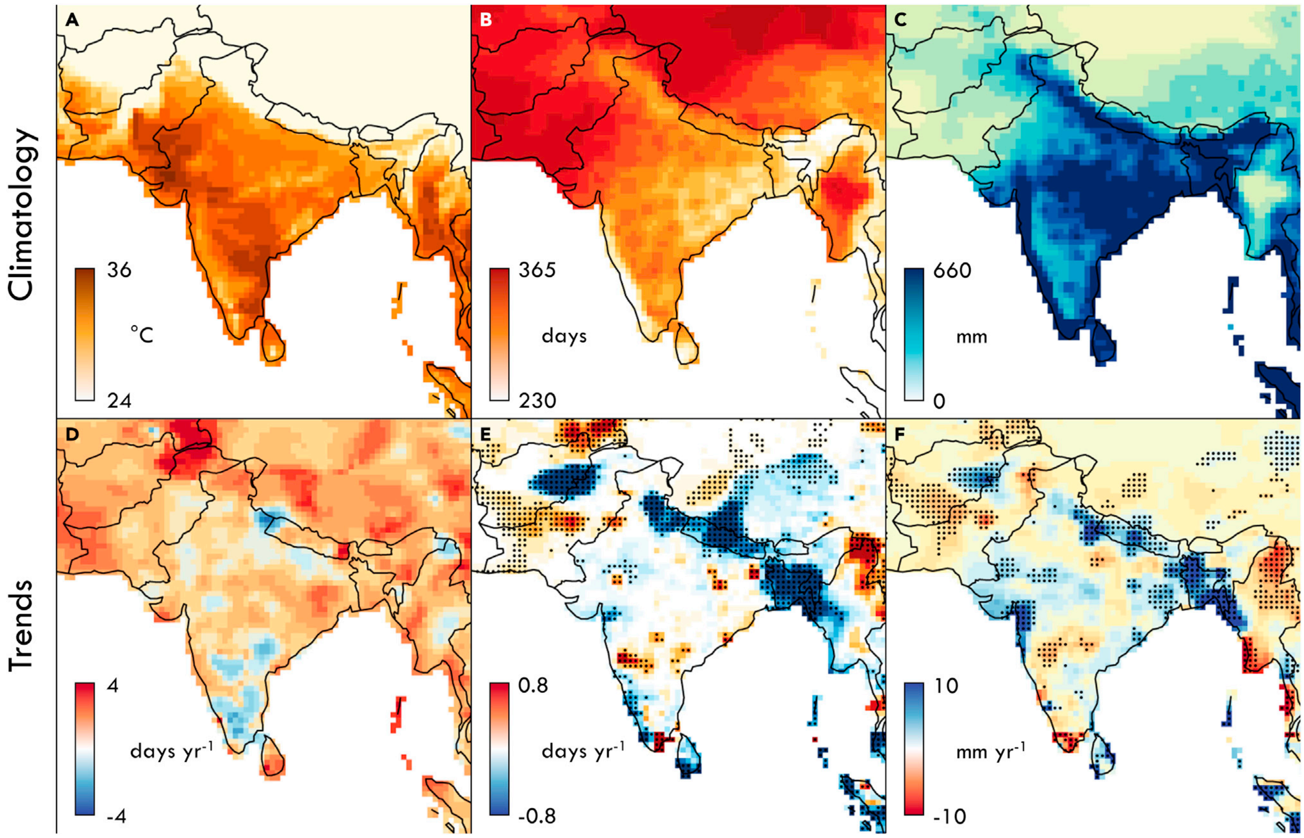

Figure 2. Regional climatology and recent climate trends

Climatology of (A) the warm extreme temperature threshold (90th percentile of daily maximum temperatures), (B) dry day frequency (days with precipitation <1 mm/day), and (C) total amount of extreme precipitation (precipitation exceeding the daily 95th percentile) during the summer monsoon season. Historical (1979–2017) trends in the (D) frequency of warm extremes (days with temperatures exceeding the threshold shown in A), (E) dry day frequency, and (F) extreme precipitation amount. Stippling in (E) and (F) indicates trends that are significant at the 10% level. Data source: NOAA CPC daily temperature and precipitation.[61]

daily temperature extremes across most of South Asia but dampened warming or cooling over parts of the Indo-Gangetic Basin and parts of southern India during the summer monsoon season[53] (Figure 2). During the pre-monsoon season, the region has witnessed an increase in heat wave frequency and intensity in certain areas, with a number of recent record-breaking seasons.[54,55] In addition, the summer monsoon circulation has weakened since the mid-20th century, associated with a weakening of the land-ocean thermal gradient that is driven largely by amplified warming of the Indian Ocean.[56–58] This weakening circulation has also induced spatially heterogeneous changes in the distribution of monsoonal precipitation and increases in extreme events across parts of the region[25,57,59,60] (Figure 2).

Trends in summer monsoon season precipitation characteristics have been attributed to anthropogenic aerosols; however, there is emerging evidence of the substantial influence of irrigation in changing regional rainfall patterns.[6,25,31,33–35,62–64] Anthropogenic aerosols are projected to increase till at least the mid-21st century to meet rising energy demands. Agricultural activities are likely to continue to intensify to meet rising food and energy demands.[65–67] Together, agricultural LULM and aerosol emissions are likely to continue to be as important as GHG emissions in influencing regional environmental conditions and their collective consequences for human health in the next few decades.

THE CLIMATE-AIR QUALITY-AGRICULTURAL LULM SYSTEM

We propose studying climate-air quality-agricultural LULM as an integrated system because multiple interactions link components of this specific system in several global regions including South Asia. Agriculture, which encompasses land-use (e.g., crops, extent of cropped area, type of cultivation) and land-management (e.g., irrigation, waste burning, fertilizer application), is the most extensive human system directly affected by climate and air quality. In addition, the vast areas occupied by agricultural systems exert considerable influence on climate and air quality via extensive land-surface changes and emissions. Given its expansive physical footprint on the land and its direct exposure to environmental and climate conditions, agriculture is uniquely and distinctly linked with climate, air quality, and the land surface in ways that other human systems, such as the energy system, are not. These tight interactions mean that change in one of these components can, therefore, influence changes in this overall system and that each system component can produce its own spectrum of environment-

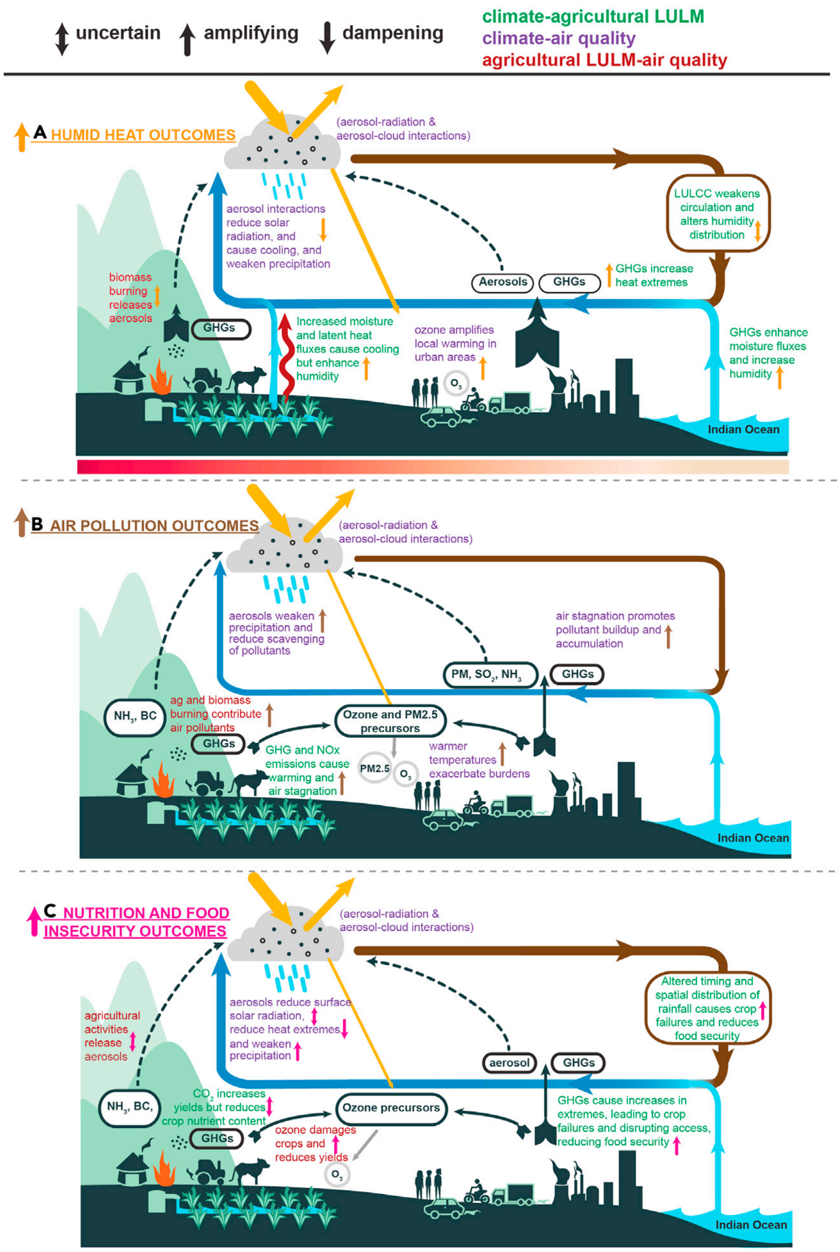

Figure 3. Connecting environment interactions and health outcomes

Schematic illustrating interactions between climate, air quality, and agricultural LULM in South Asia and their influence on (A) heat-related, (B) air pollution-related, and (C) nutrition and food insecurity related human health outcomes. Arrows beside each interaction in each panel indicate the direction of their impact (amplifying or dampening) on the specific human health outcome represented in that panel and the text color of each interaction represents the category of system interactions (see legend at the top). The interactions represented here are intended to be illustrative and not comprehensive.

related health hazards. While some of these interactions are well understood, there are several key uncertainties and unexplored interactions within this system in South Asia that we summarize below (Figure 3).

Climate-air quality interactions

Anthropogenic aerosols and other short-lived climate pollutants (SLCPs) have considerably altered temperature and precipitation patterns over South Asia.[31–33,35] Aerosols reduce radiation at the surface through absorbing (e.g., black carbon) or reflecting solar radiation (e.g., sulfate aerosols)[45] (Figure 3). Aerosol-radiation and aerosol-cloud interactions lead to surface cooling, weaken the summer monsoon, and change the spatiotemporal distribution of mean and extreme precipitation[5,31–33,35,68] (Figure 2). Such aerosol-induced changes have suppressed the expected warming and wetting influence of GHGs over the region.[31,35,69] However, there are still substantial uncertainties in the magnitude of their impact on historical and future climate because of inherent climate model uncertainties associated with representing aerosols and monsoon processes.

Weather and climate conditions also have important effects on ambient air pollution through the production, transport, and dispersion and accumulation of atmospheric pollutants. Meteorological factors, such as warmer temperatures, fewer rainy days, dry conditions, and weak winds, are linked to enhanced concentrations of two main air pollutants that are harmful for health—O_3 and $PM_{2.5}$.[70,71] Such meteorological conditions are likely to become more frequent, with the largest projected increases during the fall season,[72] coinciding with peak concentrations of $PM_{2.5}$ from biomass burning following crop harvests in northwestern India.[73] Such compounding effects support the potential improved climate and air quality co-benefits from reducing fossil fuel use.[21,74,75] Neglecting such interactions could affect assessments of the impact of air pollution control interventions on human health.

Recently, we witnessed climate-air quality interactions play out following the lockdowns to control the COVID-19 pandemic.[76] While reductions in anthropogenic emissions led to improved air quality in South Asia, numerous locations globally experienced unexpected increases in $PM_{2.5}$ and O_3 pollution due to aerosol-chemistry-climate interactions and prevailing wintertime meteorological conditions.[77–79] In addition, reduced aerosol concentrations contributed to temporary increases in surface temperatures that likely contributed to enhanced O_3.[80] While consequences of emissions reductions triggered by this unanticipated event are being actively researched, it highlights the need to better understand the climate-air quality feedbacks

	Heat Stress	Air Pollution Impacts	Nutrition and Food Insecurity Impacts
Climate-air quality interactions			
Aerosol-radiation and aerosol-cloud interactions reduce surface solar radiation, causing cooling, reduced boundary layer height, and fewer heat extremes[5,43,158]	↓	↕	↓
Aerosol-cloud interactions weaken precipitation intensity[5,29,159]	↔	↑	↑
More air stagnation conditions promote buildup and accumulation of pollutants[69]	↕	↑	↑
Warmer temperatures and less rainfall enhance PM2.5 and ozone burdens[123–127]	↑	↑	↑
Climate-agricultural LULM interactions			
Precipitation and temperature extremes reduce certain crop yields and nutrient content[17,20,82,84,85,129]			↑
Heat stress reduces productivity of dairy cows and poultry[87,88]			↑
Agricultural GHG emissions cause warming, more air stagnation and increased precipitation intensity[3,69,112,113,160]	↑	↑	↑
Irrigation causes near-surface cooling but increases near-surface humidity[6,30,116,117]	↑	↕	↕
Agricultural land-cover and land-management modifies monsoonal patterns[6,30,58,91,92]	↔	↔	↑
Rising CO_2 concentrations negatively affects protein, micronutrient and vitamin content of several crops[86,131]			↑
Agricultural LULM – air quality interactions			
Crop residue burning contributes black carbon aerosols, particulate matter and ozone precursors[96–98,122]	↓	↑	↑
Fertilizer use releases ammonia emissions and PM2.5 precursors[99,100]		↑	
Ozone causes crop damage[20,23,101,129]			↑
Aerosols reduce crop productivity via reducing surface solar radiation[23,103]			↕

↑ Interaction enhances (worsens) negative health outcomes related to heat stress-, air pollution- or nutrition and food insecurity

↓ Interaction weakens (alleviates) negative health outcomes related to heat stress-, air pollution-, nutrition and food insecurity

↕ Effects of interaction on heat stress, air pollution or nutrition and food insecurity are uncertain

↔ Interaction has varied impacts on heat stress, air pollution or nutrition and food insecurity related health outcomes across the region

Figure 4. Summary of the influence of environmental interactions on health outcomes
Impacts of the interactions between components of the climate, air quality, and agricultural LULM system on heat stress-, air pollution-, or nutrition and food insecurity (calorie production and/or nutrient content)-related health outcomes. Note that this is an illustrative subset of interactions with relatively well-understood impacts. Example references from South Asia focused studies and global assessments have also been provided for each interaction. Empty boxes indicate unknown or no relevant impacts of interaction on the specific health outcome.

for managing trade-offs of air pollution interventions and their human health consequences.

Climate-agricultural LULM interactions

Climate and agriculture interactions are critical to understanding health impacts in South Asia due to extensive agriculture-driven land-use change, cropping patterns, land-management practices, ongoing intensification to meet increases in food demands, the high prevalence of livelihoods based in smallholder farming (~67% of India's farmland and 82% of farmers),[81] and climate sensitivity of agricultural production. Regional studies on the impact of climate variability on crop productivity find projected temperature and changing rainfall distributions could reduce yields of main cereal crops such as maize and wheat.[82–85] Furthermore, elevated winter temperatures could decrease winter crop cover[86] and extreme winter heat could negatively impact wheat yields.[87] The increased frequency of extreme events will likely exacerbate the negative climate impacts on crop production, although these are largely unaccounted for in existing studies.[88] For crops with certain photosynthetic pathways (C3 crops, e.g., rice, wheat, soybeans), negative climate impacts on yield may be compensated to some extent by the increasing effect of rising CO_2 levels on photosynthesis.[88] Rising CO_2 concentrations are also likely to adversely affect the nutritional quality of cereals grains, potatoes, and other C3 plants, including reducing their protein, micronutrient, and vitamin content, although there are considerable uncertainties in the magnitude of their impacts due to limited data on key nutrients, particularly in low-income countries.[89] Climate change is also expected to affect other aspects of the agricultural system, including livestock productivity[90,91] and fisheries, but such studies are currently limited.

Agricultural LULM also influences climate in several important ways (Figure 3), with impacts extending beyond the harvest season.[34] GHG emissions from fertilizer use (nitrous oxide [N_2O]), tractors and pumps (CO_2), flood irrigation (methane [CH_4]), soil and manure management (CH_4), and enteric fermentation (CH_4) collectively contribute 19% of the GHG budget of South Asian countries,[92] with additional GHG contributions from widespread paddy rice cultivation in the region.[93] Agriculture intensification associated with the Green Revolution has also contributed to modifying regional climate patterns via changes in surface energy and moisture fluxes.[34,62–64,94] Extensive irrigation across the Indo-Gangetic Basin[95,96] has enhanced surface cooling during the major growing seasons,[34,62] contributed to weakening the summer monsoon in some areas[6,34,63] and enhanced precipitation in northwestern South Asia.[6,34,36,64] It is crucial to better understand and integrate agricultural LULM practices[97] and climate interactions into earth system models in order to more completely understand the risks to health and livelihoods of the South Asian population and to identify co-benefits and trade-offs of interventions.

Air quality-agricultural LULM interactions

The interactions between agriculture LULM and air quality are relatively understudied in South Asia (Figure 3). Regional agricultural practices are a major source of multiple harmful air pollutants. Extensive crop residue burning—particularly of rice biomass at the end of the kharif (monsoon) growing seasons in northwest India (i.e., Punjab and Haryana)—leads to seasonally elevated concentrations of $PM_{2.5}$ and nitrogen dioxide (NO_2), a precursor to O_3 and $PM_{2.5}$, across the Indo-Gangetic Basin.[98–100] Diesel pumps and electricity sourced from coal-powered plants supporting the widespread use of irrigation[93] contribute particulate matter (PM), hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x). Rising fertilizer use and animal husbandry contributed to extensive ammonia (NH_3) emissions—another $PM_{2.5}$ precursor—which peak during the monsoon season.[101,102]

In the other direction, surface O_3 pollution damages crops and has reduced the collective production of cotton, rice, soybeans, and wheat in India by 3% (or 6 Mt), with higher fractional losses for wheat and cotton;[103] rice and wheat losses in India may be as much as 20.9 Mt due to elevated surface O_3 levels.[104] Air pollution can also indirectly impact crop productivity through modifying the surface radiative budget and contributing to atmospheric warming. For example, BC and O_3 pollution reduces surface radiation and has already led to an estimated reduction of ~36% in wheat yields.[20] To the contrary, diffuse radiation from scattering aerosols is more efficiently used by plants potentially enhancing plant productivity.[105] Contradictory claims on air pollution impacts on crops and the interactions between air quality and agricultural practices support the need for more integrated research, including on nutritionally valuable crops beyond rice and wheat, in the region to enable more effective management of the consequences of existing policies and identify sustainable agricultural practices.

HEALTH IMPACTS FROM THE SYSTEM AND ITS INTERACTIONS

Changes in climate, air quality, and agricultural LULM pose significant public health risks in this densely populated region. Exposure to multiple hazards from climate extremes, rising air pollution, and food insecurity is increasing simultaneously. The increasing frequency and intensity of extreme events, such as heat waves or flooding, have displaced millions, killed thousands, and caused infectious disease outbreaks across South Asia. The disease burden and premature mortality attributable to air pollution in India is among the highest globally, contributing to millions of premature deaths annually.[14,15,41,106,107] In addition, air pollution and climate change have simultaneously reduced the yields of major cereal crops and agricultural production in the region.[19,20,82,88] Emerging work examining the interactions within the complex human-environment system,[71,108–111] combined with a growing understanding of their individual health impacts, provides important first insights for understanding the compounding human health impacts of simultaneously increasing environmental hazards in South Asia. To illustrate the pathways by which environmental system interactions can affect multiple aspects of human health, we summarize heat-, air pollution-, and nutrition (crop production and nutritional content)-related health impact categories relevant to each system component, describing the potential amplifying or confounding effects from the other components (Figures 3 and 4).

Heat-related illnesses

Heat waves are often associated with numerous deaths or illnesses from exhaustion, heat strokes, and cardiovascular illnesses.[2,112] Heat stress associated with extreme temperatures is one of the most well-understood health impacts of climate change, and high humidity can exacerbate these impacts. High wet bulb temperatures (WBTs)—a measure of the combined stress due to heat and humidity—can cause severe physiological stress to humans by limiting evaporative cooling through perspiration.[113] Prolonged exposure to such humid heat conditions can be potentially fatal, placing millions of homeless people—especially those with outdoor occupations—at particular risk.[114,115] Dangerous WBTs (>27°C) already occur across the Indo-Gangetic Basin and much of the region is likely to experience levels near the limit of human survivability (~35°C) by the end of the century.[114–117] System interactions can modify the impacts of extreme humid heat on human health. *Climate-air quality interactions* could dampen the intensity of heat waves through reducing surface solar radiation.[5] Similarly, *air quality-agricultural LULM interactions* could reduce the intensity of heat waves through air pollutant emissions from biomass burning. In contrast, *climate-agricultural LULM interactions* are shown to intensify humid heat waves through irrigation-induced enhancement of near-surface humidity leading to WBT increases despite its evaporative cooling effect.[118,119] Furthermore, the human response, such as increased electricity needs for air conditioning during heat waves, can increase air pollution and related exposure, compounding heat-related health risks.[120]

Air pollution-related illnesses

With some of the worst air pollution in the world, South Asia has been the focus of a growing body of work raising awareness of the region's persistent air pollution crisis and its health implications.[14,15,41,106,107,121,122] Air pollution exposure can exacerbate respiratory diseases such as asthma, and increase the risk of lung cancer and chronic cardiovascular and pulmonary diseases. It has been estimated that ambient $PM_{2.5}$ air pollution contributes to between 570,000 and 2.2 million premature deaths in India from a broad range of causes.[15,106,123] Interactions with agricultural LULM and climate change can exacerbate the overall health impacts of rising air pollution. A prime example of *air quality-agricultural LULM interactions* is the widespread post-monsoon crop residue burning in northwestern India that produces emissions that contribute 7%–78% of Delhi's $PM_{2.5}$ pollution.[124] In addition, denitrification of synthetic fertilizers produces reactive nitrogen species that serve as $PM_{2.5}$ precursors. *Climate-air quality interactions* have multiple exacerbating effects on air pollution. Warmer temperatures can exacerbate $PM_{2.5}$ and O_3 burdens and their associated health impacts,[125,126] with the premature mortality burden under an extreme emissions scenario (representative concentration pathway [RCP] 8.5) estimated at 29%–39% greater than under the more optimistic climate scenario (RCP 4.5).[71,110,111] This is partially the result of a phenomenon known as the "climate change penalty."[127] The strong positive correlation of surface O_3 concentrations with temperature will likely lead to greater

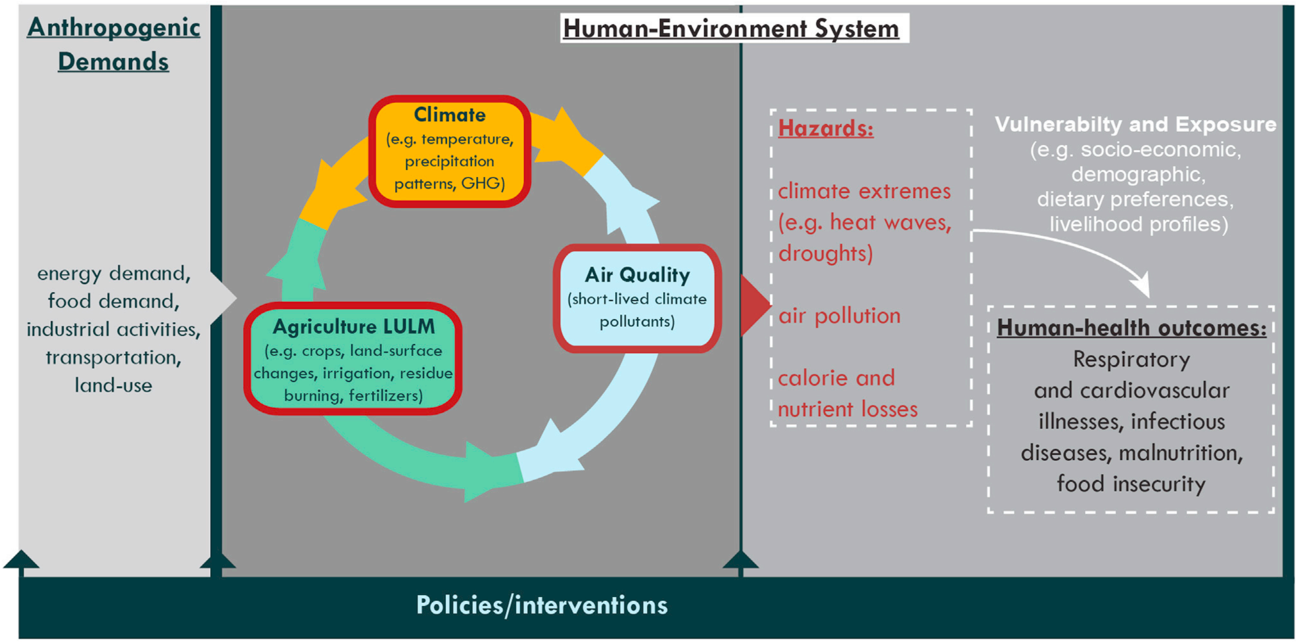

Figure 5. The human-environment system
Schematic of the human-environment system comprising climate-air quality-agricultural LULM via which anthropogenic activities affect various environment-sensitive human health hazards. Colored arrows within the human-environment system represent interactions between its three components. Various anthropogenic drivers influence the human-environment system via changes in GHGs, short-lived climate pollutants, and land-use, land-cover, and land-management practices. The black lines with arrows indicate intervention points for policy.

O_3 concentrations in the region with warming, exacerbating respiratory illnesses.[128,129] Furthermore, aerosol-induced rainfall reductions reduce the scavenging of air pollutants and promote their build up in the atmosphere. The projected increasing frequency of air stagnation events[72] is likely to increase the duration of human exposure to poor air quality, even if emissions remain unchanged. Finally, *climate-agricultural LULM interactions* could exacerbate these impacts with land-surface changes and GHG emissions from agricultural activities further amplifying air stagnation.

Nutrition-related illnesses

Production and availability of sufficient quantities of nutritious food has important consequences for human health. Recent work has shown that crop production mixes in South Asia have steadily homogenized—transitioning from a large fraction comprised of nutritious traditional grains toward high-yielding crops such as rice and wheat[49,130]—and have contributed to lower per capita supplies of key nutrients (e.g., iron) in diets.[17] Because much of the food produced in South Asia is consumed within the region, these shifts alone have important implications for human health, with 277 million people currently undernourished (the most of any world region) and nearly half of all women of reproductive age suffering from anemia.[37] In addition, there is emerging evidence of the complex impacts of climate and air pollution on crop production and nutritional content.[88,131] A few recent studies have examined the combined effects of climatic factors and air quality on selected crop yields.[20,23,132] One global analysis found that maize losses are attributable to CH_4 emissions (via temperature and O_3 production pathways), and wheat losses in tropical areas are largely associated with warming temperatures. However, where aerosol and O_3 concentrations are high, such as in South Asia, there are consistently negative effects on wheat yields but net increases in rice yields due to aerosol-induced cooling,[23] highlighting the confounding effects of *climate-air quality interactions*. However, other work in India suggest predominantly compounding negative impacts of *climate-air quality interactions* from SLCPs on rice yields due to reduced solar radiation from black carbon and of *air quality-agricultural LULM interactions*, such as through the direct vegetation damage from O_3.[20] Conversely, rising CO_2 concentrations may enhance photosynthesis in certain C3 crops but also deplete key nutrients (i.e., iron, zinc) in their tissues[133]—a development that could have substantial implications for human health in South Asia given the region's widespread incidence of micronutrient deficiencies. Furthermore, increase in extreme events could damage crops or reduce yields, affecting food supply, availability, and stability. These effects suggest a potentially negative overall impact of *climate-agricultural LULM interactions* on nutrition-related health outcomes. Reducing uncertainties in the impacts of CO_2, climate extremes, and air quality on yields and nutritional content of regionally important crops is critical for assessing the impacts of increasing anthropogenic activities on overall nutrition for the region's population.

HUMAN-ENVIRONMENT SYSTEM LENS TO SUPPORT DECISION MAKING

The climate-air quality-agricultural system coupled with environment-sensitive human health risks comprises a human-environment system with: (1) links from the human to the environment system via changes in anthropogenic demands or policy interventions, and (2) links from the environment to the human system via changes in health-relevant environmental hazards (Figure 5). Policy interventions are often designed to address individual anthropogenic drivers or components of the environmental system in response to specific negative societal outcomes but present opportunities for cascading (and potentially unintended negative) consequences through interactions with other system components, producing additional direct and indirect health impacts. The proposed human-environment systems lens can help more accurately evaluate the combined impacts of anthropogenic activities and help identify human health co-benefits, trade-offs, and unintended consequences of interventions.

Below, we demonstrate the need and utility of a systems lens to evaluate the compound human health hazards of select policies or interventions. These examples discussed below, while not comprehensive, are selected to illustrate the suite of unintended consequences or co-benefits of implemented policies or potential compounding impacts of planned policies arising from human-environment system interactions. We also discuss policies and interventions addressing various entry points within this human-environment system (black arrows in Figure 5), including anthropogenic demands, changes within the system, or the outcomes of health hazards.

Interventions to reduce GHGs

India's National Energy Plan aims to add 175 GW of renewable electricity generation capacity by 2022.[134] In addition, India plans to increase the share of renewable energy sources in their total electricity production to 40%–45% by 2030 as part of their pledge to the Paris Climate Agreement. Transitioning to alternative energy sources to reduce combustion of coal and other fossil fuels will reduce GHG and aerosol emissions, among other air pollutants, which will limit additional increases in extreme events and corresponding illnesses, including heat stress, direct loss of life, and water-borne diseases associated with extreme precipitation. Mitigating higher temperatures and extremes will likely have co-benefits for agricultural production via reduced climate damages[19,84,88,135] and for air pollution due to reduced sources. Curbing emissions will also limit air stagnation events, reducing air pollution exposure and health impacts. A potentially significant unintended consequence of reducing fossil fuels is a shift in the distribution of rainfall patterns that have historically been shaped by the competing effects of GHGs, aerosol emissions, and LULM,[6,31,34,35] which could affect the availability of water resources and food production.

Interventions to reduce air pollution

Electric vehicle use in India is being subsidized (e.g., the FAME India Scheme)[136] as a way to incentivize cleaner shared and public transportation to reduce O_3 air pollution. Reduced vehicular emissions of O_3 precursors, such as nitrogen oxides (NO_x) will generally reduce surface O_3 formation regionally, thereby reducing exposure and air pollution-attributable premature deaths. However, in distinctly urban regions with high NO_x emissions, reducing NO_x emissions tends to result in an increase in O_3 pollution because of a reduction in NO_x titration. In early 2020, this phenomenon was observed in major cities across China. As a result of city-wide lockdowns due to the COVID-19 global pandemic, NO_x declined by 71.9%–93% from 2019 as measured by both *in situ* and remote sensing observations, yet surface measurements of O_3 increased by 25.1% compared with a recent 5-year climatology report.[78] Finally, because O_3 can cause local warming,[137] its increase in urban areas could enhance heat stress on vulnerable, densely populated areas.

Interventions on agricultural practices

Widespread rice and wheat production in the Indian states of Punjab and Haryana have led to water scarcity and groundwater depletion in the region primarily resulting from the injudicious pumping for irrigation.[138] This prompted the Punjab state government to prohibit the transplanting of paddy before June 15 under the Punjab Preservation of Subsoil Water Act of 2009. This law was designed to discourage farmers from paddy cultivation, motivate farmers to adopt more water-efficient cash crops, and delay planting beyond the historically hottest summer temperatures to be closer to the onset of the monsoon. This water act served its direct purpose by avoiding vast amounts of standing irrigation water, preventing high losses due to evapotranspiration, and ultimately saving large volumes of water.[139] However, delayed rice sowing pushed harvests too close to the sowing dates of winter wheat, leaving little time for traditional systems of crop residue management. In addition, technological growth resulted in paddy varieties that grew to an even higher height, and rapid mechanization led to the adoption of combine harvesters that only plucked the top 9 inches of the rice tassels, leaving most of the straw in the ground and no time to process before the winter sowing. As a result of these confluent factors, farmers burned crop residues directly in their fields, to cheaply and effectively remove remaining straw,[73] leading to acute pollution and exacerbated health impacts along the Indo-Gangetic Plains in October and November.[14,140] In this example, two agriculture-motivated interventions to improve environmental outcomes—late sowing to preserve water and better varieties/harvesters to increase cropping efficiency—increased black carbon emissions, degraded air quality, and created severe negative health impacts.

Interventions to modify emission sources

Rather than changing the emission sources, interventions could seek to remove one or more pollutants after generation. For instance, reductions in emissions could be achieved through direct removal of pollutants, such as with the applications of smokestack scrubbers, vehicle catalytic converters, and carbon capture and sequestration methods, or by improving energy-use efficiency at production or at the consumer endpoint.[141] Despite the immediate benefits from emissions reductions, the overall human-environment system implications of these changes on human health outcomes requires consideration of cascading effects and interactions. For instance, reducing particulate emissions using smokestack scrubbers may directly improve air quality[142] but will also unmask their cooling effect on temperatures and dampening effect on rainfall[5,31,35], directly increasing heat-related health risks and indirectly influencing agriculture[20]

Figure 6. Resource needs and challenges
Key challenges, barriers, and needs associated with quantifying the impact of anthropogenic drivers on the human-environment system, understanding their interactions, and their implications for associated human health outcomes.
(A–C) Areas for improvement in the individual components of the systems; (D) highlights community needs for supporting cross-disciplinary development to study the connections across the system; (E) suggests areas of epidemiological study for increasing our current understanding at a more localized level in South Asia; and (F) includes suggestions for techniques to build robust conclusions in quantifying health outcomes.

via the interactions outlined under the *Climate-air quality-agricultural LULM system*.. (Figures 3 and 4).

Interventions within the climate-air quality-agriculture system

Adaptation measures to manage and abate impacts often have multiple co-benefits that can be identified using this systems lens. For example, climate-sensitive urban planning measures, such as green infrastructure and increased tree cover, can have co-benefits of reduced climate- and air quality-related health impacts through mitigating the urban heat island effect, reducing the likelihood of flooding and runoff, and improving local air quality.[143] Subsidies or incentives to diversify cropping patterns[135] to include more nutritious, less water-intensive,[49] and less climate-sensitive[19] crops (e.g., millets) could improve air quality through reduced crop residue burning and lower energy intensities,[93] and reduce GHG emissions and climatic changes associated with irrigation, which can collectively contribute to improved dietary nutrient availability and reduced exposure to heat and air pollution. Similarly, providing access to technologies that provide alternative crop residue disposal or financial incentives to reduce agricultural waste burning can have climate, air quality, and agricultural co-benefits.

Interventions to directly minimize health impacts

Interventions can target reducing exposure to climate-air quality-agriculture system hazards directly. Example strategies for health-focused adaptation measures include opening cooling centers during heat waves, distributing filtering masks during periods of poor air quality, supplying food aid following crop failures, or fortifying and enriching foods. Early warning systems and evacuations can minimize human health impacts in more extreme cases where persistently bad air quality or extreme climate events may threaten livelihoods, homes, or infrastructure. For example, policies can be enacted to protect outdoor laborers during severe heat and air pollution episodes. Because interventions to improve human health at this stage are downstream of the climate-air quality-agriculture system, interactions among the system components would not be directly relevant to consider unless they feedback to influence anthropogenic drivers.

DATA AND KNOWLEDGE GAPS

A number of data and knowledge gaps currently limit the ability to build a comprehensive human-environment system model that captures the dynamics and interactions discussed above (summarized in Figure 6). *First*, uncertainties in high-resolution climate datasets[25,144]; emissions inventories used for air quality modeling and analysis,[145] including for traditionally hard-to-quantify sectors, such as smaller industrial boilers, street-side waste burning, and at-home electricity generation with diesel generators[146]; and detailed agriculture and land-cover datasets[97] currently limit the accurate representation of anthropogenic drivers. *Second*, key factors for fully understanding and capturing the interactions between the various environmental system components remain uncertain or unrepresented within current earth system models. For instance, the representation of aerosol effects in climate models is a major source of uncertainty[147] and substantial inter-model differences exist in their climate impacts, limiting the understanding of aerosol-climate interactions. Also, limited representation of land-management practices, such as irrigation in climate models, currently limits the understanding of how agricultural activities might affect climate.[97] Furthermore, although a few studies have explored the impacts of extremes on crop yields, limited crop modeling tools incorporate the effects of air pollution and the effects of higher CO_2 and climate extremes on crop yields and nutrient content.[148,149] *Third*, current air pollution mortality and morbidity estimates are commonly calculated with dose-response functions from high-income countries with lower air pollution levels, questioning the validity of those functions in high-pollution environments and different climate conditions. New disease-burden metrics and estimates for South Asia are needed as studies rely on limited data from high-pollution environments,[123,150,151] and, with limitations to data availability and method transparency, exact study replication remains difficult. *Fourth*, cross-validations between empirical and modeling studies remain a challenge due to large variations in inputs, time periods, and health outcome metrics, thereby limiting comparison and reproducibility.

RESEARCH NEEDS TO ASSESS COMPOUND HUMAN HEALTH IMPACTS

To address existing challenges and assess compound health impacts attributable to simultaneous changes in health-relevant environmental hazards, there is a need to develop new tools, collect local health data, and extend current modeling approaches (Figure 6). The gaps discussed above highlight several key foci for future research to support decision making related to climate, air quality, agriculture, and public health in South Asia and other regions.

1. Environmental and human health data collection and accessibility
   More accurate, higher-resolution, and publicly available air pollution, agricultural land use and land management, meteorological, and GHG emissions data will be critical for accurately quantifying the anthropogenic drivers and their environmental impacts. Collection of and open-access to long-term, epidemiological data at high pollution concentrations and region-specific climatologies will allow for longitudinal studies across a variety of geographic and population demographic distributions to accurately evaluate health outcomes in South Asia and other developing regions.
2. Models for linking anthropogenic drivers to human health outcomes
   We recommend investments in developing a comprehensive environment-human health systems model (building on integrated assessment models [IAMs]) incorporating the links between anthropogenic demands, detailed processes connecting components of the climate, air quality, agricultural LULM system, and associated environment-sensitive human health outcomes (Figure 5). Specifically, this would include a comprehensive earth system model coupled with a dynamic vegetation model, linked to crop models and health impact models (dose-response functions). This requires improved dose-response functions to link environmental and nutrition-related factors to human health impacts and improvements in representing aerosols processes, crops, cropping calendars, and agricultural practices.[35,69] Furthermore, crop model development to simulate missing effects (e.g., O_3 damage, diffuse radiation) and tissue nutrient content will enable assessments of combined impacts on food quality and quantity. Region-specific dose-response functions will better capture the local human health impacts from climate and air pollution exposure, enabling more accurate estimates of future health hazards.
3. Simulations of future climate and pollution trajectories
   Simulations with different future anthropogenic emissions trajectories will help quantify the range of potential environmental changes and human health outcomes associated with policies that could influence emissions trajectories. Harmonizing model inputs and health outcome metrics will facilitate more comprehensive cross-comparison studies.[152] A comprehensive systems model can help follow emissions of GHGs and air pollutants from the source to a human health outcome of interest, identifying intervention points to minimize impacts at each step. Coupled with an IAM, a systems model can be used to address economic implications of different policy interventions that feed back on anthropogenic drivers and the environmental system. Using IAMs can account for various policy-driven economic changes that subsequently influence energy demand and consumption and ultimately feedback on anthropogenic emissions. Understanding pathways can help prioritize interventions that are both cost-effective and beneficial to environmental and human health.
   These resources and detailed datasets will provide the tools necessary to build a comprehensive representation of the human-environment system and lay the groundwork for large interdisciplinary collaborations to address critical research questions about the compounding health impacts of human activities. Highly resolved tools are needed to resolve the system impacts on different populations and geographic areas, providing a stronger scientific foundation to support humane state and national policies. However, this systems lens could be immediately applied for priority research areas, despite uncertainties, to inform urgently needed policies to address mounting environment and health challenges. For example, it can be applied to characterizing the overall air quality, climate, and food-related human health consequences of different projected socio-economic trajectories over South Asia[35,153] using outputs from CMIP6 scenario simulations with crop models and health impact models. Given the urgency of the groundwater depletion issue in India,[100,138] this framework could also help identify the overall environmental and health consequences of relevant policies that may alter the timing, extent, and amount of irrigation. Furthermore, the acuteness of air quality and health concerns over the region needs such an approach for evaluating the climate, agriculture, and health implications of year-round and

seasonally elevated pollution conditions, for instance due to agricultural waste burning, and assessing the unintended consequences of potential interventions. Coupled chemistry-climate simulations under scenarios of different land-management practices could provide the inputs for crop and health impact models to assess the co-benefits and trade-offs of such interventions.

CONCLUDING REMARKS

Evidence drawn from South Asia demonstrates a critical need to take a human-environment systems approach to better characterize the collective public health risks associated with a changing environmental system and identify co-benefits and trade-offs of human decisions. Using a human-environment systems lens, we have (1) highlighted key interactions within the environmental system; (2) summarized key pathways by which anthropogenic activities affect the climate-air quality-agriculture system and how interactions within the system influence multiple environment-sensitive health hazards; (3) discussed the compounding human health impacts of these simultaneously changing hazards in response to changing human activities; and (4) illustrated the ways in which policy interventions targeting one system component can have potential co-benefits or unintended consequences on human health outcomes. Furthermore, this perspective demonstrates realistic opportunities for developing an integrated understanding to support decision making and adaptation planning of countries in the region.

While human health outcomes depend on several socio-economic factors, such as age, income level, gender, access to food and healthcare, health status, and nature of work—which may leave certain groups more exposed, more vulnerable, and less resilient to adverse environmental conditions[154–156], exposure to multiple environment-related health hazards in the region continues to increase. Simultaneous exposure to multiple climate-, air quality-, and nutrition-related health risks reduces the coping capacity of vulnerable populations and poses compounding health risks. Our proposed systems lens motivates the need for interdisciplinary scientific efforts to more accurately quantify the changing risk of multiple health-related environmental hazards. Without examining the interactions between the human-environmental system and instead considering individual component impacts that affect relevant human health outcomes, the negative impacts of changing environmental conditions could be *under*estimated or overlooked when environmental system interactions are compounding. Although we acknowledge that scientific certainty and information is only part of what goes into decision making and that economic and technical constraints could weigh heavily, this lens can be used by decision makers and stakeholders in developing a suite of complementary interventions that realize multiple co-benefits for human and environmental health or better anticipate their unintended consequences. This approach can also be utilized in supporting the design of research and interventions in regions beyond South Asia that have similar human-environment interactions to develop an integrated region-specific understanding of the pathways by which humans influence and are impacted by climate change, air quality, and agriculture.

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AUTHOR CONTRIBUTIONS

A.K., D.S., K.F.D., A.C., and R.D. designed the research. A.K., D.S., and K.F.D. analyzed data and produced the figures. A.K., D.S., and K.F.D. led the writing, with regular feedback and contributions from all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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