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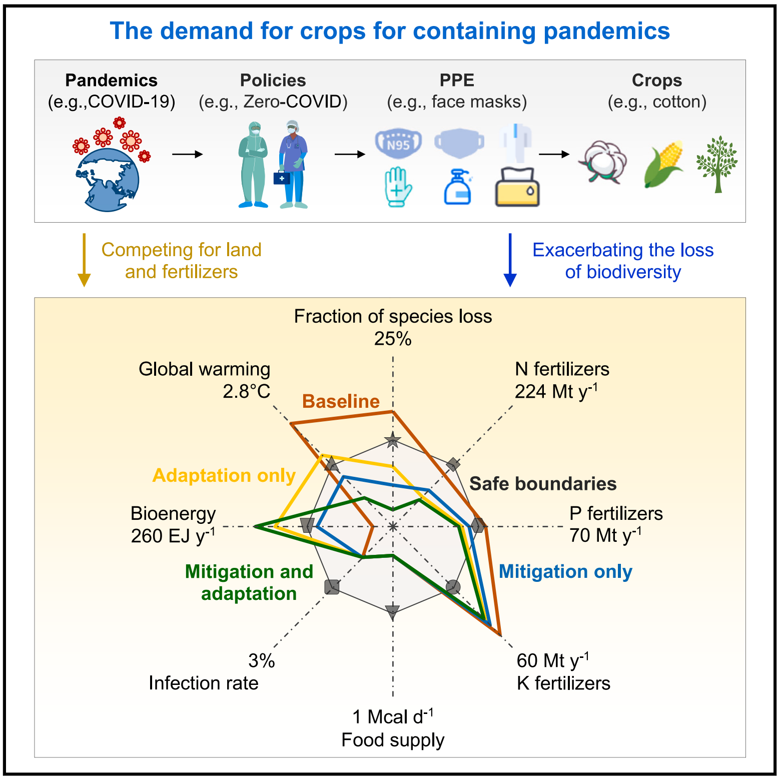
Article

Potential impacts of pandemics on global warming, agricultural production, and biodiversity loss

Graphical abstract



Highlights

- Pandemics increase crop demands in the production of personal protective equipment
- The emerging demand for crops accelerates climate change and biodiversity loss
- Pandemics reduce allowable emissions to meet the Paris climate targets
- Early mitigation and adaptation measures can reduce the impacts of pandemics

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In brief

In light of a rising frequency of infectious diseases, there is an urgent need to understand the ecological impacts of pandemics. In particular, large quantities of crops are consumed in the production of personal protective equipment. We show that the prevalence of pandemics could exacerbate food insecurity and global warming while amplifying biodiversity loss if restrictive policies of containing the pandemics continue over time. We highlight the importance of early mitigation and agricultural adaptation to reduce the impacts of pandemics.

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Potential impacts of pandemics on global warming, agricultural production, and biodiversity loss

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SCIENCE FOR SOCIETY As the risk of infectious diseases persists, the progress toward sustainable development goals is facing emerging challenges. In the containment of pandemics, large quantities of crops are consumed to produce personal protective equipment. Under a rising frequency of infectious diseases, the emerging demand for crops competes for land and fertilizers, leading to expansion of cropland and acceleration of climate change. We explore the impacts of pandemics on global warming, food supply, and biodiversity loss based on the empirical relationship between consumption of personal protective equipment and the rate of infection during the COVID-19 pandemic. The prevalence of pandemics will exacerbate food insecurity and global warming while accelerating biodiversity loss. Our results suggest that the risks of public health, food security, climate change, and ecological integrity may be inter-related, and stronger abatement of greenhouse gas emissions is needed to mitigate the impacts.

SUMMARY

The rising frequency of infectious diseases under climate change poses an emerging threat to environmental and agricultural sustainability by consuming large quantities of materials. The demand for crops to produce personal protective equipment (PPE) competes for land and fertilizers, leads to cropland expansion, and accelerates climate change, but the ecological impacts remain unclear. Here we explore the impacts of pandemics on global warming, agricultural production, and biodiversity loss in an Earth system model by developing relationships between consumption of PPE and the rate of infection during COVID-19. Meeting the demand for PPE would increase production of cotton lint, corn, and natural rubber, which accelerates global warming by 0.2°C with 1.8% additional species losses by 2100. Our results suggest that the risks of public health, food security, climate change, and ecological integrity have been connected to each other, which should be considered when predicting the impacts of future pandemics.

INTRODUCTION

Human society is entering an era with cross-scale environmental risks,[1] where the recovery from COVID-19 advances the climatic agenda and accelerates the transition toward a more sustainable world.[2] The Paris Agreement aims at limiting global warming to <2°C, with efforts to pursue a target of <1.5°C,[3] where exceeding 2°C entails a high risk of irreversible tipping points.[4] The global surface temperature in the last decade has been 1.1°C higher than the average for 1850–1900 and is continuing to increase at a rate of 0.1°C–0.3°C per decade.[5] The latest Emissions Gap Report warned that global warming would be about 2.2°C–2.4°C in 2100 even if all countries met their 2030 Nationally Determined Contributions.[6] Many regions in the world had extreme heat in summer 2022, and the risk of starvation increased in Africa due to an increase in aridity.[7] The Russia war in Ukraine has led to a sharp increase of wheat prices,[8] and the energy crisis increased the risk of reopening coal and oil-fired power plants in many countries.[9] Compensatory expansion and intensification of cropland driven by a higher food demand threatens intact ecosystems,[10] reduces endemic biodiversity,[11] and accelerates the transmission of novel viruses.[12] In particular, agricultural activities were responsible for >25% of the infectious diseases in humans due to deforestation and land-use changes (LUCs) since 1940.[13] The risk of zoonotic diseases surges under an intensification of global travel, trade, and mobility, despite improved sanitation and better access to health care.[14] More than two novel viruses are detected in humans per year, and emerging infectious diseases (EIDs) have caused >6 million deaths since 2000.[15] The prevalence of COVID-19 has temporarily changed the living styles of people under restrictive policies, such as lockdowns and Zero-COVID.[16,17] The pandemic temporarily reduced anthropogenic emissions of greenhouse gases (GHGs) in 2020,[18] but global emissions of carbon dioxide (CO_2) resurged in 2021 during the COVID-19 recovery.[19]

Prominent interactions between the COVID-19 pandemic and climate change have gained attention and discussion since the onset of the pandemic. However, these studies have predominantly focused on investigating isolated local or regional concerns or specific sectors.[20] An essential factor that magnifies the peril of climate change is the potential for intensifying climatic feedback loops, yet not all of these feedback mechanisms are comprehensively considered within climate models.[21] The ecological consequences of medical waste have been noticed,[22] but the potential impacts of increased consumption of personal protective equipment (PPE) (e.g., face masks, hand sanitizers, and gloves) on climate change and biodiversity have yet received little attention. These impacts could be significant, because new diseases such as COVID-19 may likely occur frequently in the future.[23] Face masks, hand sanitizers, and gloves are the most important PPE consumed during the confinement periods of a pandemic and helped to reduce the outbreak of COVID-19.[24] Three million face masks were consumed globally per minute in April 2020,[25] and only a small fraction of them was recycled,[26] likely because recycling can reduce the efficiency of protection.[27] After 2 years of pandemic, COVID-19 vaccination was the most effective way to protect people from serious illness or dying from the virus,[28] and countries eased COVID-19 measures in 2022.[29] The demand for PPE has not decreased despite the lifting of COVID-19 restrictions. China, the largest producer of face masks, exported 148 billion face masks in 2021 and 132 billion face masks in 2022 to other countries, which is ~30-fold higher than the production in China in 2019.[30] China relied on Zero-COVID policies until mid-2022, which maintained a persistent demand for PPE over time.[31] Even if COVID-19 disappears in the coming years, other similar pandemics might become globally prevalent,[14] in which case the source and accessibility of PPE would then become a major concern in future crises of public health.[32]

Crops such as cotton, corn, and natural rubber provide raw materials for the production of face masks, hand sanitizers, and gloves[33] that have the advantage of avoiding plastic pollution because of the use of synthetic compounds from petroleum.[22] For example, the production of a single medical mask requires the use of 12.5 (5–20) g of natural fiber (i.e., cotton) or synthetic fiber (i.e., polypropylene),[34,35] while producing 1 g of polypropylene requires the cracking of 45 (30–60) g of crude oil.[36,37] Food[38] and bioenergy[39,40] from these crops, however, compete for land and fertilizers, and the resultant cropland expansion further increases LUC emissions.[10] The expansion of cropland and global warming both exacerbate the loss of biodiversity.[11,41] Under these circumstances, in a hypothetical extreme scenario where restrictive policies would continue for decades to contain the global prevalence of pandemics such as COVID-19, the emerging demand for PPE materials may produce significant impacts on climate change, food security, and biodiversity loss, which has not yet been considered in policies designed to meet sustainable development goals (SDGs).[8]

Here we use real-world data collected during the COVID-19 lockdowns that reflect potential causal variables (i.e., per-capita gross domestic product [GDP], population density, population-weighted average travel time to a city, rate of vaccination, and indices of overall government response, containment, and health and stringency) to develop linear relationships between the observed per-capita consumption of PPE and the rate of infection of COVID-19. We find that increasing the consumption of PPE is effective in containing pandemics.[42,43] We investigate the impacts of pandemics on bioenergy, fertilizers, public health, food supply, oceanic carbon cycle (OCC), climate change, and ecological integrity into an Earth system model (Figure 1). We show that the impact of pandemics could increase global warming by up to 0.2°C with 1.8% additional global species losses by 2100 when maintenance of restrictive policies such as Zero-COVID continues to 2050. We predict the combined effects of strong measures of phasing out fossil fuels with strategies of adaptation in the agricultural systems on meeting the cross-scale environmental targets toward sustainable development in the Earth system. We show that four adaptive strategies in agricultural systems (i.e., using adaptive cultivars, increasing nitrogen-use efficiency [NUE], improving irrigation efficiency, and optimizing growing seasons) could together mitigate global warming by 0.28°C and reduce global species loss by 1.4% in 2100. Our results underscore the importance of early mitigation and adaptation toward meeting multiple goals of food security, climate change, and biodiversity protection in the presence of adverse pandemics.

RESULTS

Consumption of PPE in the containment of COVID-19

Many factors affect the rate of infection of COVID-19, but measures of confinement and PPE played a central role before vaccination became effective and widely available.[44] We examined the hypothesis that the per-capita consumption of PPE would be correlated with the rate of infection of COVID-19 by collecting data broadly for the production, export, and import of PPE by country in 2020 (experimental procedures; Tables S1 and S2).

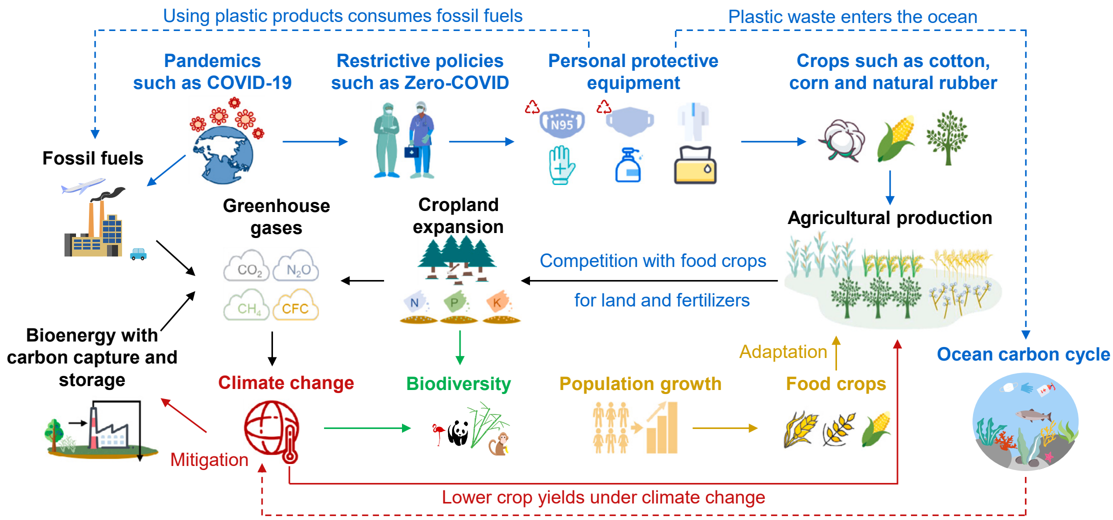

Figure 1. Potential impacts of the consumption of personal protective equipment on energy use, food supply, climate change, and biodiversity loss under global prevalence of pandemics

This illustration demonstrates how the emerging demand for crops in the production of PPE (e.g., face masks, hand sanitizers, and gloves) could accelerate climate change, agricultural production, and biodiversity loss. The green arrow denotes the impacts of cropland expansion and climate warming on biodiversity loss. The brown arrow denotes the impacts of population growth and agricultural adaptation on crop production. The red arrow denotes the feedback of climate change to crop yields. The black arrow denotes the impacts of cropland expansion and fossil-fuel consumption on greenhouse gas emissions. The blue dotted line denotes the potential impacts of pandemic-associated plastics on fossil-fuel consumption. The red dotted line denotes the potential impacts of pandemic-associated plastics on climate change.

First, the per-capita consumption of face masks was negatively correlated with the rate of infection of COVID-19 ($r_{partial}$ = −0.62, p < 0.001, N = 101) (Figure 2A), and the per-capita consumption of nonwoven cloth was positively correlated with the per-capita consumption of face masks ($r_{partial}$ = 0.65, p < 0.001, N = 32) (Figure 2D). Wearing a mask is effective in reducing the transmission of COVID-19[45] when nonwoven cloth is the raw material for face masks, protective clothing, surgical gowns, surgical caps, and wet wipes.[46] The per-capita consumption of nonwoven cloth in our study was less strongly correlated with the rate of infection of COVID-19 ($r_{partial}$ = −0.31, p = 0.14, N = 32) (Figure S1), likely because nonwoven cloth is also used for nonmedical purposes. Second, we observed a linear relationship between the per-capita consumption of hand sanitizers ($r_{partial}$ = 0.32, p = 0.039, N = 43) (Figure 2B) and gloves ($r_{partial}$ = 0.32, p = 0.014, N = 65) (Figure 2C) and the rate of infection of COVID-19 because hand hygiene behavior is positively correlated with the magnitude of COVID-19 outbreaks.[47]

We tested multiple regression models to predict the rate of infection of COVID-19 as a function of per-capita consumption of PPE by considering potential influencing variables, including per-capita GDP, population density, population-weighted average travel time to a city,[48] rate of vaccination, and indices of the overall government response, containment, and health and stringency[49] for 2020 (Table S3). Using a multiple regression model by accounting for the impacts of these influencing variables would decrease the mean squared error by 25%, 20%, and 5% relative to using a simple regression model (the rate of infection of COVID-19 was predicted as a function of per-capita consumption of PPE by ignoring potential confounding variables) for the per-capita consumption of face masks, hand sanitizers, and gloves, respectively (Figure S2). The model incorporating all three PPE variables along with other factors has good performance in prediction (Figure S3), but it cannot be used to predict the demand for each PPE when maintaining a target of the rate of infection of COVID-19. Owing to a lack of data for the consumption of PPE in 2021 and 2022, we assumed that the above relationships from multiple regressions with influencing variables could be used to predict the demand for PPE due to restrictive policies such as Zero-COVID[16,17] under a global prevalence of potential pandemics such as COVID-19 in the future. This assumption was reasonable, because pathogens such as COVID-19 are likely to coexist with humans[23] and because global environmental change and trade are increasing the frequency of new zoonotic diseases.[14] Owing to a lack of long-term data, we are as yet unable to examine the causality between changes in the consumption of PPE and the rate of infection of COVID-19.

Ecological impacts of containing the pandemics

We explored the impacts of an extreme scenario with long-term restrictive policies (such as Zero-COVID) on climate change and ecological integrity under global prevalence of a quasi-permanent pandemic such as COVID-19 and an increasing demand for food (Figure 3). We modified a compact Earth system model (OSCAR)[50] by endogenizing the effects of increasing the demand for food and the production of PPE (e.g., face masks, hand sanitizers, and gloves) from crops (cotton, corn, and natural rubber) (see experimental procedures). We also considered the potential impact of microplastics on the OCC (see experimental procedures). Interactions between climate change and the global C cycle have been constrained by the results of models in Coupled Model Intercomparison Project (CMIP) phase 5 and 6,[51] allowing us to predict the impact of cropland expansion on

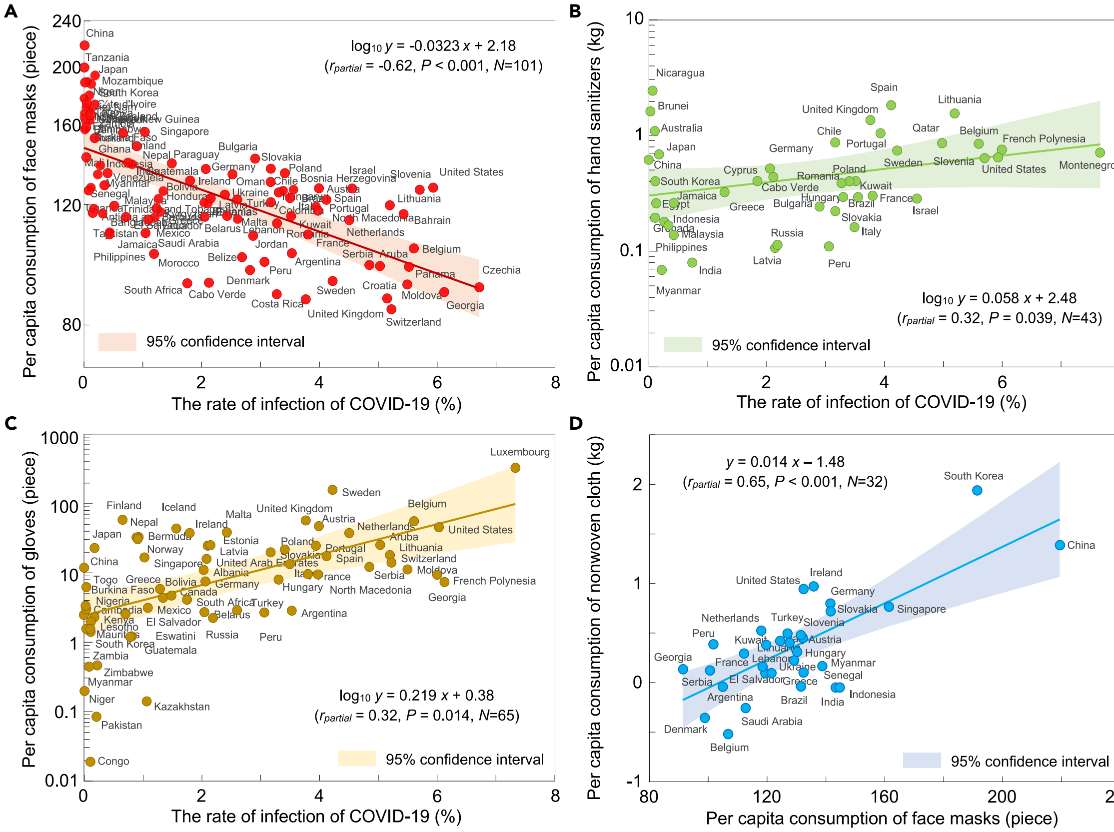

Figure 2. Relationships between the per-capita consumption of PPE and the rate of infection of COVID-19 by country in 2020

(A–C) Correlations between the per-capita consumption of face masks (A), hand sanitizers (B), and gloves (C) and the rate of infection of COVID-19. The data are log transformed to avoid skewed distributions.

(D) Correlation between the per-capita consumption of nonwoven cloth and the per-capita consumption of face masks in 32 countries. The partial correlation coefficient ($r_{partial}$) is estimated by accounting for the influencing variables, including per-capita GDP, population density, population-weighted average travel time to a city, rate of vaccination, and indices of overall government response, containment, and health and stringency.

climate change. Running Monte Carlo simulations of the modified OSCAR model with the impact of restrictive policies on pandemics allowed our results to be representative of the CMIP ensembles by combining uncertainties in the prediction of the demand for PPE and the loss of biodiversity[11,41] with uncertainties in the C cycle and climate change[50] (see experimental procedures).

We projected our modeling in three scenarios of initiating strong mitigation of GHG emissions in 2030, 2040, and 2050, at which point agricultural residues are used as feedstocks for bioenergy with C capture and storage (BECCS),[40] fossil-fuel CO_2 emissions shift from the SSP3-7.0 scenario to the SSP2-4.5 scenario,[5] and total methane (CH_4) and nitrous oxide (N_2O) emissions shift from the SSP3-7.0 scenario to the SSP2-2.6 scenario.[5] We adopted the SSP2-2.6 scenario for CH_4 and N_2O emissions, because high emissions of CH_4 and N_2O in the SSP2-4.5 scenario hinder reaching a 2°C target in 2100.[52] Fossil-fuel CO_2 emissions decreased by 7% due to COVID-19 in 2020,[18] but the impact ended in 2022 after the economy reopened.[19] We assumed that the prevalence of COVID-19-like pandemics would end in 2050, but we performed sensitivity experiments where the prevalence is assumed to end in 2030 or 2100 (Figures 3A and 3B). The production of cotton, corn, and natural rubber met a target of the per-capita consumption of PPE for a rate of infection during 2030–2050 that varied from 0% to 6% by country (Figure 2) under population growth. For food demand, the production of rice, corn, and wheat met a target of global average daily per-capita caloric intake (GCI) (1.5 or 2 Mcal day^{-1}) during 2050–2100 under population growth. Lower crop yields under a warming climate reduce the potential of BECCS and increase the demand for land and fertilizers to produce the same amount of crops.[39,53] Propylene can be used to produce PPE,[54] so we performed sensitivity experiments using propylene rather than crops to produce PPE (Figures 3A and 3B), where GHGs were emitted in the production of propylene (see supplemental methods). Given the impact of population growth on food systems,[55] our central case adopted the growth of the population (to 12 billion in 2100) in the SSP3-7.0 scenario,[5] but we performed sensitivity experiments with faster or slower growths (15 or 7 billion in 2100, respectively).[56] When necessary to meet the demand, marginal lands and forests can be converted to cropland to meet the additional demand for crops,[57] where the production and application of nitrogen (N), phosphorus (P), and potassium (K) fertilizers lead to additional GHG emissions.[58]

Global production of cotton lint, corn, and natural rubber in our central case would increase from averages of 25, 1,131 and 13.7

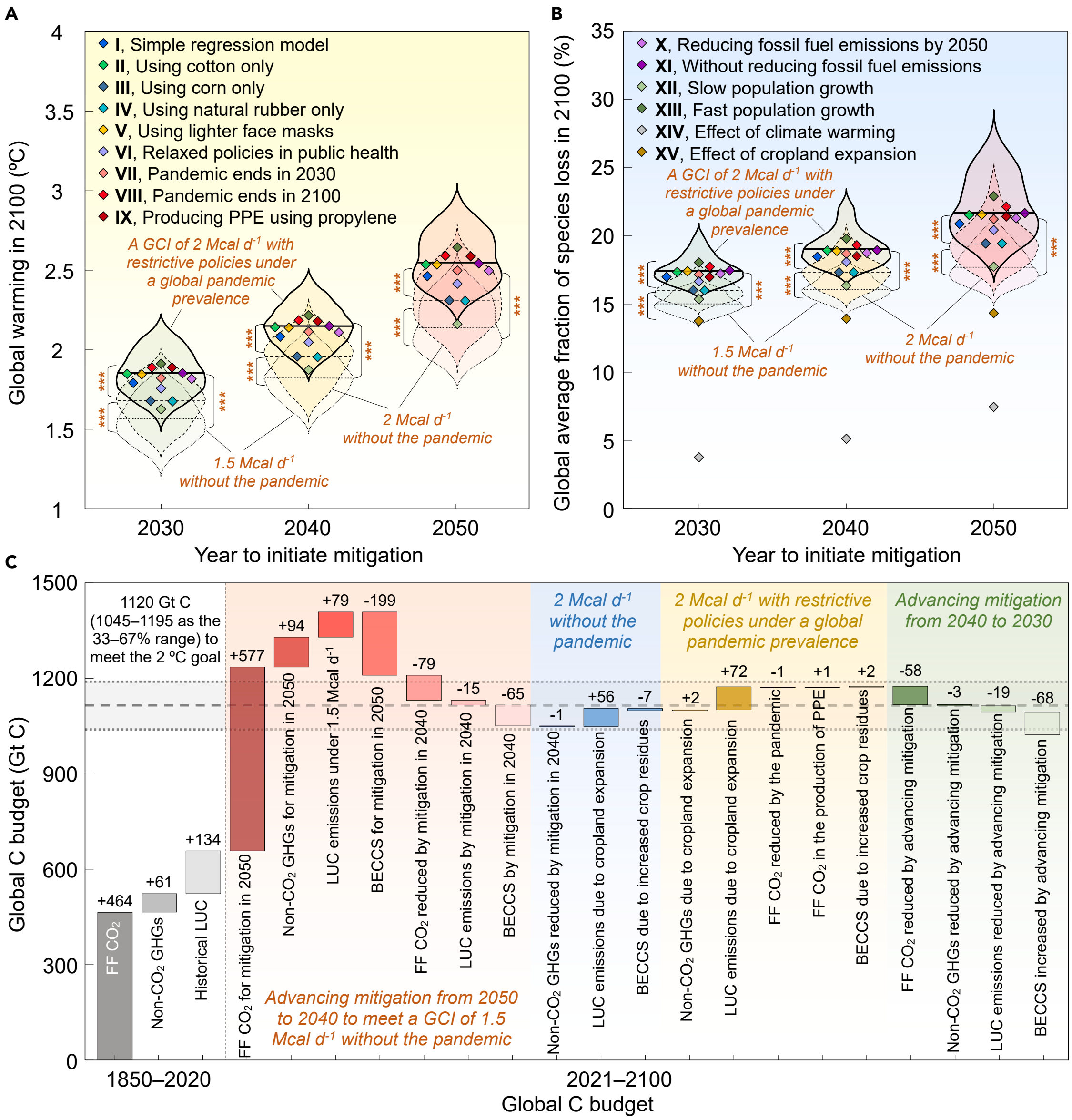

Figure 3. Global warming and biodiversity loss under the hypothetical global prevalence of COVID-19-like pandemics until 2050

(A and B) (A) Global warming and (B) the global average fraction of species loss in 2100 relative to 1850–1900 when mitigation is initiated by 2030, 2040, and 2050. Global average daily per-capita caloric intake (GCI) increases from 1.5 to 2 Mcal day^{-1} by increasing the production of rice, corn, and wheat. Achieving a rate of infection of 0% for COVID-19-like pandemics during 2021–2050 under restrictive policies increases the production of cotton, corn, and natural rubber. The following sensitivities are examined: using simple regression (I), considering the demand for cotton (II), corn (III), and natural rubber (IV) alone, using lighter face masks (5 g pce^{-1}) (V), adopting relaxed policies leading to a high rate of infection of 6% (VI), ending pandemics in 2030 (VII) or 2100 (VIII), producing PPE using synthetic compounds (propylene) (IX), reducing fossil-fuel emissions by 2050 (X), neglecting the impact of pandemics on reducing fossil-fuel emissions (XI), adopting scenarios with slow (XII) or fast (XIII) population growth, and considering the effect of warming (XIV) or the loss of forest (XV) alone for the loss of biodiversity. The difference between two neighboring violin plots is examined (***$p < 0.001$).

(C) Global carbon (C) budget when advancing strong mitigation from 2050 to 2030, increasing GCI from 1.5 to 2 Mcal day^{-1} and adopting restrictive policies to achieve a rate of infection of 0%. The cascading bars represent a decomposition of the global C budget into fossil fuel (FF), land-use change (LUC), and emissions of non-CO_2 greenhouse gases (GHGs). Estimated historical GHG emissions and allowable emissions for meeting the 2°C goal are taken from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.[5]

Mt y^{-1} for 2017–2019[59] to 83.6, 1,190 and 14.04 Mt y^{-1} in 2030 (Figure S5), respectively, in response to adopting and maintaining restrictive policies to achieve a rate of infection of 0% for a permanent COVID-19-like pandemic. Increasing GCI from 1.5 to 2 Mcal day^{-1} increased the cumulative production of rice, corn, and wheat from 88.7 to 94 Gt during 2021–2050 (Figure S6). For other crops, the area of cropland was maintained at the same level as in 2020, but the total production decreased due to the detrimental effects of climate change on yields[39] (Figure S7). To meet a demand for sufficient food (GCI of 2.0 Mcal day^{-1})

under maintained restrictive policies (infection rate of 0%), global warming in 2100 would increase temperatures by 1.9°C (1.6°C–2.1°C as 90% uncertainty hereafter), 2.2°C (1.9°C–2.4°C), and 2.5°C (2.1°C–3.2°C), with global losses of species of 17.4% (16.1%–20.0%), 19.0 (17.5%–22.3%), and 21.6% (19.2%–26.7%) when mitigation is initiated in 2030, 2040, and 2050, respectively. In the scenarios of achieving a GCI of 2.0 Mcal day^{-1} but without the impact of pandemics, global warming would increase temperatures by 1.7°C (1.5°C–1.9°C), 2.0°C (1.7°C–2.2°C), and 2.3°C (2.0°C–2.6°C), with global losses of species of 16.0% (15.0%–17.4%), 17.3% (15.7%–19.9%), and 19.4% (17.0%–23.9%) in 2100, respectively. Considering a very low GCI of 1.5 Mcal day^{-1} without pandemics, global warming would increase temperatures by 1.6°C (1.4°C–1.8°C as 90% uncertainty), 1.8°C (1.6°C–2.0°C), and 2.1 (1.9°C–2.4°C), with global losses of species of 15.0% (14.0%–16.4%), 16.1% (14.8%–17.7%), and 17.7% (15.6%–20.7%) in 2100, respectively (Figures 3A and 3B). By considering the impact of pandemics (taking COVID-19 as an example) under a demand for sufficient food (GCI of 2.0 Mcal day^{-1}), strong mitigation should therefore be initiated in 2030 to meet the 2°C goal[3] and to limit the global losses of species to <20%.[60] When mitigation is initiated in 2040, the impacts of the pandemics accompanied by a demand for sufficient food would increase global cumulative CO_2 and non-CO_2 (CH_4 and N_2O, converted to equivalent C) emissions during 1850–2100 from 1,050 to 1,174 Gt C, higher than the allowable emissions of 1,120 Gt C required to limit global warming to <2°C in 2100.[5] Further advancing the time of mitigation from 2040 to 2030 would abate an extra 148 Gt C in the energy systems, allowing us to meet the 2°C goal[3] (Figure 3C). Total LUC emissions due to cropland expansion when increasing GCI from 1.5 to 2 Mcal day^{-1} (56 Gt C) and achieving a rate of infection of 0% (72 Gt C) would offset 102% of the emission abatements by reducing the use of fossil fuel (58 Gt C) and deploying BECCS (68 Gt C) when advancing the time of mitigation from 2040 to 2030 (Figure S8).

We further performed sensitivity experiments to examine the impacts of varying assumptions in the modified OSCAR model for meeting a GCI of 2 Mcal day^{-1} and maintaining a rate of infection of 0% (Figures 3A and 3B; Table S4). First, the effect of using simple regression was almost negligible due to the moderate impact of confounding variables on the relationships between PPE and infection (Figure S2). Second, when mitigation is initiated in 2050, global warming in 2100 was 0.04°C lower if pandemics ended in 2030 but 0.05°C higher if pandemics ended in 2100 relative to our central case, because the marginal lands and forests converted to cropland cannot be easily recovered in a short time.[10] Third, with respect to the same central case, global warming in 2100 would be only 0.01°C lower if we used lighter face masks (5 rather than 12.5 g pce^{-1}), because >50% of the cotton is consumed in producing protective clothing, surgical gowns, surgical caps, and wet wipes.[46] Fourth, global warming would be 0.13°C lower if the per-capita consumption of PPE (mainly face masks and nonwoven cloth) was reduced by ending containment, which would lead to a high rate of infection of 6% for COVID-19-like diseases. Fifth, global warming would be 0.002°C higher if the pandemic did not temporarily reduce CO_2 emissions from fossil fuels during 2020–2021[18] and would be 0.05°C lower if the pandemic reduced CO_2 emissions from fossil fuels during 2020–2050 but would be 0.10°C higher if the population grows more rapidly[56] or would be 0.40°C lower if the population grows more slowly[56] than in the SSP3-7.0 scenario[5] (Figure 3A). In addition, the sensitivities of the loss of biodiversity are shown in Figure 3B. The impact of the global loss of biodiversity was larger than warming for cropland expansion, but the effect of warming doubled if the onset of mitigation was delayed from 2030 to 2050. Alternatively, using synthetic materials (propylene) rather than crops to produce PPE would increase global warming by 0.03°C due to CO_2 emissions from the production of propylene, but 0.5% of the global loss of species could be avoided by reducing the area of cropland expansion (see the individual effects of cropland expansion and climate warming on the loss of biodiversity in Figure S9).

Combined effects of pandemics and food demand

We explored how policies for achieving different rates of infection of a permanent pandemics and different targets of food demand could affect global warming and the loss of biodiversity (Figure 4). Under a global prevalence of pandemics, uplifting of containment measures (e.g., uplifting the face mask mandate) would increase the rate of infection, the number of people in hospitals, and the consumption of hand sanitizers and gloves (see the relationships in Figures 2B and 2C), the total impacts of which were simulated using the modified OSCAR model. In the case of a low GCI (1.5 Mcal day^{-1}) and a high rate of infection (6%), global warming could be limited to <2°C, with the global average fraction of species loss <20% in 2100 if mitigation was initiated in 2040. If we considered the impacts of increasing food requirements (GCI increasing from 1.5 to 2 Mcal day^{-1}) and keeping restrictive policies for containment (reducing the rate of infection from 6% to 0%), meeting the targets of global warming <2°C and the loss of biodiversity within 20% would require initiating mitigation in 2030. In particular, the sensitivities of global warming and the loss of biodiversity to the demand for crops would increase for meeting a target of a higher GCI or a lower rate of infection when mitigation was delayed, mainly due to the feedback of climate change on agricultural production.[39] For example, an additional 17.6 Mha of cropland would be required in the case of a GCI of 2 Mcal day^{-1} and a rate of infection of 0% if the onset of ambitious mitigation was delayed from 2030 to 2050, because producing the same amounts of crops would require more land and fertilizers due to the lower crop yields under a warming climate.[53] As a result, increasing GCI from 1.5 to 2 Mcal day^{-1} and reducing the rate of infection of COVID-19-like pandemics from 6% to 0% would increase global warming in 2100 by 0.20°C (from 1.65°C to 1.85°C), 0.24°C (from 1.91°C to 2.15°C), and 0.31°C (from 2.23°C to 2.54°C) and increase the global average fraction of species loss by 1.8% (from 15.6% to 17.4%), 2.2% (from 16.8% to 19.0%), and 3.0% (from 18.6% to 21.6%) if mitigation was initiated in 2030 (Figures 4A and 4D), 2040 (Figures 4B and 4E), and 2050 (Figures 4C and 4F), respectively. Our model identified these feedbacks on climate change by coupling agricultural production with climate change. In a hypothetical scenario without considering the feedback of climate change on crop yields by maintaining crop yields at the 2020 levels, global warming in 2100 would be 0.2°C lower when meeting the same targets of the rate of infection and the demand for food. As a result, the

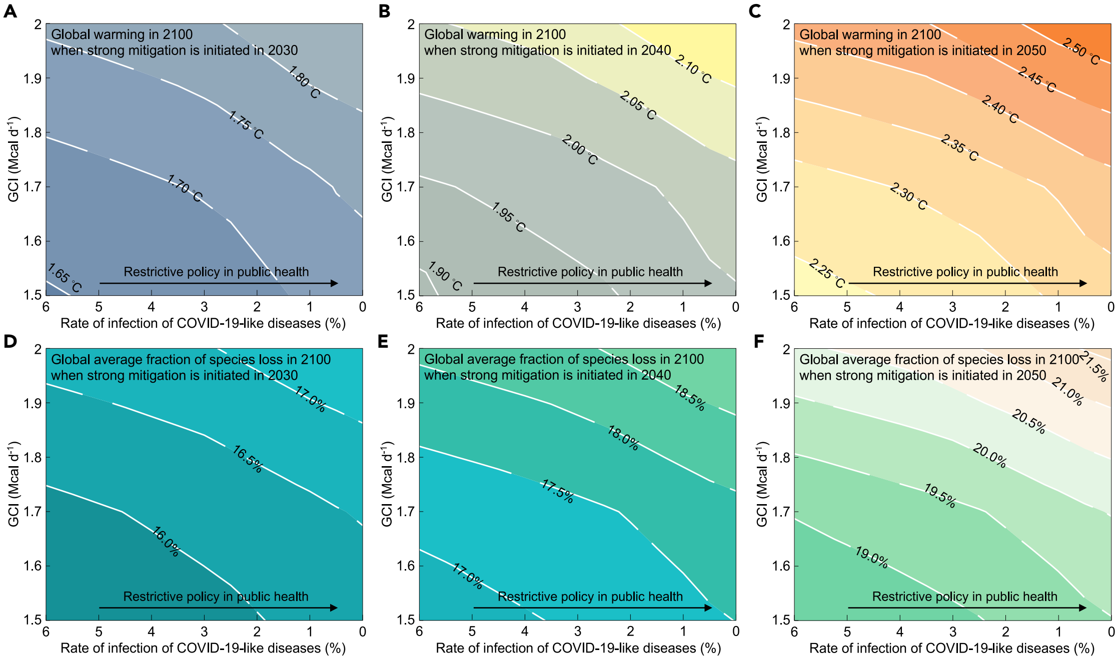

Figure 4. Combined effects of containing the pandemics and increasing food supply on global warming and the loss of biodiversity under a global prevalence of COVID-19-like pandemics by 2050

Global warming (A–C) and the global average fraction of species loss (D–F) in 2100 relative to 1850–1900 when strong mitigation is initiated in 2030 (A and D), 2040 (B and E), and 2050 (C and F). Global average daily per-capita caloric intake (GCI) increases from 1.5 to 2 Mcal day^{-1} by increasing the production of rice, corn, and wheat during 2021–2100. Cotton, corn, and natural rubber are used to produce PPE under restrictive policies such as Zero-COVID, which reduces the rate of infection from 6% to 0% for COVID-19-like diseases during 2021–2050.

responses of global warming and the loss of biodiversity to changes in GCI and to the rate of infection of a permanent pandemic in this scenario would be almost insensitive to the time of mitigation (Figure S10). Our results, therefore, provide a better understanding of the connections among climate, food, and health relative to various previous studies,[10,11,13,38,60–62] which will trigger strong feedback in agricultural systems that could accelerate global warming and exacerbate the loss of biodiversity due to maintaining restrictive policies[16,17] for decades to contain the global prevalence of COVID-19-like pandemics.

Allowable GHG emissions

We next explored how restrictive policies (such as Zero-COVID)[16,17] could affect allowable GHG emissions for meeting the targets of global warming and the loss of biodiversity. We found an increasing rate of global warming and losses of biodiversity due to cumulative GHG emissions when mitigation was delayed to after 2050 by considering the impacts of restrictive policies under a higher food demand (Figure 5). For example, the response of the global average fraction of species loss to an increase in cumulative GHG emissions from 1,000 to 1,100 Gt C would be +0.9% higher under a GCI of 1.5 Mcal day^{-1} without pandemics (green solid line in Figure 5B), which increased to +2.1% when GCI increased from 1.5 to 2 Mcal day^{-1} (blue solid line in Figure 5B), and to +4.2% by considering the impact of restrictive policies to maintain a rate of infection of 0% in COVID-19-like diseases (red solid line in Figure 5B). In contrast, the response was only +0.8% in a hypothetical scenario that did not consider the feedback of climate change on crop yields by maintaining crop yields at the 2020 levels or was +1.3% based on the projection of climate change[5] and the loss of biodiversity.[11,41] We, therefore, anticipated a faster warming and a larger loss of biodiversity than previously thought in response to delays in mitigation by coupling the connections among food, climate, and ecology with the impacts of continuous restrictive policies to contain hypothetical pandemics by 2050.

Effects of early mitigation and adaptation

We explored the impacts of restrictive policies (such as Zero-COVID)[16,17] on the cross-scale environmental risks, including public health, food security, bioenergy, global warming, the loss of biodiversity, and the demand for N, P, and K fertilizers in 2100 under a global prevalence of COVID-19-like pandemics to 2050 (Figure 6). Initiating strong mitigation in 2030 would limit global warming within 2°C,[3] limit global species loss[60] to <20%, allow to reach a GCI[63] of 2 Mcal day^{-1}, achieve a rate of infection of 0%, limit the use of N fertilizers[64] to <202 Mt year^{-1}, limit the use of P fertilizers[65] to <61 Mt year^{-1}, and keep the demand for bioenergy within the potential[66] of 200 EJ year^{-1}, but lead to a large gap in the demand for K fertilizers for crops relative to an availability[63] of 50 Mt year^{-1} (Figure S11). Advancing the time of mitigation from 2050 to 2030 would increase the need for bioenergy and C capture and storage from 154.1 to 192.8 EJ year^{-1} during 2030–2100, and the demand for N, P, and K fertilizers would decrease from 198.6, 61.7, and 57.6 Mt year^{-1} to 193.0, 60.0, and 56.0 Mt year^{-1}, respectively. When achieving a rate

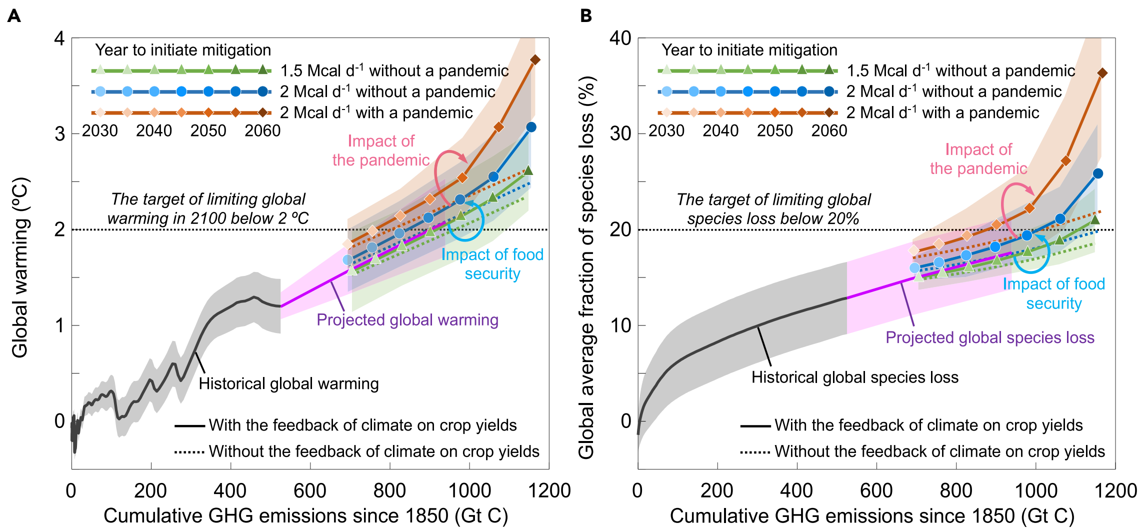

Figure 5. Dependencies of global warming and biodiversity loss on cumulative GHG emissions under a global prevalence of COVID-19-like pandemics by 2050

(A) Global warming and (B) the global average fraction of species loss in 2100 relative to 1850–1900 when the time of mitigation is varied from 2030 to 2060. Increasing the production of rice, corn, and wheat during 2021–2100 increases the global average daily per-capita caloric intake (GCI) from 1.5 to 2 Mcal day^{-1}. Restrictive policies such as Zero-COVID achieving a rate of infection of 0% increases the production of cotton, corn, and natural rubber during 2021–2050. Historical (black lines) and projected (purple lines) global warming in the SSP3-7.0 scenario from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[5] and estimated global species loss[11,41] are shown for comparison. Global warming and the loss of biodiversity without the feedback of climate change on crop yields by maintaining crop yields at the 2020 levels (dashed lines) are shown for comparison with our central case (solid lines) by considering the feedback of climate change on crop yields. The shaded areas denote the 90% uncertainties from Monte Carlo simulations of the modified OSCAR model.

of infection of 0% for COVID-19-like diseases, the use of synthetic compounds (propylene) rather than crops to produce PPE would decrease global species loss and reduce the gap of K fertilizers but would increase global warming due to additional emissions from fossil fuels (Figure S12), very likely leading to additional plastic contamination in soil and water when the waste of the products entered the environment.[20] We are not yet able to predict the impact of plastic contamination because of our limited understanding of the complex marine-atmosphere cycle of plastics,[67] which deserves further attention.

Considering the impact of a resurgence of pandemics reinforces the importance of strategies of adaptation in the next decade for meeting multiple environmental targets. Given the stricter target of 1.5°C warming in the Paris Agreement,[3] we explored the effects of adaptation in agricultural systems using four strategies: adaptive cultivars (ACVs),[68] increasing NUE,[69] improving irrigation efficiency (IRE),[68] and optimizing growing seasons (PGS)[39] (Figures 6A–6C). If strong mitigation is initiated in 2030, these strategies would together mitigate global warming in 2100 by up to 0.28°C (1.85°C–1.57°C) in 2100, decrease global species loss by 1.4% in 2100, and moderately reduce the gap of K fertilizers but increase the demand for bioenergy by 43 EJ $year^{-1}$. Of these strategies, NUE and PGS were the most effective in alleviating N limitation in cropland[69] and counteracting the damage of climate change to crop yields.[53] Both early mitigative and adaptive strategies would nevertheless be needed to reduce the trade-offs among health, food, and ecology.[11] For example, a combination of early mitigation in 2040 and the four adaptive strategies would save up to 10% of the species in foci of losses of biodiversity such as India and Bangladesh (Figures 6D–6G). We identified 142, 96, and 64 countries with fractions of species loss exceeding 10%, 20%, and 30% when mitigation was initiated in 2050 without adaptation, the number of which decreased to 130, 87, and 56 by advancing mitigation from 2050 to 2040 and to 123, 78, and 54 by further adopting adaptive strategies. The losses of species were highest in tropical regions, but the sensitivity of biodiversity loss to the timing of mitigation and adaptation was highest in temperate regions at latitudes 30–60°N, which contributed >50% to global crop production (Figure 6H).

DISCUSSION

Our study takes COVID-19 as an example to demonstrate a potential impact of the increasing consumption of materials for containing pandemics on food supply, climate change, and ecological integrity. First, the emerging demand for materials (crops or synthetic materials) to produce PPE will increase GHG emissions (LUC or the consumption of fossil fuel), which will accelerate global warming and exacerbate biodiversity loss. Second, the introduction of pandemic-associated plastics into the oceans could affect the OCC. Third, the negative effects of climate change on crop yields could amplify the ecological impacts of pandemics by requiring more cropland and consuming more fertilizers to produce crops.[39,53] Fourth, the expansion of cropland, global warming, and intensified agricultural activities could probably further increase the frequency of re-emerging and emerging infectious disease outbreaks.[13–15] Under this circumstance, a rising frequency of infectious diseases might further increase the consumption of materials for containing the pandemics.[30–32] Our results suggest that global warming could increase by up to 0.2°C with 1.8% additional global species losses by 2100 if

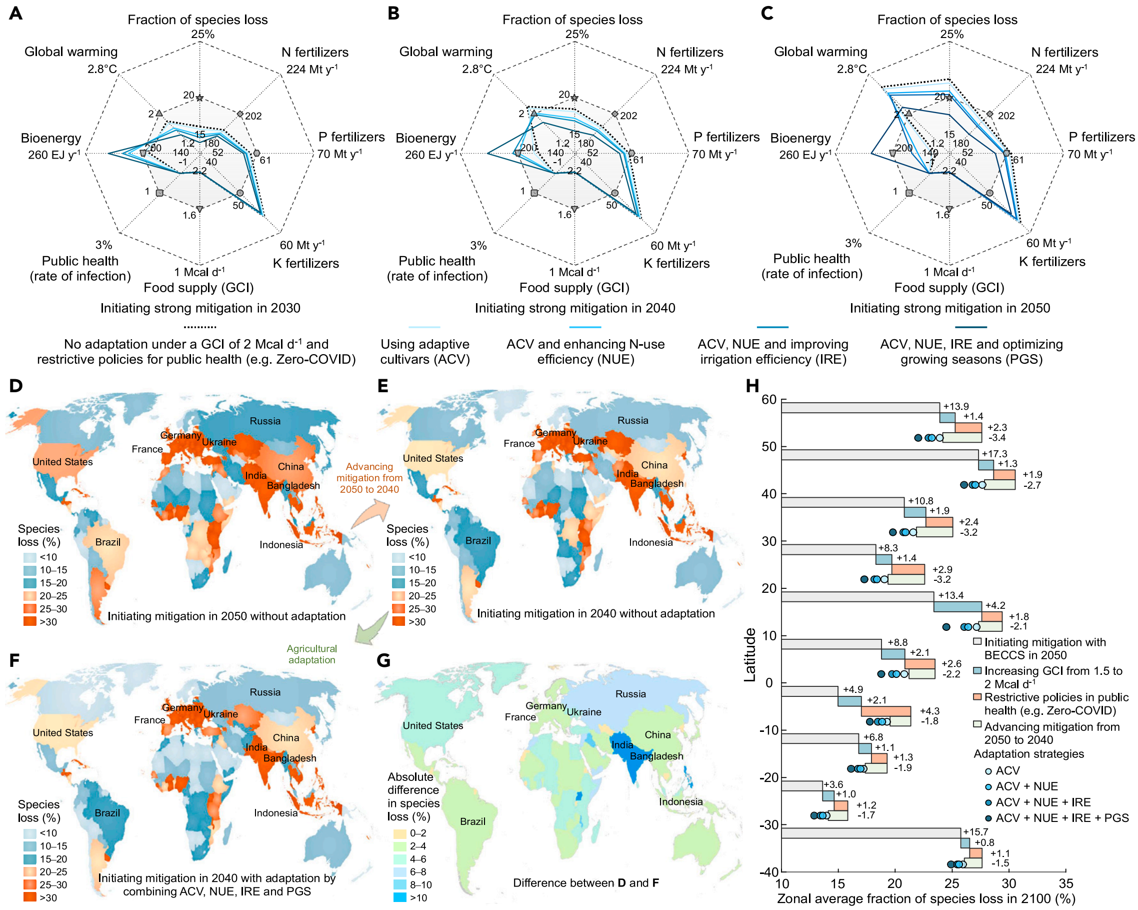

Figure 6. Effects of taking early mitigation and adaptation measures on reducing cross-scale environmental risks under a global prevalence of COVID-19-like pandemics by 2050

(A–C) Global warming in 2100, global average daily per-capita caloric intake (GCI) during 2050–2100, global average bioenergy potential during 2030–2100, global average demand for fertilizers during 2030–2100, global average fraction of species loss in 2100, and rate of infection of COVID-19-like diseases during 2030–2050 when strong mitigation is initiated in 2030 (A), 2040 (B), or 2050 (C). Four adaptive strategies are adopted sequentially: using adaptive cultivars (ACV),[68] increasing N-use efficiency (NUE),[69] improving irrigation efficiency (IRE),[68] and optimizing growing seasons (PGS).[39] We adopt the thresholds 2°C target in the Paris Agreement (triangles),[3] 20% global species losses (pentagrams),[60] nitrogen (N) availability of 202 Mt year^{-1} (diamonds),[64] phosphorus (P) availability of 61 Mt year^{-1} (hexagons),[65] potassium (K) availability of 50 Mt year^{-1} (circles),[63] rate of infection of 0.03% as the average for COVID-19 during 2020–2022 (squares),[70] GCI of 1.6 Mcal day^{-1} (downward triangles),[71] and capacity of bioenergy of 200 EJ year^{-1} (trapezoids).[66]

(D and E) Fraction of species loss in 2100 relative to 1850–1900 under GCI of 2 Mcal day^{-1} and rate of infection of 0% for COVID-19-like diseases when mitigation is initiated in 2050 (D) or 2040 (E).

(F) The same as (E), except for a scenario adopting the four adaptive strategies.

(G) Absolute differences between (D) and (F).

(H) Effects of climate warming (gray bars), food security (blue bars), restrictive policies in pandemics (orange bars), advancing the time of mitigation from 2050 to 2040 (green bars), and adaptation (blue circles) on the zonal average fraction of species loss in 2100.

maintenance of restrictive policies continues to 2050. Therefore, we propose that the synergies and trade-offs between energy, fertilizers, public health, food supply, climate change, and ecological integrity should be embodied in the framework of risk interconnectivity.[72]

A combination of mitigation and adaptation could reduce the ecological impacts of pandemics. We find that taking strong measures to reduce CO_2 emissions (accelerating phasing out of fossil fuel and using agricultural waste to develop negative emission technologies) before 2040 combined with strategies of adaptation in agricultural systems (ACV[68], NUE[69], IRE[68] and PGS[39]) could achieve a high food supply above 2 Mcal day^{-1}, keep global warming below 2°C, and limit global biodiversity losses to below 20%.

Some caveats in our modeling deserve attention. First, we are unable to consider the combined effects of using different PPE on the infection rate of COVID-19-like pandemics, which requires more epidemiological data to identify the contribution of using individual PPE to reduce to the infection rate. Second, we assume that future pandemics such as COVID-19 are occurring without accommodating the differences in virulence. Our current model cannot predict the occurrence of a specific disease because we do not have the explicit data to predict the frequency of different types of pandemics under climate change.

Third, understanding the impacts of the losses of biodiversity[12] and climate change[62] on the frequency of pandemics such as COVID-19 requires quantitative evidence for the cause(s) of COVID-19.[73] Perturbation of intact ecosystems and reduction of endemic biodiversity are possible causes of an increasing number of EIDs,[12] while an intensification of agricultural activity is a likely cause of zoonotic infectious diseases that have emerged in humans.[13] Fourth, the impacts of pandemics on population growth and investments in developing low-carbon energy remain unclear due to uncertainty in the variants of viruses.[14] The fatality rate is temporarily low for COVID-19 (0.15% as a global estimate[74] and 2.9% for community-dwelling elderly[75]) but is potentially higher for other infectious diseases (e.g., 10.6% for monkeypox[76]). A negative impact of COVID-19 on fertility might decelerate global population growth,[55] whereby a lower population will reduce the burden of food demand on crop production. Lastly, the threat of pathogens might reduce financing for low-carbon energy investments due to an increasing demand for finance by the incumbent fossil-based industries in the pandemic recovery[77] and the need to invest more in healthcare before pandemics emerge.[15]

Human society is entering a post-COVID-19 era where humans will coexist with these pathogens for a long time,[14] so the climatic and ecological impacts of restrictive policies such as Zero-COVID[16,17] should be broadly noted. Climate change is threatening agricultural systems by increasing the frequency of extreme drought and heat[39,52] and creating new zoonotic infectious diseases by increasing cross-species viral transmission.[61] However, funding to climate change research has declined since the pandemic crisis, which requires efforts to upkeep the levels of funding to support research.[78,79] The synergies of food security and public health could create unprecedented burdens on agricultural production,[8] which could in turn affect the land-based mitigative technologies such as BECCS and afforestation.[70] The long-term impacts of pandemics such as COVID-19 should be fully considered in the future projection of climate change.[5] Furthermore, a combination of an early transition from fossil fuels to low-carbon energy with substantial adaptive strategies is urgently needed to mitigate cross-scale environmental risks.[80,81] Public health, food security, ecological integrity, mitigative technology, climate change, and agricultural production should no longer be considered independent but as integrated and interconnected components in social-ecological systems. Facing these crises together and considering the interconnectivity of risks underscore the importance of global joint actions as early as possible to reduce the impacts of pandemics. Our analysis of the relationship between the consumption of PPE and the rate of infection of COVID-19 could offer insights for future containment of EIDs. The results of this study help us understand how policies for containing other pandemics could affect climate change, biodiversity loss, and SDGs.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Rong Wang (rongwang@fudan.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

Additional material is available in supplemental information. Code and data used for our analyses are available on the GitHub repository: https://github.com/rongwang-fudan/OSCAR-COVID-19.

Materials and methods

Epidemiological data

We compiled the data of confirmed daily COVID-19 cases by country in 2020 from the World Health Organization (https://covid19.who.int/table)[82] and the National Health Commission of China (NHC) for China (http://www.nhc.gov.cn/xcs/xxgzbd/gzbd_index.shtml)[83] following the method developed in a previously published study.[44] We calculated the COVID-19 infection rate by country as the number of confirmed COVID-19 infections per 100 people, using the population by country in 2020 provided by the World Bank (https://databank.worldbank.org/).[84]

Consumption of PPE

We estimated the consumption of face masks (M_i) by country for the containment of COVID-19 in 2020 by considering the consumption of face masks in hospitals, non-hospital working places, and the retail & recreation locations, respectively:

$$M_i = h_i \cdot n_h \cdot W_i + e_i \cdot n_w \cdot W_i \cdot \max(m_i, v_i) + o_i \cdot n_r \cdot R_i \cdot \max(m_i, v_i), \quad \text{(Equation 1)}$$

where i is a country; m_i is the fraction of time that people are subject to mask mandate in country i; v_i is the fraction of time that people are voluntarily wearing face masks; h_i, e_i, and o_i are the number of doctors and nurses, employees, and the unemployed in country i, respectively; n_h, n_w, and n_r are daily per-capita consumption of face masks on average for people when they are staying at hospitals ($n_h = 2$), non-hospital working places ($n_w = 1$), and the retail & recreation locations ($n_r = 0.5$) estimated by Worby and Chang,[85] respectively; and W_i and R_i are the change in the number of days on average when people are staying at the working places and retail & recreation locations after the outbreak of COVID-19 in 2020, respectively.

We determined the number of days when a mask mandate is enforced in 2020 (m_i) for 165 countries (https://masks4all.co/what-countries-require-masks-in-public/).[86] We determined the fraction of time when people are voluntary to wear mask (v_i) for 136 countries based on a global survey performed by The University of Maryland Social Data Science Center (https://gisumd.github.io/COVID-19-API-Documentation/).[87] We estimated the change in the number of days on average for people when they are staying at the working places (W_i) and the retail & recreation locations (R_i) based on the daily mobility data for China compiled from the Baidu mobility index (https://qianxi.baidu.com/#/)[88] and the daily mobility data for the other 135 countries compiled from the Google mobility reports (https://www.google.com/covid19/mobility/).[89] We estimated the number of employee (e_i) and unemployed (o_i) for 103 countries based on the labor data compiled from the Global Trading Economics (https://tradingeconomics.com/country-list/employed-persons).[90] We estimated the number of doctors and nurses (h_i) for China using the labor data compiled from the National Bureau of Statistics of China (http://www.stats.gov.cn/tjsj/) and for the other 100 countries using the labor data compiled from the global labor dataset published by the World Health Organization (https://www.who.int/data/gho/data/indicators).[91,92] The parameters h_i, e_i, o_i, W_i, R_i, m_i, and v_i are listed by country in Table S1.

We estimated the consumption of nonwoven cloth, hand sanitizers, and gloves due to the COVID-19 pandemic in 2020 on the basis of the data from production and trade by country:

$$P_{i,p} = D_{i,p} + I_{i,p} - E_{i,p}, \quad \text{(Equation 2)}$$

where i is a country; p is one type of PPE (nonwoven cloth, hand sanitizers, and gloves); and $D_{i,p}$, $I_{i,p}$, and $E_{i,p}$ are the production, import and export of product p. We followed the difference-in-difference method developed by Chen et al.[93] to estimate $D_{i,p}$, $I_{i,p}$, and $E_{i,p}$ from the real-world production, import, and export in 2020 subtracted by the production, import, and export in 2020 that are predicted by applying their linear trends during 2010–2019 without considering the impact of COVID-19.

We compiled the production of nonwoven cloth for China, United States, Germany, India, Turkey, Italy, South Korea, France, Brazil, Indonesia, Saudi

Arabia, Belgium, the Netherlands, Argentina, Denmark, Ukraine, and Ireland, which together contributed 95% to global total nonwoven cloth production (18.76 Mt) in 2020.[94–97] We compiled the production of hand sanitizers for China, Germany, United States, Spain, France, Belgium, Mexico, United Kingdom, Turkey, the Netherlands, Canada, South Korea, Czech, Costa Rica, Guatemala, India, Italy, Argentina, Denmark, and Poland, which together contributed 86% to global total hand sanitizers production (2,769 kt) in 2020.[98–100] We compiled the production of gloves for Malaysia, Thailand, China, and Indonesia, which together contributed 98% to global total production of gloves (726 kt) in 2020.[101–103] We compiled the import and export of nonwoven cloth, hand sanitizers, and gloves following the HS Code for nonwoven cloth (#5603), hand sanitizers (#380894), and gloves (#401511) by country over 2010–2020 from the United Nations Comtrade Database (https://comtrade.un.org/data/).[100] We assumed that the production of nonwoven cloth is zero for countries where the import is twice as large as the export in the trade.[104] We also assumed that the production of hand sanitizers is zero for countries where the import is twice as large as the export in the trade and the per-capita consumption of hand sanitizers is larger than 100 g.[99] Data compiled for the production, import, and export of nonwoven cloth, hand sanitizers, and gloves due to the impact of COVID-19 in 2020 are listed in Table S2.

Demand for crops to produce PPE

We considered the production of face masks by cotton or nonwoven cloth,[105] the production of nonwoven cloth by cotton,[106] the production of hand sanitizers by alcohol,[107] the production of 75% alcohol by corn,[108] and the production of gloves by natural rubber.[109] Cotton is a favorable material for nonwoven cloth,[110] widely used in the production of face masks, protective cloth, surgical gowns, surgical caps, and wet wipes.[46] We also considered that face masks can be produced by cotton lint directly.[105] Finally, we estimated the demand for cotton ($D_{i,cotton}$), corn ($D_{i,corn}$), and natural rubber ($D_{i,rubber}$) based on the demand for PPE as

$$D_{i,cotton} = \left(\frac{M_i \cdot w_{mask} \cdot f_c \cdot \gamma_{cotton}}{r_{mask}} + W_i \cdot \gamma_{cloth} \right) \cdot (1 + \chi_{cotton}) \cdot P_i, \quad \text{(Equation 3)}$$

$$D_{i,corn} = H_i \cdot \gamma_{alcohol} \cdot \gamma_{corn} \cdot (1 + \chi_{corn}) \cdot P_i, \quad \text{(Equation 4)}$$

$$D_{i,rubber} = G_i \cdot w_{glove} \cdot \gamma_{rubber} \cdot (1 + \chi_{rubber}) \cdot P_i, \quad \text{(Equation 5)}$$

where i is a country; P_i is the population; W_i, M_i, H_i, and G_i are per-capita consumption of nonwoven cloth, face masks, hand sanitizers, and gloves, respectively; f_c is the fraction of face masks that are produced by cotton directly without using nonwoven cloth as an intermediate product; r_{mask} is the number of times for a face mask to be reused (5 times)[34,111]; w_{mask} and w_{glove} are the weight of a face mask (12.5 g)[53] and glove (3.5 g),[53] respectively; γ_{cotton} is the ratio of cotton to the weight of face mask (1.08)[112]; γ_{cloth} is the ratio of cotton to the weight of nonwoven cloth (1.08)[112]; $\gamma_{alcohol}$ is the ratio of 75% alcohol to the weight of hand sanitizer by considering a weight fraction of 75% for alcohol in hand sanitizer (0.81)[112]; γ_{rubber} is the ratio of natural rubber to the weight of glove (1.1)[112]; γ_{corn} is the ratio of corn to the weight of alcohol (3.12) as an average of four estimates[113–116]; and χ_{cotton}, χ_{corn}, and χ_{rubber} are the fraction of loss and waste in the harvest, transport, and processing of cotton (74%),[117–119] corn (65%),[117–119] and natural rubber (63%),[117–119] respectively.

China contributed almost half the global production of face masks.[120] In China, 54% of face masks are produced by nonwoven cloth,[121] so we adopted an f_c value of 46% for China and other countries. The per-capita consumption of nonwoven cloth (W_i) (kg capita^{-1} year^{-1}), face masks (M_i) (pieces capita^{-1} year^{-1}), hand sanitizers (H_i) (kg capita^{-1} year^{-1}), and gloves (G_i) (pieces capita^{-1} year^{-1}) are predicted by multiple regression models as a function of the COVID-19 infection rate.

A meta-model calibrated on Earth system models

We used a compact Earth system model (OSCAR v2.2) calibrated on CMIP5 and CMIP6 Earth system models. Although the OSCAR model is not developed as a spatially explicit model, the emissions and key responses of climate to forcing have been well calibrated by region or country.[50] Using outputs from complex Earth system models to calibrate model parameters and applying the observational constraints to overcome some limitations of the model can ensure the quantitative behavior of the OSCAR model in line with CMIP5/6 models or Intergovernmental Panel on Climate Change reports.[122] Therefore, the OSCAR model is appropriate for studying the climate-carbon feedback. In addition, the OSCAR model is highly flexible,[39,50] allowing us to represent the impact of COVID-19-like pandemics on food supply, climate change, and ecological integrity. The OSCAR model has limitations in accurately simulating comprehensive spatial distributions and intricate characteristics of resource systems.[123] These limitations could potentially be addressed by enhancing the model to incorporate the intricate physics of the climate system at a granular process level along with achieving higher spatial resolutions in forthcoming iterations.

We modified this model by accounting for the interactions among agricultural production, LUC, the global C cycle, non-CO_2 greenhouse gases (GHGs), and regional climate warming.[50] This Earth system model has been introduced in a previously published paper,[50] which has been further developed by considering agricultural production in our previously published study.[39] The OSCAR model has been widely used in simulating the interactions between anthropogenic and natural processes under a warming climate (e.g., Gasser et al.[123,124]). For this study, the OSCAR model has been modified to account for the feedback of reduced crop yields to bioenergy with C capture and storage (BECCS) in the mitigation of climate change following the method of Xu et al.[39] The change in the global annual average surface temperature in response to radiative forcings of CO_2, other GHGs, and aerosols is represented by the impulse response function.[125] The regional temperature is scaled by global surface temperature using region-specific regression models calibrated by the comprehensive process-based climate models adopted by CMIP5 and CMIP6.[50] As the major drivers of global climate warming, changes in surface albedo and the effective radiative forcing for CO_2 and non-CO_2 GHGs including CH_4, N_2O, nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), sulfur dioxide (SO_2), ammonia (NH_3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), ozone-depleting substances, stratospheric water vapor, organic carbon (OC), black carbon (BC), sulfate aerosols, primary organic aerosols, nitrate aerosols, and secondary organic aerosols are considered in the OSCAR model by calibrating the OSCAR model to the CMIP5 and CMIP6 models.[50] The oceanic C cycle is represented by a mixed-layer impulse response function,[126] the parameters of which are calibrated by the response of oceanic C sink to atmospheric temperature change in the CMIP5 or CMIP6 models.[124] The terrestrial C cycle is simulated for five biomes, namely bare soil, forest, grassland and shrubland, cropland, and pasture.[50] The transient responses of the global C cycles to changes in annual average atmospheric CO_2 concentration, annual average surface temperature, and annual average precipitation are calibrated by the corresponding responses in the CMIP5 and CMIP6 models,[127] except for crops calibrated by field experiments and statistical models.[39] The terrestrial C cycle for the preindustrial period (1850–1900) is calibrated by the C fluxes predicted by the TRENDY v2 models.[128]

We estimated the impact of a global prevalence of a potential pandemic such as COVID-19 on climate change and ecological integrity by predicting the demand for rice, corn, wheat, cotton, natural rubber, and other crops (barley, sorghum, potato, cassava, sweet potato, soybean, dry bean, chickpea, dry pea, oil palm, rapeseed, coconut, sunflower, groundnuts, jute, flax, sugar beet, sugar cane, apples, and pears) as a function of the rate of infection of diseases under the projected global growth of population. We accounted for the feedback of a warming climate on lower crop yields as well as the increasing demand for land and fertilizers when increasing the amount of crops under a warming climate in different scenarios of emission mitigation.[39] The impact of climate change on crop yields, negative emissions by BECCS, food calories from cereal crops, terrestrial C sink, CO_2 emissions from LUC, GHG emissions from agricultural fertilizers, and life-cycle emissions due to production of PPE by petroleum products are considered in the modified OSCAR model and detailed in supplemental methods.

We considered that strong mitigation is initiated in 2030, 2040, and 2050 to deploy BECCS, shift the path of fossil-fuel CO_2 emissions from the SSP3-7.0 scenario to the SSP2-4.5 scenario,[5] and shift the paths of total CH_4 and N_2O emissions from the SSP3-7.0 scenario to the SSP2-2.6 scenario.[5] Historical CO_2 emissions from fossil-fuel combustion and cement production from 1750 to 2010 were prescribed from the CDIAC dataset.[129] Anthropogenic emissions of CH_4, N_2O, NO_x, CO, VOCs, SO_2, NH_3, 11 HFCs, 8 PFCs, and 16 ozone-depleting substances from 1750 to 2010 were prescribed from the

EDGAR inventory.[130] Anthropogenic and natural emissions of OC and BC from 1750 to 2010 were prescribed from the ACCMIP inventory for energy-related sources[131] and the GFED v3.1 inventory for biomass burning.[132] Global GHG emissions from LUC from 1700 to 2010 were prescribed from the LUH1.1 dataset,[133] while the LUC emissions from 2011 to 2100 were simulated in the OSCAR model endogenously by considering the impact of the projected cropland expansion. The forcing data for anthropogenic emissions of NO_x, CO, VOCs, BC, OC, SO_2, NH_3, 11 HFCs, 8 PFCs, and 16 ozone-depleting substances for years after 2010 were prescribed from the SSP3-7.0 or SSP2-2.6 scenario.[134] Permafrost is an important sink of microplastics[135] from atmospheric deposition, and among its notable sources long-range atmospheric transport and deposition play a crucial role in introducing microplastics into permafrost.[136] The simulation of interactions between permafrost degradation, climate change, and global microplastic cycling within Earth system models is important because it aids in estimating the potential risk of amplifying climatic feedback loops. However, the availability of data supporting these quantitative studies is limited.[137] Therefore, further investigation into the impact of permafrost degradation on plastic cycling under the influence of climate change is warranted in future studies.

Cropland expansion to meet the food demand

We estimated the area of marginal lands and forests that are converted to cropland to meet the demand for crops under the projected global growth of population as a function of crop yields in the modified OSCAR model. We considered the effects of climate warming on reducing crop yields and the potential of negative emissions by BECCS, which uses agricultural residues as the feedstocks of biomass. We followed the method by Xu et al.[39] to estimate the demand for rice, corn, and wheat when increasing the target of global average daily per-capita GCI from 1.5 or 2 Mcal day^{-1} in 2050 (see supplemental methods). We estimated the demand for cotton, corn, and natural rubber to produce PPE when the rate of infection of COVID-19-like diseases is reduced from 6% to 0% during 2030–2050 under global population growth. Our central case adopted the growth of population (i.e., 12 billion in 2100) in the SSP3-7.0 scenario.[5] We performed sensitivity experiments to examine the impact of adopting the growth of global population (i.e., reaching 7 or 15 billion in 2100) projected by the United Nations[55] that is faster or slower than the projected population growth in the SSP3-7.0 scenario.[5] We assumed that the area of cropland for rice, corn, and wheat increases during 2021–2050 at a constant rate in each country to achieve the area of cropland that meets a target of GCI in 2050. We assumed that the area of cropland for cotton, corn, and natural rubber increases during 2021–2030 at a constant rate in each country to achieve the area of cropland to produce the amount of crops that are needed to produce nonwoven cloths, face masks, hand sanitizers, and medical gloves under a rate of infection of COVID-like diseases in 2030. By considering the continuous growth of global population and the declining crop yields under a warming climate, we accounted for that the area of cropland will continue to increase for rice, corn, and wheat to maintain the targeted GCI after 2050, where the demand for PPE will end by 2050 (or 2030 and 2100 in two sensitivity experiments). Based on the projected area of cropland expansion, the change in biome area is predicted:

$$\Delta A_{i,t,b} = \sum_{b1} A_{i,t,b_1\rightarrow b} - \sum_{b2} \Delta A_{i,t,b\rightarrow b_2}, \quad \text{(Equation 6)}$$

where i is a country; t is a year; b is a biome type (i.e., forest, marginal land, and cropland); $A_{i,t,b1\rightarrow b}$ is the area of biome b_1 that is converted to biome b; and $A_{i,t,b\rightarrow b2}$ is the area of biome b that is converted to biome b_2.

Fraction of biodiversity loss

We estimated the fraction of biodiversity loss in each pixel at a spatial resolution of 1° × 1° by combining the effect of climate warming using the method by Urban[41] and the effect of cropland expansion using the method of Kehoe et al.[10]:

$$L_{g,t} = L_{g,0} + \left\{ z\cdot\left[exp\left(w\cdot\Delta T_{g,t}\right) - exp\left(w\cdot\Delta T_{g,0}\right)\right] + \Delta S_g^{b\rightarrow b_1}\right\}\cdot\left(1 - L_{g,0}\right), \quad \text{(Equation 7)}$$

where g is a pixel; t is a year; $L_{g,0}$ is the biodiversity loss in 2020 relative to the preindustrial; $\Delta T_{g,0}$ and $\Delta T_{g,t}$ are the temperature change in 2020 and year t relative to the preindustrial (1850–1900), respectively; z (1.95) and w (0.46) are coefficients in the regression models between biodiversity loss and temperature change that are calibrated by Urban,[41] respectively; and $\Delta S_g{}^{b\rightarrow b1}$ is the fraction of biodiversity loss due to the conversion of land from biome b to biome b_1 (i.e., −1.8% in the conversion of marginal land to cropland and 36.7% in the conversion of forests to cropland).[10,11] We determined the fraction of global biodiversity loss in 2020 (i.e., 1.54% for warming effect and 11.33% for cropland expansion)[11,41] based on regional warming in 2020 from the historical simulation in the modified OSCAR model, the historical LUC from 1850 to 2020,[138] and the spatial patterns of birds,[139] mammals,[140] amphibians,[140] and reptiles[140] in 2020. We derived the area-weighted biodiversity loss for each country using the method of Kehoe et al.,[10] because global distribution of biodiversity abundance is unavailable to us.

Ecological impacts of pandemic-associated plastics

We estimated the impact of pandemic-associated plastics on the OCC by considering that the plastics affect the development and reproduction of marine phytoplankton, zooplankton, fish, and corals when the plastics enter the oceans.[141] We calculated the impact of pandemic-associated plastics on dissolved inorganic C concentration in the surface ocean (Δdic_t) in the OSCAR model based on the plastic-induced growth inhibition of the marine biological pump[50,141]:

$$\Delta dic_t = \frac{\alpha_{sol}}{\alpha_{atm}^{CO_2}}\cdot\frac{h_{mld,0}^{-1}}{A_{ocean}}\cdot\left(1+\frac{\Delta h_{mld,t}}{h_{mld,0}}\right)^{-1}\cdot\Delta C_{surf,t}\cdot\left(1+\mathrm{GIR}_t\right), \quad \text{(Equation 8)}$$

$$\mathrm{GIR}_t = \omega\cdot C_{mic,t}{}^{\varphi}, \quad \text{(Equation 9)}$$

where t is a year; α_{sol} is a conversion factor to calculate the total surface C storage; $\alpha_{atm}^{CO_2}$ is the conversion factor to calculate the atmospheric CO_2 concentration; A_{ocean} is the global area of oceans; $h_{mld,0}$ is the mixed-layer depth in the preindustrial period; $\Delta h_{mld,t}$ is change in the mixed-layer depth relative to the preindustrial level; $\Delta C_{surf,t}$ is change in the oceanic surface C pool relative to the preindustrial level; GIR_t is the growth inhibition rate of microplastics on phytoplankton, zooplankton, fish, and corals (Table S5); $C_{mic,t}$ is the global pandemic-associated microplastic concentrations in the surface ocean; and ω and φ are coefficients determined by fitting the relationships between the measured growth inhibition rate (%) and the microplastics concentration (mg L^{-1}) in the literature (Figure S4).

We adopted the parameters α_{sol}, A_{ocean}, and $h_{mld,0}$ estimated by Joos et al.[126] We calculated $\alpha_{atm}^{CO_2}$ using a method proposed by Prather et al.[142] We calculated $\Delta h_{mld,t}$ as a function of the maximum relative intensity of the stratification and the sensitivity of mixed-layer depth to sea surface temperature change.[50] To determine the coefficients ω and φ, we collected the measured growth inhibition rates of phytoplankton, zooplankton, fish, and corals under different microplastic concentrations (Figure S4) from laboratory-scale experiments (Table S5). We used a power function recommended by previous studies[143] to fit the data of growth inhibition rates. We obtained the global pandemic-associated microplastic concentrations in the surface ocean at a spatial resolution of 2° × 2.5° for the period 2020–2100 from the Nanjing University MITgcm-Plastic model (NJU-MP).[144] According to the NJU-MP model, the consumption of 1 kg of pandemic-associated plastic could generate 0.19 kg of mismanaged plastic waste (MMPW), while 0.3% of the generated MMPW would be released into the oceans and 47.5% of the injected MMPW could be converted to microplastics.[144] In the NJU-MP model, the generated MMPW due to the spread of COVID-19 reached 11 million tons by the end of 2021, while the global average pandemic-associated microplastic concentration in the surface ocean was predicted to reach 4.3 kg km^{-2} in 2021 and 0.14 kg km^{-2} in 2100. We adopted the global average pandemic-associated microplastic concentrations in the surface oceans in 2020 and 2021 from the NJU-MP model[144] and calibrated these results based on the estimations of pandemic-associated MMPW provided by Benson et al.[145] and Yuan et al.[146] to reduce the uncertainty associated with their estimates of pandemic-associated MMPW release. Assuming that the majority of zooplankton and phytoplankton live in the ocean depth between 0 m and 200 m,[147] we predicted the global average pandemic-associated microplastic concentrations in the surface oceans from 2022 to 2100 based on the annual generation of pandemic-associated MMPW when PPE were produced from petroleum products.[148] Since PPE produced from crops can biodegrade within a period of several months,[148] we applied the global average pandemic-associated microplastic concentrations in the surface oceans from 2022 to 2100 from the NJU-MP model by assuming the natural degradation of MMPW.[144] In addition, microplastics may reduce the efficiency of the marine biological pump by increasing the mortality of marine plants and animals,[141] which cannot be considered in our model owing to a lack of data to quantify this relationship. Further research is needed to improve the marine biological pump by modeling its underlying mechanisms comprehensively.

Uncertainty analyses

We estimated the uncertainty in the prediction of global warming and biodiversity loss by running Monte Carlo ensemble simulations 1,000 times in the modified OSCAR model by randomly varying parameters from their uncertainty distributions.[149] These parameters include: (1) anthropogenic emissions of CO_2, CH_4, N_2O, NO_x, CO, VOCs, BC, OC, SO_2, O_3, NH_3, sulfate, nitrate, halogenated compounds, and LUC emissions of CO_2 from different emission datasets[50]; (2) radiative forcings of volcanic aerosols and solar irradiance from different estimates[50]; (3) the oceanic and terrestrial C fluxes, atmospheric photolysis, LUC, wildfires, wetland emissions, tropospheric ozone, stratospheric ozone, nitrate formation, sulfate formation, direct and indirect radiative forcings of aerosols, secondary organic aerosols, changes in surface albedo, ocean acidification, and the feedback of agriculture to climate change using different parameterizations of the OSCAR model[50]; (4) the coefficients in multiple regression models determining the relationships between the demand for PPE and the COVID-19 infection rate (Table S6); (5) the coefficients in regression models determining the relationships between the crop yields and the annual average atmospheric CO_2 concentration, average surface temperature during the growing season, the intensity of N fertilization over croplands and annual average precipitation[39]; and (6) the empirical parameters determining the effects of climate warming and cropland expansion on biodiversity loss (Table S7). We estimated the interquartile ranges and 90% uncertainty ranges from Monte Carlo simulations to indicate uncertainties in global warming, crop production, GCI, and the global average fraction of species loss.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.02.012.

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AUTHOR CONTRIBUTIONS

R.W. led the project, conceived the research, and designed the study. Y.X., X.X., and Y.D. compiled data, performed the research, and prepared graphs. T.G. and S.X. provided tools simulating climate change. P.C., J.P., J.S., J.H.C., X.T., and R.Z. provided tools analyzing the impact of climate change on crop yields. P.C., J.P., J.S., L.W., and J. Chen provided tools analyzing the ecological consequence of climate change and LUC. T.G. and S.X. provided tools analyzing the implications for risk interconnectivity and governance. J. Cao provided tools analyzing the impact of green production. R.W. wrote the first draft of the paper and supplemental information. All authors critically revised successive drafts of the paper and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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