Zhao, Dandan; Liu, Junguo; Sun, Laixiang; Hubacek, Klaus; Pfister, Stephan; Feng, Kuishuang; Zheng, Heran; Peng, Xu; Wang, Daoping; Yang, Hong; Shen, Lei; Lun, Fei; Zhao, Xu; Chen, Bin; Keskinen, Marko; Zhang, Shaohui; Cai, Jialiang; Varis, Olli

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Published in:
Science Bulletin

DOI:
10.1016/j.scib.2024.03.049

Published: 30/08/2024

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Zhao, D., Liu, J., Sun, L., Hubacek, K., Pfister, S., Feng, K., Zheng, H., Peng, X., Wang, D., Yang, H., Shen, L., Lun, F., Zhao, X., Chen, B., Keskinen, M., Zhang, S., Cai, J., & Varis, O. (2024). Water consumption and biodiversity : Responses to global emergency events. *Science Bulletin*, *69*(16), 2632-2646.
https://doi.org/10.1016/j.scib.2024.03.049

Science Bulletin 69 (2024) 2632–2646

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Article

Water consumption and biodiversity: Responses to global emergency events

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ARTICLE INFO

Article history:
Received 19 September 2023
Received in revised form 19 March 2024
Accepted 21 March 2024
Available online 25 March 2024

Keywords:
Global emergency events
Water-biodiversity causal effect
COVID-19
Biodiversity
MRIO-enhanced DPSIR framework
Supply-chain network
High-resolution water consumption dataset
Supply-constrained multi-regional input-output (mixed MRIO) model

ABSTRACT

Given that it was a once-in-a-century emergency event, the confinement measures related to the coronavirus disease 2019 (COVID-19) pandemic caused diverse disruptions and changes in life and work patterns. These changes significantly affected water consumption both during and after the pandemic, with direct and indirect consequences on biodiversity. However, there has been a lack of holistic evaluation of these responses. Here, we propose a novel framework to study the impacts of this unique global emergency event by embedding an environmentally extended supply-constrained global multi-regional input-output model (MRIO) into the drivers-pressure-state-impact-response (DPSIR) framework. This framework allowed us to develop scenarios related to COVID-19 confinement measures to quantify country-sector-specific changes in freshwater consumption and the associated changes in biodiversity for the period of 2020–2025. The results suggest progressively diminishing impacts due to the implementation of COVID-19 vaccines and the socio-economic system's self-adjustment to the new normal. In 2020, the confinement measures were estimated to decrease global water consumption by about 5.7% on average across all scenarios when compared with the baseline level with no confinement measures. Further, such a decrease is estimated to lead to a reduction of around 5% in the related pressure on biodiversity. Given the interdependencies and interactions across global supply chains, even those countries and sectors that were not directly affected by the COVID-19 shocks experienced significant impacts: Our results indicate that the supply chain propagations contributed to 79% of the total estimated decrease in water consumption and 84% of the reduction in biodiversity loss on average. Our study demonstrates that the MRIO-enhanced DSPIR framework can help quantify resource pressures and the resultant environmental impacts across supply chains when facing a global emergency event. Further, we recommend the development of more locally based water conservation measures—to mitigate the effects of trade disruptions—and the explicit inclusion of water resources in post-pandemic recovery schemes. In addition,

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https://doi.org/10.1016/j.scib.2024.03.049

innovations that help conserve natural resources are essential for maintaining environmental gains in the post-pandemic world.

1. Introduction

Humans and ecosystems are deeply intertwined through hydrological and biogeochemical cycles, and this complex adaptive system is accompanied by an interplay between biophysical and social processes [1–3]. The overexploitation of water resources through human activities has progressively affected ecosystems, causing biodiversity loss, habitat degradation, and river alternations [4–6], ultimately threatening the biosphere's integrity around the globe [7,8]. In other words, water-related ecosystems (e.g., wetlands, rivers, and riparian zones) produce specialized biodiversity and serve multiple irreplaceable functions (e.g., supporting, regulating, and provisioning) for humans; however, they are degrading due to socio-economic factors such as drainage systems, urbanization, land conversion, and water pollution [9]. Thus, human water consumption is causing water bodies to dry up and altering the distribution of soil moisture, affecting biodiversity levels in natural systems that vastly rely on water availability [10]. In this regard, the interlinkages between water consumption and biodiversity are widely recognized by academia, the public, and governments [11].

The coronavirus disease 2019 (COVID-19), which was declared as a global pandemic by the WHO in March 2020, has exerted profound and lasting impacts on human society, with different repercussions across countries and continents. Since its initial outbreak, more than 700 million people have been infected, and more than 6.5 million have died of this disease [12]. The effects of this sudden global emergency event were unprecedented, complex, and far-reaching [13]. In many cases, governments implemented a variety of confinement orders and measures, including stay-at-home orders and limiting the movement of people to slow down the contagion of the virus. This engendered restrictions on many societal activities, limited travel, and movement [14], and had both direct and indirect impacts on work and employment—all of which intensively impinged on both the economy and peoples' lives. As one consequence, restrictions in many sectors (e.g., transportation, retail markets and shops, public events, tourism, and restaurants) caused drastic disruptions in supply chains. On the one hand, global supply chain networks allow nations to benefit economically by redistributing their comparative advantages with regard to producing goods and services. On the other hand, globalization also results in amplified effects when an unprecedented event breaks the balance along supply chains. Such disturbances in the human economic system have notable impacts on water resources and biodiversity. For example, there have been hundreds of reports of unusual species-related observations from around the world, elucidating the quick responses of animals to reductions in human presence [15]. The COVID-19 pandemic can be considered to represent a once-in-a-century global crisis, offering a unique opportunity to study its implications for water resources and biodiversity. Until now, only a few studies have assessed the effects of the non-pharmaceutical interventions (which mainly refers to containment measures) of COVID-19 on water and the associated biodiversity [16–19]; certain studies have addressed this topic either for individual countries [20–23] and specific sectors [24] or through qualitative descriptions without data-driven investigations [25–27]. Therefore, this study aims to bridge this knowledge gap by quantifying these impacts in an integrated and systematic manner on a global scale.

The recovery process has offered governments and societies a historical opportunity to accelerate the sustainability transition. The focus of some recovery packages has been on "green" and climate-neutral recovery schemes [28,29] that revolve around decarbonization in energy and transport systems [30]. The corresponding scholarly debates have paid significant attention to the rebound of greenhouse-gas emissions in the post-COVID-19 era [31–34]. However, concrete policies to promote better water-resource management and the associated biodiversity conservation have not been prioritized in the post-pandemic world. Only a few countries have identified nature-related investments in their stimulus actions, with relatively minor funding [35], whereas most countries allocated essentially zero stimulus funds to water or biodiversity even though many of them are facing threats related to water scarcity and biodiversity loss [36]. The lack of an integrated framework and evaluation of the responses in terms of water consumption and the associated biodiversity to the shocks of the COVID-19 pandemic is hindering the inclusion of water resources and biodiversity in governments' stimulus actions. Hence, insufficient attention has been given to the role of water management and the associated biodiversity consequences in the recovery process. To address this vital niche, this study proposes a holistic framework and evaluates the changes in freshwater consumption at the country-sector level in response to COVID-19 confinements and the relevant impact on biodiversity. To this end, we explore ways to prevent the ecological benefits from slipping away once the world returns to normalcy.

To achieve the aforementioned objectives, we embed a supply-constrained global multi-regional input-output (MRIO) model into the framework of drivers, pressure, state, impact, and response (DPSIR; see Fig. 1). The DPSIR framework has been frequently employed by organizations such as the European Environment Agency, Organisation for Economic Co-operation and Development (OECD), Food and Agriculture Organization of the United Nations (FAO), and UN Environment Programme (UNEP) for assessing complex natural-resource issues, e.g., freshwater management [37–39], while the supply-constrained MRIO model has been employed to determine the spillover effect of supply chain disruptions both directly and indirectly. Using this MRIO-enhanced DPSIR framework, we can estimate the impacts of COVID-19 interventions on freshwater consumption at the country and sector level and the resultant changes in biodiversity (fractions of potential species extinctions (PDFs) as proxy) through the spillover effect in supply chains. Our study demonstrates that this framework is capable of not only capturing the direct and indirect effects across global supply chains of an emergency event but also effectively extending the emergency's responses from resource pressures to their environmental consequences. The impacts of the COVID-19 confinements have been assessed for 141 countries over six years (2020–2025) under four scenarios that reflected the levels of confinements and were obtained from different sources during a dynamic period. These scenarios were defined at the country-sectoral scale by considering factors such as sectoral lockdown levels, government stringency index, work-from-home capability, immunity level, and medical intensive care unit (ICU) occupation. Detailed

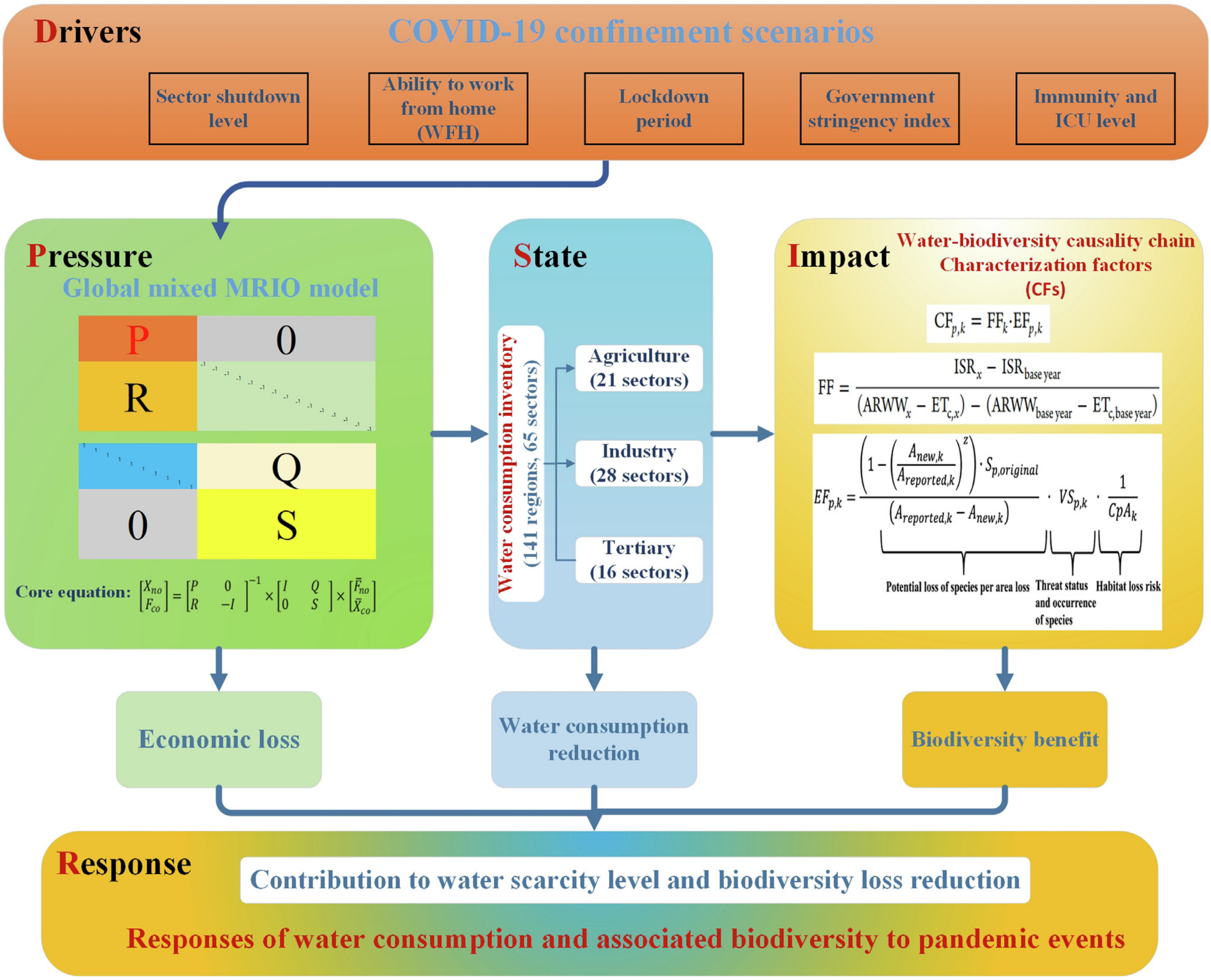

Fig. 1. Flowchart of our evaluation within the MRIO-enhanced DPSIR framework.

information about this aspect can be found in Table S1 (online) and the Methods and materials section. These 141 countries contributed to more than 90% of the global GDP and freshwater consumption in 2020. The difference in the assessment results between a scenario and the baseline quantifies the effect of the COVID-19 confinements on water consumption and the associated changes in biodiversity.

2. Methods and materials

2.1. Supply-constrained global multi-regional input-output (Mixed MRIO) model driven by COVID-19 confinements

Two main approaches have been used to evaluate the economic consequences of COVID-19: Computational general equilibrium (CGE) modeling and input-output (IO) analysis [40,41]. Both these approaches are widely popular in the context of disaster impact assessment due to their capability to quantify the interdependencies between regions and sectors. The neo-classical CGE approach assumes that price adjustments will push economic markets to reach equilibrium. This assumption usually overestimates the flexibility of economic systems in a post-disaster situation, especially when considering sudden shocks [42]. By contrast, the IO-based impact model has comparative advantages regarding quantifying such disequilibrium shortfalls originating from the supply and demand sides given that not all consumers or producers can adjust accordingly in the short or medium term. Thus, IO-based models are more suitable for capturing the influences of sudden shocks on the economy. However, the standard IO model (see Eq. (1)) assumes that the economy will adjust to changes in spending patterns or, in other words, that final consumption or demand will drive production activities in all sectors. This means that supply is assumed to be fully elastic in all production activities, and the changes in production outputs and incomes at the region-sectoral level are determined by changes in final demand. However, for the COVID-19 pandemic, some supply sectors that are constrained by COVID-19 interventions will not automatically and proportionally follow the changes in final demand. As a result, Eq. (1) would provide unrealistically large multipliers due to a fully elastic supply assumption.

$$\Delta \boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\Delta \boldsymbol{f}. \tag{1}$$

Therefore, a supply-constrained MRIO model is more suitable for our study given that specifying gross outputs in certain region-sectors and final consumption in the remaining region-sectors are strictly exogenous. This approach has advantages with respect to the quantification of the gross economic consequences of the changes in exogenous variables that result from constrained supply, such as shocks caused by earthquakes, flooding, COVID-19 lockdowns, or trade barriers [43,44]. To demonstrate the supply restrictions caused by COVID-19, we provide a hypothetical example with three sectors (1, 2, and 3) in two regions (I and J; see Table S2 online). In this case, products manufactured by each sector can be traded as intermediate or final commodities. Table S2 (online) can be written as a system of linear equations:

$$\begin{bmatrix} X^I \\ X^J \end{bmatrix} = \begin{bmatrix} Z^{II} & Z^{IJ} \\ Z^{JI} & Z^{JJ} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \begin{bmatrix} Y^{II} + Y^{IJ} \\ Y^{JI} + Y^{JJ} \end{bmatrix}, \tag{2}$$

where X^I represents the gross output of Sector r in Region I; the Z matrix represents the intermediate input by Sector r from Regions I and J; Y^{IJ} represents the final consumption/demand of Region J for products from Sector r of Region I.

The technical coefficients are $A^{IJ} = Z^{IJ}\left(\hat{X}^J\right)^{-1}$, and Eq. (2) is rewritten as:

$$\begin{bmatrix} X^I \\ X^J \end{bmatrix} = \begin{bmatrix} A^{II} & A^{IJ} \\ A^{JI} & A^{JJ} \end{bmatrix} \begin{bmatrix} X^I \\ X^J \end{bmatrix} + \begin{bmatrix} Y^I \\ Y^J \end{bmatrix}. \tag{3}$$

Next, rearranging Eq. (3) yields the following:

$$\begin{bmatrix} I - A^{II} & -A^{IJ} \\ -A^{JI} & I - A^{JJ} \end{bmatrix} \begin{bmatrix} X^I \\ X^J \end{bmatrix} = \begin{bmatrix} Y^I \\ Y^J \end{bmatrix}. \tag{4}$$

For the standard MRIO model, Y is regarded as an exogenous variable, while X is considered an endogenous variable. Accordingly, for the example with three sectors and two regions, Eq. (4) can be solved as follows:

$$\begin{bmatrix} x_1^I \\ x_2^I \\ x_3^I \\ x_1^J \\ x_2^J \\ x_3^J \end{bmatrix} = \begin{bmatrix} (1-a_{11}^{II}) & -a_{12}^{II} & -a_{13}^{II} & -a_{11}^{IJ} & -a_{12}^{IJ} & -a_{13}^{IJ} \\ -a_{21}^{II} & (1-a_{22}^{II}) & -a_{23}^{II} & -a_{21}^{IJ} & -a_{22}^{IJ} & -a_{23}^{IJ} \\ -a_{31}^{II} & -a_{32}^{II} & (1-a_{33}^{II}) & -a_{31}^{IJ} & -a_{32}^{IJ} & -a_{33}^{IJ} \\ -a_{11}^{JI} & -a_{12}^{JI} & -a_{13}^{JI} & \left(1-a_{11}^{JJ}\right) & -a_{12}^{JJ} & -a_{13}^{JJ} \\ -a_{21}^{JI} & -a_{22}^{JI} & -a_{23}^{JI} & -a_{21}^{JJ} & \left(1-a_{22}^{JJ}\right) & -a_{23}^{JJ} \\ -a_{31}^{JI} & -a_{32}^{JI} & -a_{33}^{JI} & -a_{31}^{JJ} & -a_{32}^{JJ} & \left(1-a_{33}^{JJ}\right) \end{bmatrix}^{-1} \cdot \begin{bmatrix} y_1^I \\ y_2^I \\ y_3^I \\ y_1^J \\ y_2^J \\ y_3^J \end{bmatrix}. \tag{5}$$

We suppose that some unpredictable disruptions (e.g., pandemic-related restrictions and lockdowns) occur in Sector 3 of Region J, which will suppress the production capacity of this constrained sector. The initial external disruption reduces the direct gross output in the affected sector; subsequently, the need for goods from the manufacturers selling intermediate products to the affected sector will be cut down both directly and indirectly due to this initial reduction. For this example, the change in y in Sector 3 of Region J is endogenous, while that in x should be exogenous; accordingly, we rearrange Eq. (5) to place the exogenous variables on the right side and the endogenous variables on the left side. Thus, we obtain the Eq. (6):

$$\begin{bmatrix} (1-a_{11}^{II}) & -a_{12}^{II} & -a_{13}^{II} & -a_{11}^{IJ} & -a_{12}^{IJ} & 0 \\ -a_{21}^{II} & (1-a_{22}^{II}) & -a_{23}^{II} & -a_{21}^{IJ} & -a_{22}^{IJ} & 0 \\ -a_{31}^{II} & -a_{32}^{II} & (1-a_{33}^{II}) & -a_{31}^{IJ} & -a_{32}^{IJ} & 0 \\ -a_{11}^{JI} & -a_{12}^{JI} & -a_{13}^{JI} & \left(1-a_{11}^{JJ}\right) & -a_{12}^{JJ} & 0 \\ -a_{21}^{JI} & -a_{22}^{JI} & -a_{23}^{JI} & -a_{21}^{JJ} & \left(1-a_{22}^{JJ}\right) & 0 \\ -a_{31}^{JI} & -a_{32}^{JI} & -a_{33}^{JI} & -a_{31}^{JJ} & -a_{32}^{JJ} & -1 \end{bmatrix} \cdot \begin{bmatrix} x_1^I \\ x_2^I \\ x_3^I \\ x_1^J \\ x_2^J \\ y_3^J \end{bmatrix} = \begin{bmatrix} 1\,0\,0\,0\,0 & a_{13}^{IJ} \\ 0\,1\,0\,0\,0 & a_{23}^{IJ} \\ 0\,0\,1\,0\,0 & a_{33}^{IJ} \\ 0\,0\,0\,1\,0 & a_{13}^{JJ} \\ 0\,0\,0\,0\,1 & a_{23}^{JJ} \\ 0\,0\,0\,0\,0 & -\left(1-a_{33}^{JJ}\right) \end{bmatrix} \cdot \begin{bmatrix} y_1^I \\ y_2^I \\ y_3^I \\ y_1^J \\ y_2^J \\ x_3^J \end{bmatrix}. \tag{6}$$

Solving Eq. (6), we get the following equation:

$$\begin{bmatrix} x_1^I \\ x_2^I \\ x_3^I \\ x_1^J \\ x_2^J \\ y_3^J \end{bmatrix} = \begin{bmatrix} (1-a_{11}^{II}) & -a_{12}^{II} & -a_{13}^{II} & -a_{11}^{IJ} & -a_{12}^{IJ} & 0 \\ -a_{21}^{II} & (1-a_{22}^{II}) & -a_{23}^{II} & -a_{21}^{IJ} & -a_{22}^{IJ} & 0 \\ -a_{31}^{II} & -a_{32}^{II} & (1-a_{33}^{II}) & -a_{31}^{IJ} & -a_{32}^{IJ} & 0 \\ -a_{11}^{JI} & -a_{12}^{JI} & -a_{13}^{JI} & \left(1-a_{11}^{JJ}\right) & -a_{12}^{JJ} & 0 \\ -a_{21}^{JI} & -a_{22}^{JI} & -a_{23}^{JI} & -a_{21}^{JJ} & \left(1-a_{22}^{JJ}\right) & 0 \\ -a_{31}^{JI} & -a_{32}^{JI} & -a_{33}^{JI} & -a_{31}^{JJ} & -a_{32}^{JJ} & -1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1\,0\,0\,0\,0 & a_{13}^{IJ} \\ 0\,1\,0\,0\,0 & a_{23}^{IJ} \\ 0\,0\,1\,0\,0 & a_{33}^{IJ} \\ 0\,0\,0\,1\,0 & a_{13}^{JJ} \\ 0\,0\,0\,0\,1 & a_{23}^{JJ} \\ 0\,0\,0\,0\,0 & -\left(1-a_{33}^{JJ}\right) \end{bmatrix} \cdot \begin{bmatrix} y_1^I \\ y_2^I \\ y_3^I \\ y_1^J \\ y_2^J \\ x_3^J \end{bmatrix}. \tag{7}$$

Finally, our supply-constrained MRIO model can be written as

$$\begin{bmatrix} X_{no} \\ F_{co} \end{bmatrix} = \begin{bmatrix} P_{(r\times r)} & 0_{(r\times(n-r))} \\ R_{((n-r)\times r)} & -I_{((n-r)\times(n-r))} \end{bmatrix}^{-1} \cdot \begin{bmatrix} I_{(r\times r)} & Q_{(r\times(n-r))} \\ 0_{((n-r)\times r)} & S_{((n-r)\times(n-r))} \end{bmatrix} \cdot \begin{bmatrix} \bar{F}_{no} \\ \bar{X}_{co} \end{bmatrix}. \tag{8}$$

The meaning of each sub-matrix in Eq. (8) has been explained below (the conceptual framework can be found in Block pressure of Fig. 1 and in Table S3 online):

$P_{(r\times r)}$ is the $r \times r$ matrix from the first r rows and r columns of the matrix (I–A) and denotes the expenditure structure among non-supply-constrained sectors. The matrix is reordered by the r/n–r sectors; the first r sectors are endogenous, and the last (n–r) sectors are exogenous. $R_{((n-r)\times r)}$ represents the expenditure structure of the COVID-19 non-supply-constrained sectors on the COVID-19 supply-constrained sectors, which is the (n–r) $\times$ r matrix derived from the last (n–r) rows and the first r columns of the ($-A$) matrix. $Q_{(r\times(n-r))}$ denotes the expenditure structure of COVID-19 supply-constrained sectors on the COVID-19 non-supply-constrained sectors, which is obtained from the last (n–r) rows and first r columns of A matrix. $S_{((n-r)\times(n-r))}$ denotes the average expenditure structure among the COVID-19 supply-constrained sectors, which is extracted from the last (n–r) rows and columns of $-$(I–A) matrix. $\bar{F}_{no}$ represents the exogenous final consumption/demand for the COVID-19 unconstrained sectors on the supply side, which is the column vector that includes the elements y_1 to y_r. $\bar{X}_{co}$ represents the exogenous gross output for the

COVID-19 supply-constrained sectors, which is the column vector that includes the elements x_{r+1} to x_n. X_{no} represents the endogenous gross output of COVID-19 unconstrained sectors on the supply side, which is the column vector that includes the elements x_1 to x_r. F_{co} represents the endogenous final consumption/demand of the COVID-19 supply-constrained sectors, which is the column vector that includes elements y_{r+1} to y_n. Finally, n denotes the total sectors in the IO table by region, and r corresponds to the number of sectors directly affected by COVID-19 confinements.

We could convert Eq. (8) into a difference form easily, with $\Delta\bar{X}_{co} = \bar{X}^0_{co} - \bar{X}_{co}$, i.e., the output reduction in constrained sectors can be compared with the reference economy ($\bar{X}^0_{co}$) without the implementation of the lockdown measures, which will be achieved in the following scenario section. $\Delta\bar{F}_{no}$ represents the change in the final consumption triggered by COVID-19 restrictions. Since the supply-constrained MRIO model is integrated into opening global markets, it is possible to import products from outside regions that are less affected by COVID-19 during the considered period to compensate for its shrinking number of final products. This study focused on the effects of the shrinking production supply chains. Thus, one assumption was that no exogenous change occurs in the y for COVID-19 non-constrained sectors ($\Delta\bar{F}_{no} = \bar{F}^0_{no} - \bar{F}_{no} = 0$), implying that $\bar{F}_{no}$ remains the same as in the reference economy ($\bar{F}^0_{co}$) without the implementation of COVID-19 confinements. ΔX_{no} refers to the change in the gross economic output in the COVID-19 non-constrained sectors driven by the indirect propagation of COVID-19-constrained sectors. ΔF_{co} corresponds to the change in the final consumption of the COVID-19-constrained sectors. In addition, the traditional mixed MRIO model assumes that a drop in the output of one industry will cause a corresponding output reduction in relevant industries. This assumption may not be entirely unrealistic, particularly in the short run. A more accurate representation of this is that some firms can continue production as long as they have access to the necessary inputs [45]. For example, the metal industry cannot produce metal products without critical inputs, such as iron and energy, but it can operate for a considerable period without non-critical inputs, such as canteen services or management consultants. To address this issue, we apply Eq. (8) to the critical or important inputs only while ignoring non-critical ones. Specifically, we extracted the dependencies matrix (IHS) among inputs at the industrial level from the work of Pichler et al. [45] and mapped it to GTAP (global trade analysis project) sectors (see Table S4 online). Next, we pre-multiplied the HIS matrix by Eq. (8) before calculating the effects on water consumption and the associated biodiversity from the perspective of production by pre-multiplying the water consumption intensity e and the associated biodiversity CFs c by $\Delta\underline{X}_{no}$ and $\Delta\bar{X}_{co}$, respectively, in Eq. (8). The code of the mixed MRIO model can be obtained from the work of Zhao et al. [46], and the global MRIO table is compiled from the latest GTAP database (v.11) [47] because GTAP has a higher resolution on the country-sectoral scale that the other three data sets (Exiobase, WIOD, and Eora). The confinement measures varied considerably across countries and time, and the MRIO table with coarse resolution (for example, Exiobase only covers 28 EU members plus 16 major economies) would have led to significant distortions in our estimation. The original GTAP covers intermediate consumption transactions between 65 sectors within 141 countries/regions; hence, there are 9,165 region-industries in total. The RAS technique [48] was used to convert GTAP 2017 into the year 2020 based on 2019 GDP values provided by the World Bank [49] and the annual growth rates of sectoral GDP from IIASA's GAINS model [50].

2.2. Pandemic confinement shocks to supply constrained sectors

Supply shocks due to the pandemic spread to downstream and upstream sectors, and the suppressed production capacity of suppliers created shortfalls for customers, leading to shocks in downstream industries. Subsequently, factories also required less inputs for production because of lowered production capacities, thus adversely affecting the upstream suppliers of these inputs. Many studies have indicated that the losses incurred from the deaths and illnesses of employees were minor compared with those caused by national lockdown measures aimed at containing the spread of the virus [51]. During the confinement period, workers employed by non-essential industries who could not work remotely were unable to accomplish their tasks [52,53], which led to direct output losses in the shut-down sectors (variable $\bar{X}^0_{co}$ in Eq. (8)). Based on previous studies [51,54], we developed a linear equation to estimate the direct output loss resulting from supply shocks based on factors that affect the movement of labor in non-essential industries due to social distancing. These factors include sectoral shutdowns, the ability to work from home by sector and region, the government's stringency regarding lockdown measures, and the duration of the policy:

$$\Delta x_{i,j} = x_{i,j} \times \left[\left(1 - s_j\right) \times \left(1 - wfh_j\right) \times (1 - wfh_i) \right] \times si_i \times d, \tag{9}$$

where $x_{i,j}$ is the economic output per day in Country i for Sector j; s_j is the operating level of Sector j. A sector is defined as essential if it is not affected by lockdown restrictions, and, in such cases, its s_j equals 1. In contrast, non-essential industries are affected by social-distancing measures to varying extents. We obtained four scenarios from the work of Dorn et al. [55] and Fana et al. [56] to represent the extent of operating levels of industries during the COVID-19 lockdowns. In general, certain essential sectors of the economy, such as the pharmaceutical industry, utilities (electricity and gas manufacturing and distribution), human health, agriculture, and forestry sectors, continue operating at full capacity for all four scenarios. Among the non-essential economic sectors (most belong to industrial and tertiary sectors), for certain sectors, such as entertainment and recreation, accommodation, and dinning services, we assume a nearly complete shutdown during the strict confinement period; for the remaining non-essential economic sectors, we allocate low-level losses (0.5–0.8) for Scenario 1 and high-level losses (0.5–0.9) for Scenario 2 (see Table S1.1 online for detailed information). In addition to Scenarios 1 and 2, we introduce Scenario 3 to illustrate the expected extent of the decline in production based on business expectations using the IFO Business Climate Index as one proxy [55]. In Scenario 3, some manufacturing and service sectors are divided into quintiles according to their corresponding business expectations. For sectors with the highest deterioration expectations in the future, the assumption is that production will cease. For the sectors with the least pessimistic expectations with respect to future business activities, we assign a relatively moderate decrease of 20% in their business activities (see Table S1.1 online for detailed information). In addition to the three aforementioned scenarios proposed by Dorn et al. [55], we developed Scenario 4 based on the European Commission's projections with regard to the impacts of restrictions on the EU labor market [56]. Similar to Scenarios 1–3, some essential sectors can continue to operate fully even with the strictest restrictions, but non-essential sectors are either fully closed or can operate partially under certain conditions. Table S1.1 (online) presents the details of each scenario, including the operating levels of each sector.

Some employees from non-essential industries have the ability to accomplish their work from home to some extent, and wfh_j represents the output share that can be achieved by working from home in Sector j, which was obtained from the study conducted by Dingel and Neiman [52]. wfh_i represents the ability to work from home at the country level, which was also obtained from the said study [52]. In summary, a wfh value of 0 means that none of the occupation's activities can be undertaken remotely, while a wfh value of 1 means that all tasks associated with an occupation can be performed at home. Hence, we could obtain the sectoral shutdown level (see Table S1.2 online). si_i is the stringency index, which assesses the severity of lockdowns in Country i using nine indicators (closing schools, closing workplaces, cancelling public events, restricting gatherings, staying at home, etc.). The original value of si_i is between 0 and 100; the higher this value, the more stringent the lockdown that the government imposed. We have normalized this value to 0–1 to directly incorporate it in Eq. (9). si_i is an aggregated index that captures governments' overall response to COVID-19 on a daily scale. This indicator was obtained from OxCGRT (Oxford COVID-19 Government Response Tracker) [57]. OxCGRT collects systematic information from more than 180 countries regarding the policy measures that governments implemented to tackle COVID-19 and compares policy responses consistently between countries on a daily basis. d is the duration of each period. We take semimonthly time steps for the period of 2020–2022 and quarterly time steps thereafter. Finally, we estimate the direct output loss in Country i, Sector j triggered by COVID-19 confinement measures ($\Delta x_{i,j}$). $\Delta x_{i,j}$ represents the input data for Eq. (8).

2.3. Stringency index projection in the future (2023–2025)

To estimate the effects of COVID-19 lockdown measures on economic systems in the future, we have to project the stringency index level by country. Considering potential herd immunity and learning experiences, most countries are adjusting their restriction policies based on the herd immunity rate and the ICU bed level, with the extent of strictness being negatively correlated with the herd immunity rate and positively correlated with the occupation rate of ICU beds. Following the work of Shan et al. [58], we suggest that the future stringency index in the year 2022 will be determined by the following formula:

$$si_i^p = si_{\mathrm{base},i} \times \left(\frac{\mathrm{Im}R_{\mathrm{remain},i}}{0.9}\right) / icu_i \times \left(\frac{1}{2}\right)^n, \tag{10}$$

where $\mathrm{Im}R_{\mathrm{remain},i}$ is the difference between the threshold and immunity rate by country at the end of 2022. Based on the fact that herd immunity will work only after the immunity rate reaches 90% [59,60], we set the threshold to 0.9. We calculated the immunity rate for each country based on Gu Yongyang's model [61], with the relevant data being obtained from *Our World Data* [62]. The variable icu_i is the ratio between the country's ICU level [63–66] and global average standard. If the icu_i value is greater than 1, we keep the ratio unchanged; if it is less than 80% of the global average, we assume the icu_i to be 0.8; if it is less than 50%, we consider the ratio to be 0.5. We take quarterly time steps for the year 2023 and assume si_i^p remains unchanged after 2023.

2.4. Water consumption accounts and water-biodiversity causal effect chains

To capture the changes in water consumption due to COVID-19 confinements and the consequent impacts on biodiversity from the production perspective at the country-sectoral level based on Eqs. (1)–(10), we need water consumption data matched with the GTAP data set and characterization factors that define the relation between water consumption and biodiversity. For the compilation of the environmental extensions in the area of blue-water consumption for the GTAP data set, we used two basic data sources of water consumption: The water footprint data set [67] for agricultural water consumption based on FAO water statistics and the WaterGAP model [68] for industrial and tertiary water consumption. The disaggregation to GTAP sectors is based on water consumption intensities by region and sector from the global EXIOBASE 3 data set [69]. Combined, these data sets are currently among the most comprehensive and best available water consumption data sets at the country-sectoral level.

Specifically, we calculate crop water consumption for GTAP sectors 1–12 based on the water footprint per ton of crop or derived crop products [70] and crop production of each sector by country [71]. Similarly, we calculate livestock water consumption for GTAP sectors 19–22 based on the water footprint per ton of animal or animal-derived products [72] and livestock production by country [71]. As for industrial and tertiary water consumption (sectors 13–18 and 23–65), total blue-water consumption at the industrial and tertiary sectors is disaggregated into 49 sectors based on water consumption per unit of economic output from EXIOBASE 3. Table S5 (online) shows the sector and region bridge between GTAP and EXIOBASE. The water consumption account of the GTAP model is shown in Table S6 (online). Furthermore, Verones et al. [10] developed characterization factors (CFs) to quantify the causal effect chain between water consumption and biodiversity across the globe based on the life cycle impact assessment theory. The CFs address potential losses in endemic species of various animal taxa (i.e., mammals, reptiles, birds, and amphibians) in wetlands and vascular plant species in terrestrial ecosystems as a function of groundwater and surface-water consumption. We adopted CFs as proxies to represent the relation between water consumption and biodiversity loss, which are expressed as global fractions of PDFs per m^3 of water consumed annually (PDF/(m^3·a)). This method does not model the immediate effect on biodiversity but, instead, the long-term effect of species loss. As such, the unit can be interpreted as PDF under a steady state of an additional water consumption rate (m^3/a) or as the time-bound species loss (PDF·yr) caused by 1 m^3 of water consumption per year. Table S7 (online) displays the CFs of each GTAP country. We assigned the global average value to the four regions that do not have specific CFs. To sum up, this new data set could serve as significant data support for academics, governments, and the public in the water domain, especially for studying the role of international trade and how to achieve SDG 6 equally.

2.5. Contribution of COVID-19 confinements to water scarcity and biodiversity loss reduction

For a certain region, water scarcity (ws) is measured as the ratio of regional water consumption to water availability by considering a balance between human water consumption and ecosystem protection:

$$ws = \frac{wc}{Q - EFR}, \tag{11}$$

where wc is the total blue-water consumption; Q is the water availability; EFR is the environmental flow requirement. We extracted EFR by country from AQUASTAT [73]. In our assessment, we calculate ws for the baseline and the various lockdown scenarios. The difference between the scenarios and the baseline measures the contribution of COVID-19 to water scarcity levels. Water scarcity levels are classified into four categories: (1) Low water scarcity (<100%); (2) moderate water scarcity (100%–150%); (3) significant water scarcity (150%–200%); and (4) severe water scarcity (>200%). In terms of the effect of COVID-19 on biodiversity, we used the ratio of biodiversity increase to the baseline value to represent biodiversity recovery. Fig. 1 presents the flowchart of this evaluation within the DPSIR framework.

2.6. Model validation based on relative error

To check the accuracy of our assessment based on the MRIO-enhanced DPSIR framework (Fig. 1), we compare the estimated GDP in 2020 with the actual GDP for the 141 regions for which the data are available from the World Bank and International Monetary Fund (IMF) [49,74]. We selected the relative error (*RE*) as the indicator to illustrate the difference between the calculated and actual GDP, which is as follows:

$$RE = \frac{E_{c,i} - E_{m,i}}{E_{m,i}} \times 100, \tag{12}$$

where *RE*, E_c, and E_m are the relative error (%), calculated (simulated) GDP per year (billion \$ a^{-1}), and measured (actual) GDP per year (billion \$ a^{-1}), respectively, for Country *i*. Certain factors, such as the imperfectness of simulation models and scenario assumptions, can lead to differences between the measured and simulated GDP. In this study, the relative error is 0.6% for the global GDP. At the country level, for 82% of the countries (115 out of 141), the *RE* was within 15% of the measured GDP obtained from the World Bank and IMF, and, for 30% of the countries, the *RE* was within 5% of the measured GDP (see Table S8 online). This indicates that our models performed well, which suggests that our results are reliable when interpreting the water and the associated biodiversity outcomes (Table S9 online presents partially measured water consumption in 2020). Several case studies also demonstrated a trend of reduction in water consumption during the pandemic [20,75,76]. In Africa, our estimated values are lower than the measured GDP values for most regions; this underestimation is caused by the difference between the various governments' theoretical response to COVID-19 and their actual actions to contain the transmission of virus.

3. Results

3.1. Impacts of COVID-19 confinements on water consumption and associated biodiversity

Over the course of the pandemic, countries have implemented a range of confinement measures to curtail the transmission of the virus. These measures have also varied with time, particularly through the different waves of the pandemic. The study period starts with the spread in January 2020 and ends in 2025.

Fig. 2 and Table S10 (online) summarize the bimonthly results of the four scenarios for the effects of COVID-19 confinement measures on water consumption and the associated biodiversity. Before March 2020, the impacts of COVID-19 were mainly restricted to very few countries. The Chinese government implemented numerous strict lockdown measures to control the spread of COVID-19, so the virus had not yet spread to other regions at a considerable scale. This led to domestic supply chain issues in China only. Our results indicate that the reduction in water consumption would range from 6.9 billion m^3 (Gm^3) in Scenario 3 (lockdown level based on the IFO Business Climate Index) to 9.8 Gm^3 (Scenario 2: High-level lockdown) under different scenarios, accompanied by a reduction in potential biodiversity loss between 0.000509 PDF·yr (fractions of PDFs during a year) in Scenario 3 to 0.000686 PDF·yr in Scenario 2 during this early stage of the pandemic that affected only China. During this period, water consumption reduction in China accounted for 25% of the total global change, while the biodiversity loss reduction accounted for 5.2% of the same.

The situation changed drastically as COVID-19 spread across the globe. Consequently, the various COVID-19 confinement policies reached a global dimension, with almost all economies going into recession, and the impacts on water use and biodiversity declined dramatically in volume and spatial outreach. The reduction in water consumption fluctuated with the development of the

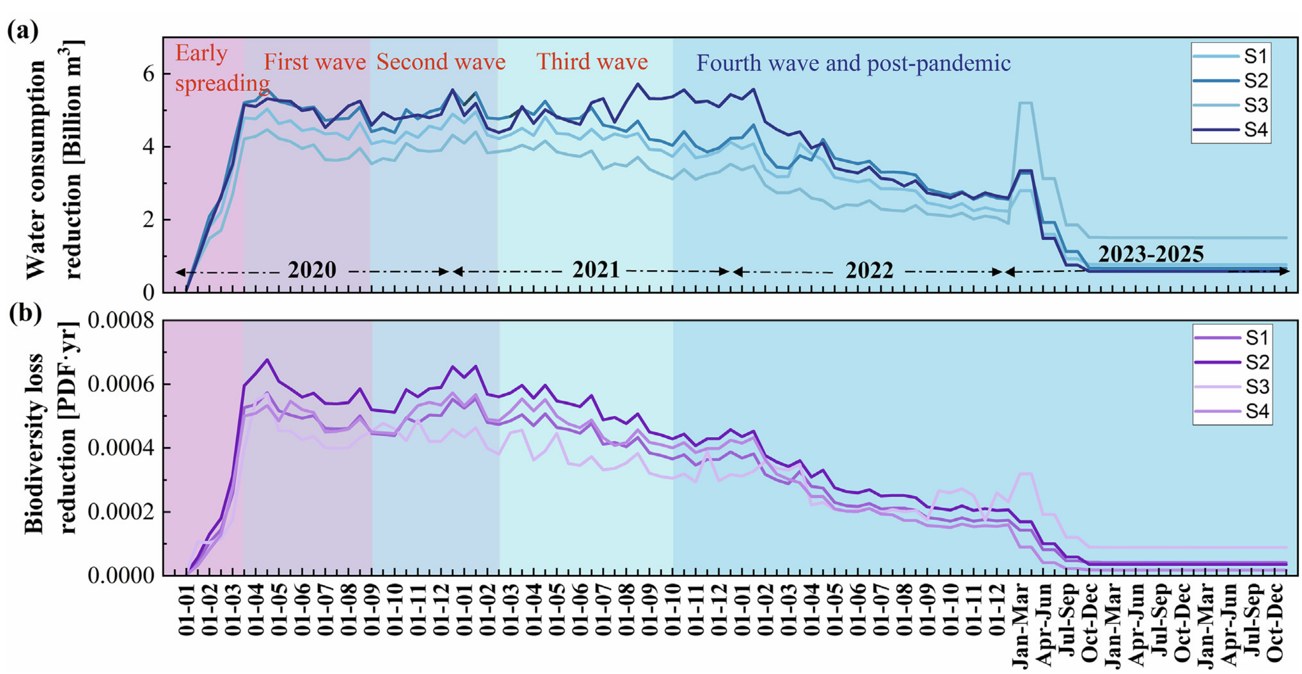

Fig. 2. The impacts of COVID-19 confinement measures in different scenarios on the global scale (S1, low level; S2, high level; S3, shutdown level based on the IFO Business Climate Index; S4, shutdown level based on European Commission. Table S1 online shows the technical parameters). (a) Water consumption reduction; (b) biodiversity loss reduction. Note: Before 2023, the time path is semimonthly; thereafter, the time path is quarterly.

pandemic and the strictness of the confinement interventions. In the beginning, the actual effects of the intervention policies on reducing infection rates remained unknown [77]. Many restriction measures, such as closing restaurants, shopping centers, and schools or restricting travel, which were aimed at decreasing virus transmission, were implemented to the maximum extent, leading to serious disruptions in the economic system [78]. As a result, water reduction [24] and declines in biodiversity pressure peaked in early April 2020. With an increase in the information and knowledge available about the disease, the approaches to anti-contagion policies evolved, and their implementation was highly dynamic based on the severity of infection and death rates as well as political-power dynamics and strategies in different countries [57]. This induced temporal fluctuations in the effects on water consumption and the associated biodiversity after March 2020. Several sub-peaks occurred during the global spread stages, but they remained lower than the early and late peaks. In summary, our global results demonstrate the fluctuations in water consumption and biodiversity impacts through this time period driven by policy interventions related to COVID-19. Thereafter, all four scenarios suggest progressively diminishing impacts due to the implementation of COVID-19 vaccines and the socio-economic system's self-adjustment to the new normal after the pandemic (see Fig. S1 online).

3.2. Hotspot regions and countries of water and biodiversity benefits driven by COVID-19 confinements in 2020

Fig. 3 and Table S11 (online) illustrate how the global COVID-19 confinement measures led to differential water and biodiversity benefits across countries and scenarios in 2020. The country-level benefits for water reduction and biodiversity range from Indonesia's 1.14% to 39.3% in the rest of the South African Customs Union, expressed as the average of the four scenarios. Globally, the decline in water consumption varied from 82.0 Gm^3 (4.8% of total water consumption, Scenario 3) to 104.4 Gm^3 (6.2%, Scenario 2: High-level lockdown) in 2020, accounting for about 5.7% of the global water consumption (1,698 Gm^3) in 2020 on average across all scenarios. Correspondingly, the recovery of biodiversity induced by the redirection of water resources from the economic system to the natural system ranged from 0.00902 PDF·yr (4.7%, Scenario 3) to 0.01164 PDF·yr (6%, Scenario 2), accounting for about 5.2% of the baseline biodiversity loss due to freshwater consumption in 2020.

Specifically, water consumption reduction was highest in China in 2020, at 12.8 Gm^3, which accounts for 13.3% of the overall reduction in global water consumption reduction and 4.9% of China's total water consumption. Pakistan (reduction of 10.7 Gm^3; 11.1%), India (reduction of 6.9 Gm^3; 7.2%), Egypt (reduction of

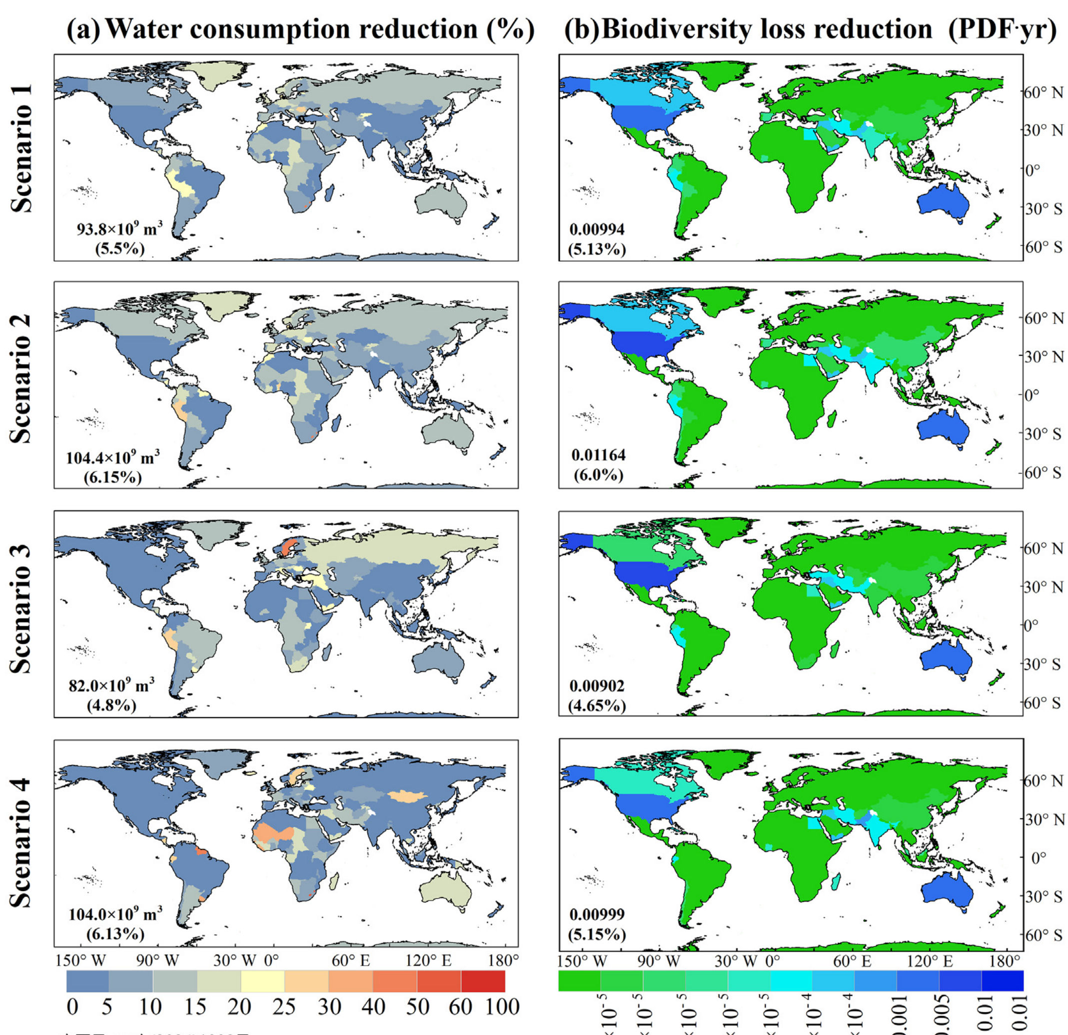

Fig. 3. Regional impacts of COVID-19 confinements in different scenarios in 2020. (a) Water consumption reduction; the legend indicates the ratios of the reduction in a country's baseline; (b) biodiversity loss reduction; the legend indicates loss reduction by country. The numbers in the figure refer to the total global change per scenario.

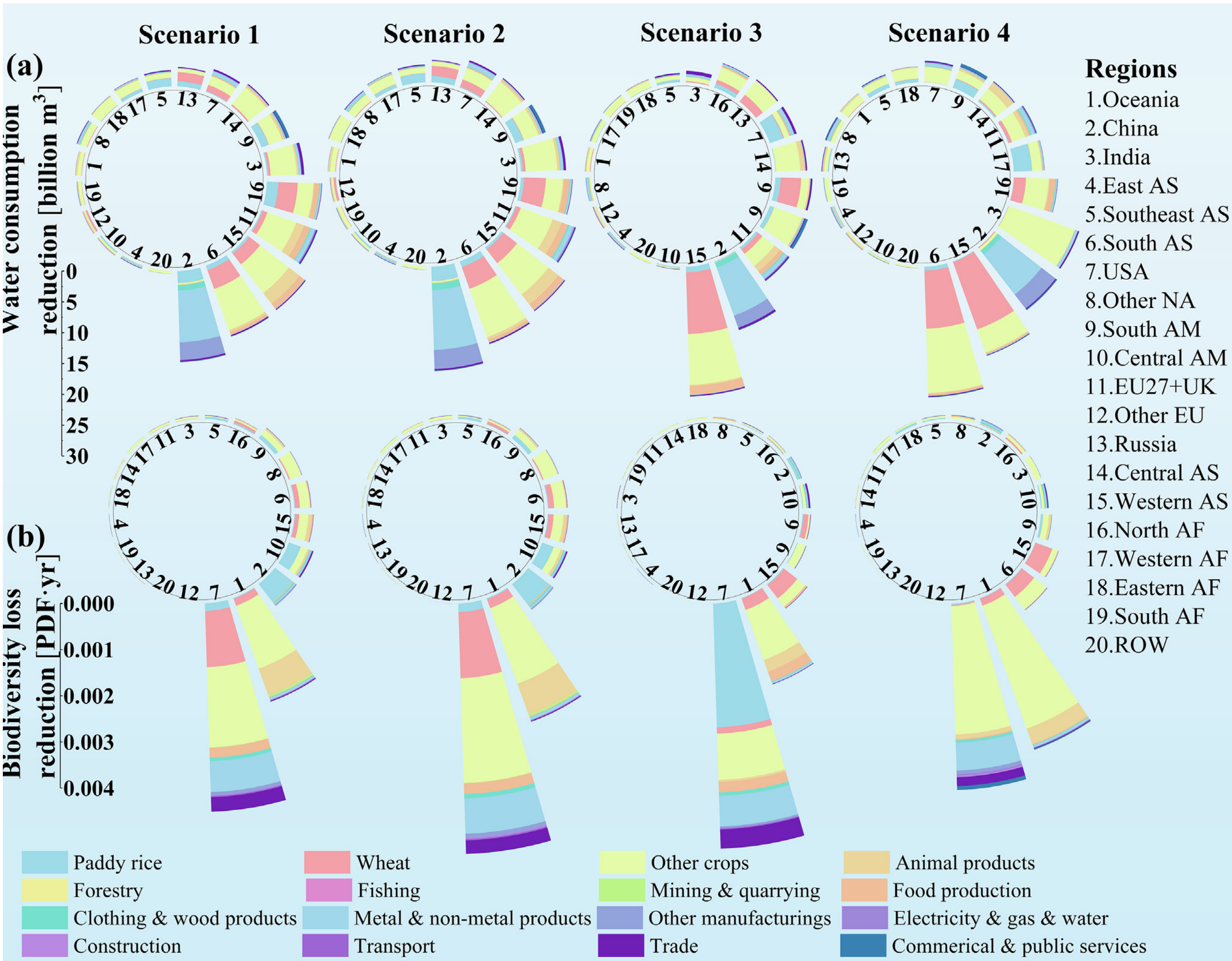

Fig. 4. Sectoral impacts of COVID-19 in different scenarios in 2020; the full spectrum of regions is listed in Table S4 online.

5.9 Gm^3; 6.2%), Iran (reduction of 4.9 Gm^3; 5.1%), the USA (reduction of 4.2 Gm^3; 4.4%), Russia (reduction of 3.1 Gm^3; 3.3%), and Spain (reduction of 2.3 Gm^3; 2.4%) also showed substantial reductions in water use in 2020. These reductions were driven not only by the lockdowns in their own countries (direct impacts) but also by the restrictions imposed by other countries (indirect impacts via supply chains; Table S12 online). For example, in 2020, 21% of the overall water reduction in the economic system was caused by direct lockdown restrictions in the country itself, while the remaining 79% was triggered by the ripple effects of supply chain disruptions throughout international trade (see Table S12 online). Additionally, although certain agricultural sectors (paddy rice, wheat, animal products, etc.) did not impose any lockdown measures for all scenarios, its potential virtual water use still decreased during the whole pandemic period (see Table S13 online). On the one hand, these reductions originated from indirect effects along the value chain caused by disruptions such as agricultural trade restrictions and processing-plant closures and can potentially lead to variations in production and stock in the coming years [79,80]. On the other hand, these variations in water consumption in the agricultural sector might not be immediately reflected in water consumption, but they are highly likely to be buffered by water bodies or some human-made water infrastructures (such as reservoirs) [81].

In comparison, the hotspot regions in terms of biodiversity loss reduction during the pandemic were rather different from the water resource hotspots. The reductions in biodiversity loss in the USA and Australia were the highest in the world, with these two countries contributing 47.5% (0.00482 PDF·yr) and 26.4% (0.00268 PDF·yr), respectively, to the overall biodiversity increase, while their ranks with regard to water contribution were 7th and 15th. Other top countries in terms of reduction in biodiversity loss were the rest of the Caribbean (0.00028 PDF·yr; 2.8%), Canada (0.000193 PDF·yr; 1.9%), and Ecuador (9.29×10^{-5} PDF·yr; 0.9%), which presented similar patterns. This regional disparity in the distributions of water reduction and biodiversity increase was created by differences in the CFs linking the causal-effect chain between water consumption and biodiversity. For example, the CF of the USA is about 1.15×10^{-12} (PDF·yr/m^3), which indicates the change in local species per cubic meter of water consumed annually in this region, while the global average CF is 1.63×10^{-13}, which is just one-seventh of the USA's baseline value. One of the consequences in this context is that more species loss will be avoided in locations characterized by high CFs than those characterized by low CFs with the same amounts of water resources returned to the natural environment.

3.3. Impacts on water consumption and associated biodiversity across sectors

With regard to the four scenarios, Fig. 4 and Table S13 (online) summarize the effects of COVID-19 on water consumption and the associated biodiversity across regions and sectors. For presentation purposes, the results from the 141 countries have been aggregated

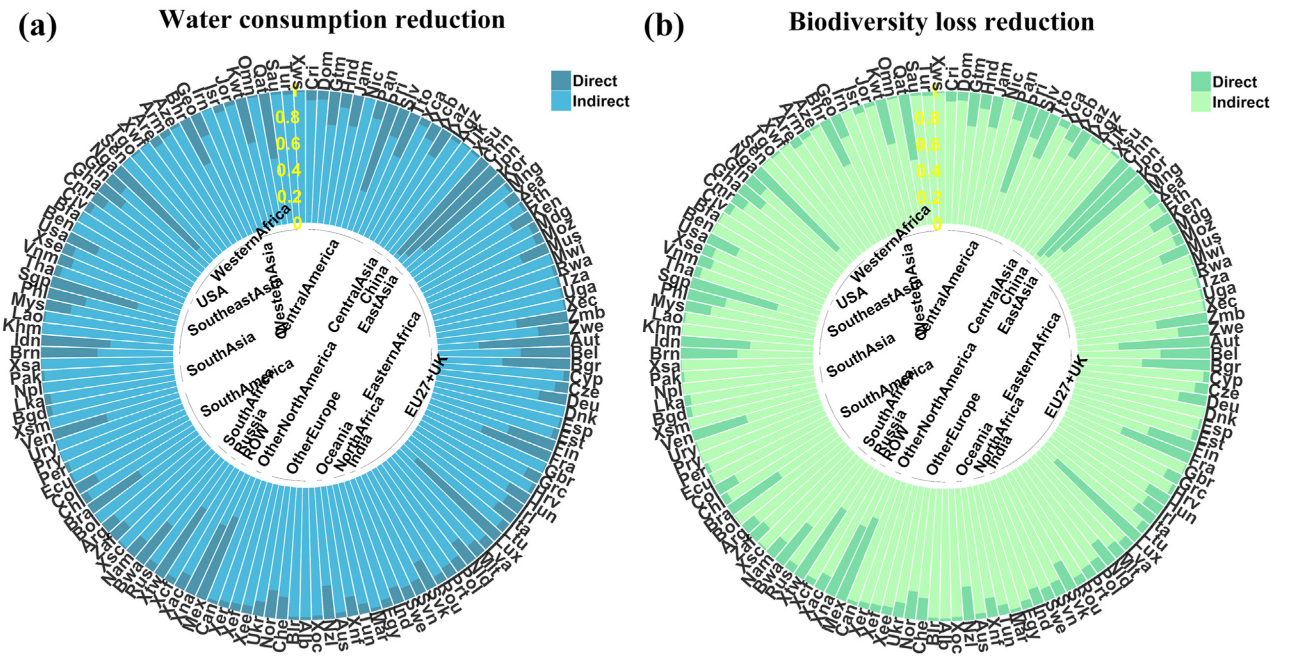

Fig. 5. The direct and indirect impacts of COVID-19 confinements on water consumption (a) and biodiversity (b) by country; the full spectrum of countries is listed in Table S5 online.

into 20 regions (see Table S14 online), and 65 sectors have been aggregated into 16 sectors (see Table S14 online). Specifically, we found that paddy rice, wheat, and other crops contributed the most to reducing water consumption. These three related agricultural sectors reduced their water consumption by 8.5 Gm^3 (8.9%), 17.4 Gm^3 (18%), and 41.2 Gm^3 (42.9%), respectively, on average, in 2020. Similarly, these three sectors were also the highest contributors in terms of reducing biodiversity pressure and accounted for 13.5% (0.00137 PDF·yr), 13.5% (0.00138 PDF·yr), and 47.5% (0.00482 PDF·yr), respectively, of the overall biodiversity loss reduction in 2020. In fact, COVID-19 shows a limited direct influence on food sectors because of their low-exposure and high-social-distancing aspects. We assumed that the lockdown level in agriculture is zero, similar to other necessary sectors, for all four scenarios (see Table S1 online). As a result, nearly all water reductions from these sectors can be attributed to restricted production in their supply chains, such as food production, trade, and commercial and public services. In addition, biodiversity was also affected by their indirect propagation via the linkage with water resources.

Reductions in water consumption in different sectors varied significantly across regions (Fig. 4). Certain regions (such as South Asia, West Asia, North Africa, and the USA) had a high reduction in water consumption in relation to agricultural sectors, while other regions (such as China and EU27 + UK) had high water reductions in manufacturing-related industries. These differences corresponded to their underlying economic and water-usage structures. For example, the production of metal and non-metal products contributed to 11.3% of China's and 2.3% of the USA's total water consumption in 2020. Thus, the water reductions in China's metal and non-metal products would be greater than those in the USA, and the sectoral disparities across countries would be propagated throughout the heterogeneity of supply chains to propagate the initial effects. As for the impact on biodiversity, our results showed no obvious sectoral discrepancy across the 20 regions, but biodiversity in the USA and Oceania showed the biggest improvements because of their higher background species density compared with other regions.

3.4. Propagation through supply chains amplifies the impacts of pandemic confinements

Fig. 5 and Table S12 (online) indicate the importance of propagation through supply chains. Even countries or sectors that were not directly influenced by COVID-19 confinement measures experienced spillover effects, and low- and middle-income countries were more vulnerable to such indirect linkages. Overall, the indirect impacts accounted for around 79% of the total estimated water reduction and for around 84% of the biodiversity benefits across different scenarios. We found that the direct impacts of domestic containment measures played a dominant role in emerging economies, such as China, Indonesia, and Mexico. For example, in China, the reduction in water consumption caused by domestic measures accounted for 90% of the country's total water-consumption reduction, while the remaining 10% was from upstream measures implemented along supply chains. On the one hand, China maintained its high food self-sufficiency in terms of staple grains (e.g., wheat and rice); the shrinking exports in food-related sectors with high water intensity driven by the pandemic had a limited influence on China. Thus, the indirect water savings induced by the fluctuations in the global food network mostly did not affect this region. On the other hand, the local COVID-19 confinements focused on manufacturing and non-essential service industries. Manufacturing supply chains in China possess a robust industry-clustering effect, i.e., there is a clustered hub in electronics and chemical and metal production, with connections to large numbers of factories in other countries through international trade. Similar trends can also be observed for biodiversity impacts, where direct effects on biodiversity mainly occurred in several emerging economies, whereas other regions were primarily affected by indirect supply chain propagation.

3.5. Impacts of COVID-19 confinements on regional water scarcity and biodiversity

The confinement measures alleviated regional water scarcity to some extent because of the shutting down of factories and public infrastructure but had limited effects on general water security and water sustainability. An analysis of global water consumption without COVID-19 indicated that regional water scarcity levels did not decrease much, not to mention that the level was reduced from high to lower (see Fig. 6 and Table S15 online). In contrast, the positive impacts on biodiversity were more substantial than those on water resources, especially in regions with high species density (e.g., Sweden, Peru, Nicaragua, and Armenia). Considering ongoing fiscal stimuli, the situation could have been even worse, as the recovery packages involve no plans to improve water security, but enormous amounts of investment flows and transfers have been put into traditional sectors to restart the economy [34]. Our world is facing huge risks regarding water consumption rebounding to higher levels after the temporary reductions seen during the pandemic are eased, making it difficult to change in the future if development pathways are locked into water-intensive sectors.

4. Discussion

Our study presents a systematic assessment of the responses in terms of water consumption to the shocks of COVID-19 confinements at the country-sector level and the associated consequences on biodiversity both directly and indirectly. For this purpose, we combined the mixed MRIO model of footprint accounting with the DPSIR framework. This enabled us to obtain a comprehensive understanding of how water consumption is affected by global emergency events such as the COVID-19 pandemic, how this pressure creates environmental impacts, and how these impacts affect and reshape regional water scarcity and biodiversity patterns.

Such an approach is important, as traditional impact assessments mainly quantify drivers and pressures with limited consideration of the broader implications as done by the DPSIR framework. Therefore, we rarely analyze how the pressures influence the state of the environment and its responses to initial disturbances [82], even when policymakers and governments should respond to not only resource pressures but also relevant environmental impacts [83]. For example, water policies should consider the environmental issues triggered by water use and not just the amount of consumption itself [84]. Thus, understanding the causality responses is important to enhance the resilience and flexibility of water and ecological networks to sudden shocks, and a quantitative framework, such as the one presented in this article, can help policymakers realize the related cascade effects. Our MRIO-enhanced DPSIR framework has great potential for evaluating resource pressures and the resultant environmental impacts across supply chains caused by sudden events or disasters.

Our analysis highlights the importance of propagation through global supply chains in terms of environmental benefits, indicating that this "supply chain contagion" is an important feature of global emergency events. Companies, individuals, and governments experience supply chain perturbations due to public health shocks, which has led to a sudden de-globalization. It is possible that the COVID-19 pandemic may even induce a partial reversal in globalization to reduce the potential indirect risks caused by similar events [85–87]. It has been reported that the pandemic has encouraged the shortening of supply chains to strengthen local self-sufficiency and reduce supply chain vulnerability, especially in key domains such as the food, water, and energy sectors, which are the foundations for achieving the 2030 UN Sustainable Development Goals [88–90]. Further, more practical measures, such as

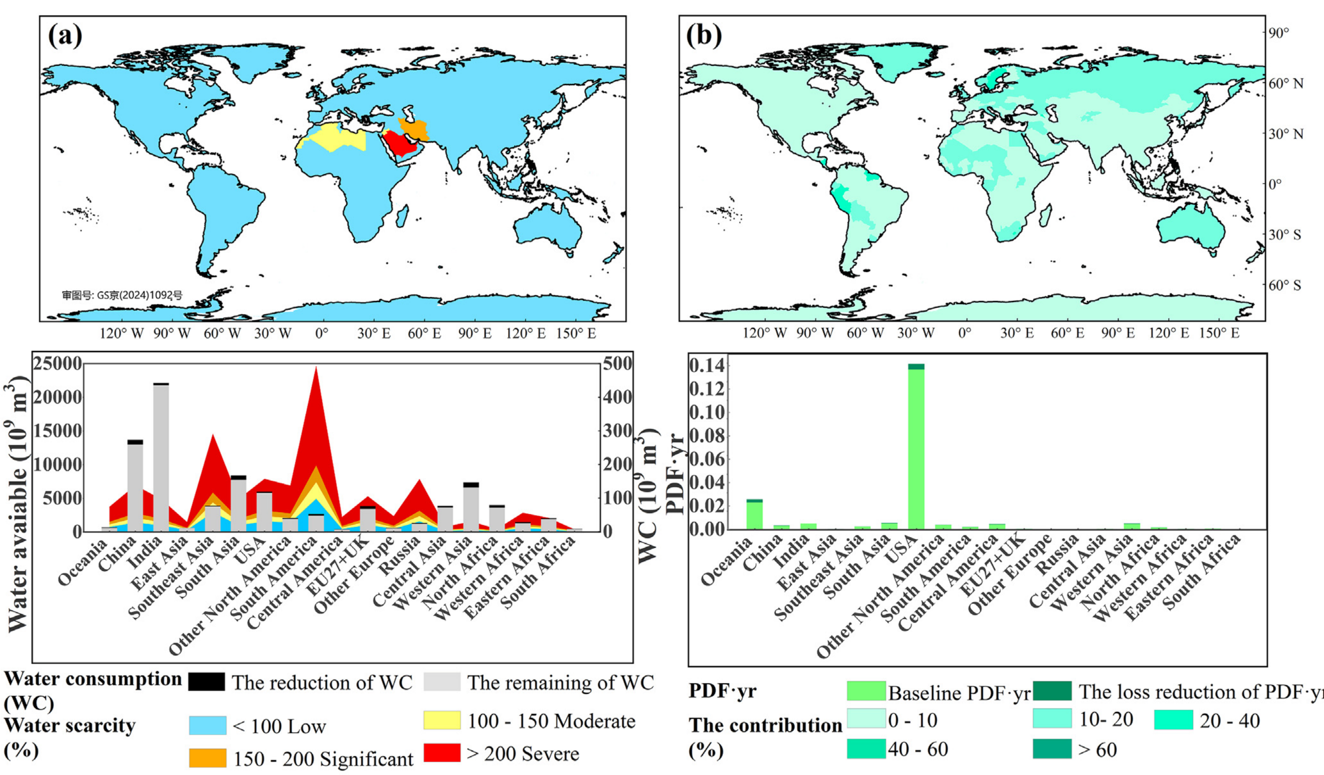

Fig. 6. Impacts of reduced water consumption (a) and biodiversity (b) on regional water scarcity and biodiversity richness. Note: The histogram on the bottom left represents water stress levels by region; different color tones represent different water scarcity levels. For each region, the color shades interlinked with the bars demonstrate the water scarcity level. For example, when the water consumption (grey and black bars) touches a yellow zone, moderate water scarcity occurs in that region.

community gardening, vertical farming, rooftop agriculture, and bio-energy usage, have been boosted by this development [88]. While reduced trade flows may save water in exporting regions, as indicated in this study, they may exacerbate water shortage problems in high-consumption water-scarce regions, which are the main beneficiaries of the "virtual water" inflows embodied in international trade [91,92]. Therefore, more attention needs to be paid to developing locally based water conservation measures (such as building green infrastructures, rainwater utilization, and desalination) in case of trade disruptions caused by sudden shocks, such as the COVID-19 pandemic, extreme weather events in or around key supply centers, and geopolitical crises, such as the Russia-Ukraine war.

Our findings reveal the overall beneficial impacts of COVID-19 confinement measures on water resources and the related biodiversity implications across global supply chains. However, most of the environmental benefits observed during the pandemic are more likely to be temporary, as they do not reflect structural changes in socio-economic systems [93]. In addition, a rebound in resource use may occur and be larger than the decline triggered by the crisis as soon as travel restrictions and lockdown measures are eased and traditional stimulus packages are launched and implemented [58,94]. For example, in late March 2020, CO_2 emissions in China rebounded due to the restarting of industries [94]. Thus, the designing and implementation of economic stimulus plans present a major opportunity to implement collective efforts by governments and societies to "build back better" by interlinking economic recovery efforts with sustainability transformation, which includes water conservation transitions and biodiversity protection. Nevertheless, there are indications that environmental regulations may even be eased to facilitate construction projects on the pretext of the pandemic and economic recovery [95]. One important avenue for building back better is the massively funded EU Green Deal (1.85 trillion euros) that aims to create the first climate neutral continent by 2050 [96]. Although, the assessment indicators in the Green Deal are mainly focused on cleaner energy, carbon neutrality, and climate stabilization, and water sustainability and biodiversity seem to have been given less attention in this initiative as well as in other post-pandemic stimulus funds. In fact, research has shown that improved water security has co-benefits for both climate mitigation and adaptation. Water must be accurately considered in the recovery framework to manage trade-offs and increase synergies between water and climate security [97].

Understanding the cascade effects of the pandemic confinement actions on water systems can help decision-makers prioritize future actions to overcome potential challenges and ensure the fundamental right to clean water and sanitation facilities for all communities [20]. Global spillover effects driven by supply chain disruptions in non-essential sectors illustrate the importance of enhancing water resilience in response to increasingly unpredictable hazards in our fast-paced and highly connected world. However, more water saving focused on the agricultural sector may hint at the fierce competition between food requirements and other water-consuming sectors, as regions tend to increase their crop production to ensure greater food self-sufficiency and food sovereignty [98]. It is helpful to increase the diversity of water sources (surface, underground, recycling, reusing, desalination, etc.) to mitigate the risks of future supply shocks. Our quantification of changes in water in response to global emergency events is vital for governments to take actions to ensure the availability of water resources for human well-being and the maintenance of essential ecosystem functions and services. Our research also contributes to improving the understanding of the sensitivity of the global water-biodiversity nexus to large-scale behavioral change. Our research approach can be adopted as a part of an integrated risk assessment framework to enable informative supply chains-related risk-accounting during or prior to emergency situations.

The short-term pandemic confinement measures introduced during the COVID-19 outbreak show that easing human pressure on the environment leads to the recovery of environmental systems [15,99]. Thus, to avoid diminishing the environmental gains once the world returns to normalcy, it is crucial to maintain these improvements in the post-pandemic world. These measures may include strengthening telecommunication and information technologies (hybrid work, e-commerce, e-learning, teleconferencing, etc.) to reduce the need for environmental resources [100], changing resource-intensive lifestyle patterns to eco-friendlier alternatives (e.g., vegan-based diets, healthy home-cooked food, reduced travel, and less consumption) [101], leveraging temporary benefits obtained by the COVID-19 pandemic to long-term gains through coordinating institutional behaviors at the individual, community, government, and international levels, and improving the standards and enforcement of manufacturing, business, and environmental regulations.

For a long time, the role of biodiversity in preventing the spread of zoonic diseases has been frequently overlooked by mainstream epidemiology because of its weak interlinkages with infectious diseases. However, the COVID-19 outbreak has highlighted the extreme importance of the combat against biodiversity loss [102], as the disturbance of natural ecosystems is considered to be among the main causes for the transmission of impactful human diseases [103]. A loss of biodiversity and the degradation of ecosystem buffer zones that serve as a "firewall" to contain the spread of viruses will exacerbate the spillover of infectious diseases [104]. Correspondingly, higher biodiversity will exert a "dilution effect" on the impact of principal disease reservoir species, thereby rendering the spreading of pathogens more difficult [105]. The Global Biodiversity Outlook 5 (GBO-5) concluded that biodiversity loss might lead to infectious diseases emerging and re-emerging at a faster rate, and actions to increase species diversity are essential to prevent future pandemics [106]. Hence, conservation and sustainable management of biodiversity might be essential to mitigate emerging infectious diseases and prevent pandemics to safeguard human well-being and health for generations to come [107].

5. Limitations, uncertainty and future directions

Some limitations and uncertainties should be taken into consideration when interpreting our results. First, our mixed MRIO model excluded changes in production mix and structures, as both will remain fairly stable for a short or medium period [108]. Second, the economic growth projections were collected from IIASA's GAINS model, the World Bank, and the IMF for all the scenarios without the pandemic. As our mixed MRIO model focused on the repercussions of sudden exogenous shocks (for example, COVID-19 confinements) in the supply chain network, an updated capital matrix will produce better economic projections. However, this approach is rarely used at the global level due to data limitations. Third, the pandemic also brought about demand shocks, especially for industries that are strongly affected by demand constraints. Consequently, our results may underestimate the propagation impacts caused by the pandemic. While some scholars [109] pointed out that most of these impacts stem primarily from input-related bottlenecks, it remains necessary to evaluate both supply and demand shocks simultaneously in future studies [45]. Fourth, for some less-developed countries or regions, the A matrix in the GTAP table was compiled based on some idealized assumptions rather than survey-based statistics due to data unavailability. These assumptions are likely to lead to biased results in some sectors when confinement orders are implemented in these regions. For these regions, we assumed a 10% ratio of indirect supply chain impacts to total impacts to smooth the initial results and make them reliable. Fifth, we developed one linear equation to represent the direct economic loss triggered by COVID-19 confinements. The confinement effects will not vary strictly according to the linear trend; certain external factors, such as people's willingness to obey the government's orders and the government's ability to effectively implement restriction policies, will affect the actual outputs of confinement measures.

Sixth, the water intensity of the sectors considered in this study was estimated based on several different data sources, some of which had not been updated to the latest year because of data limitations, which is likely to produce some uncertainties when compiling water accounts. Additionally, the water accounts are assumed to be stable during the study period, which might involve overestimating water consumption to some extent, given that some degree of decoupling has been detected [110–112]. Moreover, varying climate conditions result in varying water demand, especially in the context of crop production, which has not been accounted for. In addition, fiscal stimulus actions may have complicated but significant long-term effects on economic performance and relevant water consumption. Our scenarios excluded the water impacts triggered by stimuli because of a lack of detailed confirmed recovery data on the global scale. Research on the impacts of fiscal and monetary policies on water consumption should be evaluated when the corresponding data are ready.

Furthermore, we excluded green water from the water accounts because of the difficulty in evaluating its relationship with biodiversity. In fact, green water over-deprivation for human activities will have a negative influence on the species' habitat and biodiversity but is covered to some extent by the biodiversity impacts of land use [39,113,114]. Land-use conversion is another big driver of biodiversity loss, as terrestrial systems feed vast species of different taxa [110]. Additionally, certain factors, such as climate change, extreme events, and water pollution, are threatening the security of various species' habitats. The quantification of additional impacts of other driving forces on biodiversity should be studied in the future. While the characteristics of biodiversity loss vary across space because of the spatial heterogeneity of the CFs, we utilized country-average CFs, which is a simplification. In future research, integrating high-spatial-resolution biodiversity assessments with national-based input-output tables would be beneficial, building upon approaches used for water scarcity [115,116]. However, given the country-level resolution of the MRIO, it would not be possible to identify changes within specific regions of a country without the development of sub-national MRIO models. Further, households could see an increase in their water usage because of more frequent hygiene and cleaning habits to prevent the transmission of viruses and due to people working from home. However, decreasing office water use could probably compensate for some of this change [76]. Our scarcity assessment is based on conventional physical water scarcity, and we acknowledge the importance of economic water scarcity. Economic water scarcity occurs when water transfer becomes difficult due to economic, institutional, and infrastructural constraints and can occur even in certain water-abundant regions [117–119]. Finally, we did not assess the effects of improved water quality on biodiversity in natural environments brought about by the ceasing of many industrial activities [18].

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This study was supported by Aalto University and the Henan Provincial Key Laboratory of Hydrosphere and Watershed Water Security. Additional support was provided by the National Natural Science Foundation of China (42361144001, 72304112, 72074136, and 72104129) and the Key Program of International Cooperation, Bureau of International Cooperation, the Chinese Academy of Sciences (131551KYSB20210030). The paper was developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences and the Key Laboratory of Integrated Surface Water-Groundwater Pollution Control, Southern University of Science and Technology. The present work was partially developed, within the framework of the Panta Rhei Research Initiative, by the "Water Scarcity Assessment: Methodology and Application" working group. We also give big thanks to Professor Matti Kummu from Aalto University for his valuable comments on this manuscript.

Author contributions

Dandan Zhao, Olli Varis, Junguo Liu, and Laixiang Sun conceived the central idea and leaded the research. Dandan Zhao collected the data, performed the calculations, and created all figures. Olli Varis, Junguo Liu, Laixiang Sun, Klaus Hubacek, Jialiang Cai, Stephan Pfister, Hong Yang, Xu Zhao, Marko Keskinen, Kuishuang Feng, and Bin Chen participated in discussing the results. Heran Zheng, Xu Peng, Daoping Wang, and Shaohui Zhang contributed the tools and auditing. Dandan Zhao wrote the draft. All authors contributed to the analysis and development of the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2024.03.049.

Data availability

Authors can confirm that all relevant data are included in the article, cited references and/or its supplementary information files. Some main datasets include: GTAPv.11 dataset is from https://www.gtap.agecon.purdue.edu/; The economic outputs of GAINS model is from https://gains.iiasa.ac.at/gains/EUN/index.login?logout=1; The stringent index is from Oxford COVID-19 GOVERNMENT RESPONSE TRACKER (OxCGRT) (https://covidtracker.bsg.ox.ac.uk/); Water use deprived from WaterGAP model is downloaded from https://doi.pangaea.de/10.1594/PANGAEA.918447?format=html#download; Product water footprint by crop and livestock is from https://waterfootprint.org/en/resources/waterstat/; FAO crop and livestock production is from https://www.fao.org/faostat/en/#data; EXIOBASE 3 is derived from https://zenodo.org/record/3583071#.Y2zmUstBw2w. Some data that support the findings of this study are available from GTAP (Global Trade Analysis Project) and IIASA (International Institute for Applied Systems Analysis), but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of GTAP and IIASA.

Code generated datasets in the current study are available from the corresponding author on reasonable request.

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