SUSTAINABILITY

Geological resource production constrained by regional water availability

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Although the global economy requires geological resource mining, production has substantial environmental impacts, including the use of regional available water. In this study, we shed light on the global production capacity of 32 mined geological resources, considering regional water availability as a constraint. We found that current resource mining greatly exceeds regional water constraints for several, notably copper (37% of current production exceeds available water capacity) in 2010. Changing the location of production to regions of lower water stress would alleviate current exceedances of water constraints; however, considering economic factors shows that this is not always feasible. Future demand for geological resources is expected to require a considerable increase in water consumption. Considering the constraints of water resources in geological resource production is crucial for sustainability.

Mined geological resources, for example, minerals, metals, and rocks, are essential for developing and sustaining the global economy. Since the early 2000s, geological resource extraction has risen by more than 50% (*1*), driven by increasing demand for raw materials, and this upward trend is expected to continue because of the build-up of global material stocks (*2*) and the expansion of low-carbon infrastructures, such as wind and solar energy and battery storage capacities (*3*, *4*). The extraction and processing of geological resources can lead to several adverse environmental effects, including land use changes (*5*–*10*), biodiversity loss (*11*–*13*), increased CO_2 emissions (*14*), acid mine drainage (*15*), periodic tailings dam disasters (*16*), and water pollution (*17*). The significant increase in the production of mined geological resources is a part of the "great acceleration" (*18*) arguably pushing the global socioeconomic metabolism beyond planetary boundaries (*19*, *20*), which defines a safe operating space for the current society to develop and thrive while maintaining the resilience and functioning of the earth system.

Mining and processing operations of geological resources require great amounts of water, often entering the operations from surface and underground water sources (*21*–*23*). Moreover, water use and consumption in geological resource mining and processing is a critical challenge, as it competes with water use in other production systems, such as agriculture. Mining, although constituting a small fraction of global water use (2 to 4.5% in mining-intensive countries), substantially strains regional water supplies, impacting quantity and quality (*24*). Our previous study determines sustainable water use by regional carrying capacities (RCCs), which are defined as the remaining water for humanity after securing water for ecosystems (*25*). According to the estimate based on this approach, freshwater use currently exceeds the limits of water resources at the regional level, depriving aquatic ecosystems of the water they need to endure. Therefore, geological resource production at the location where water is overexploited beyond the carrying capacity will need to reduce production (to the limit for aquatic ecosystem conservation).

In this study, we aimed to determine a sustainable capacity for geological resource production under the constraint of regional available water and identify the potential gaps between sustainable production and projected future demand. Firstly, we established datasets on water consumption intensity for producing 32 geological resources in 2010 (table S1), representing all geological resources available in the SNL database, through an extensive literature review. The SNL database provides the operational data of global mines with the largest coverage, including the mined volume of each geological resource (*26*). Linking water consumption intensity with geological resource production data from the SNL database enabled estimates of the water consumption volume for geological resource production on a global scale. Secondly, we defined the overproduction of geological resources based on the water volume consumed for geological resource production beyond the RCCs of water resources of global watersheds, which were estimated in a previous study (*25*). Thirdly, we explored the theoretical potential of alleviating the overproduction of geological resources based on three defined scenarios. Lastly, we demonstrated how water constraints may cause gaps between sustainable production and projected future demand for geological resources following socioeconomic pathways (SSPs) as future scenarios (see details in materials and methods) (*27*–*29*). The definitions of key terms in this work are available in table S2.

Results

Water consumption for geological resource production and its spatial distribution

The total water consumption for geological resource production [including extraction, crushing, processing, and refining (see details in materials and methods)] in 2010 from the 3319 mines studied was estimated to be 6739 (±1564) million m^3. The estimated volume of water consumption for geological resource production was equivalent to 7 (±2)% of total industrial water consumption in 2010 (96,146 million m^3). Six major geological resources accounted for 94% of the total water consumption for geological resource production in the world: iron (33%), coal (24%), phosphate (15%), copper (10%), gold (8%), and nickel (4%) (Fig. 1; see table S8 for details). Iron and coal required a relatively smaller volume of water consumption per ton produced (table S3), whereas the relatively larger production volumes contribute to the dominant water consumption for these geological resources (table S4). By contrast, phosphate production was less than one-tenth that of iron and coal but resulted in a comparable amount of water consumption for its production because it is so water intensive.

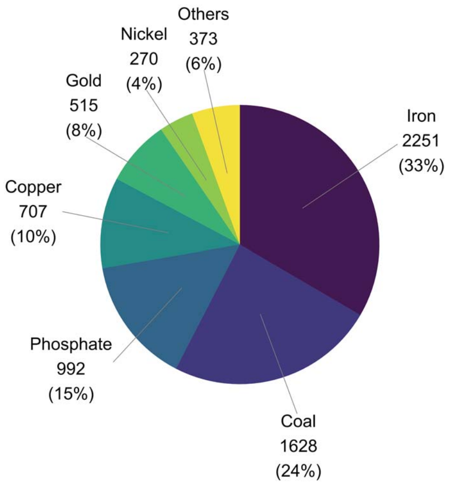

Fig. 1. Breakdown of the total water consumption (million cubic meters) for mineral production by geological resource.

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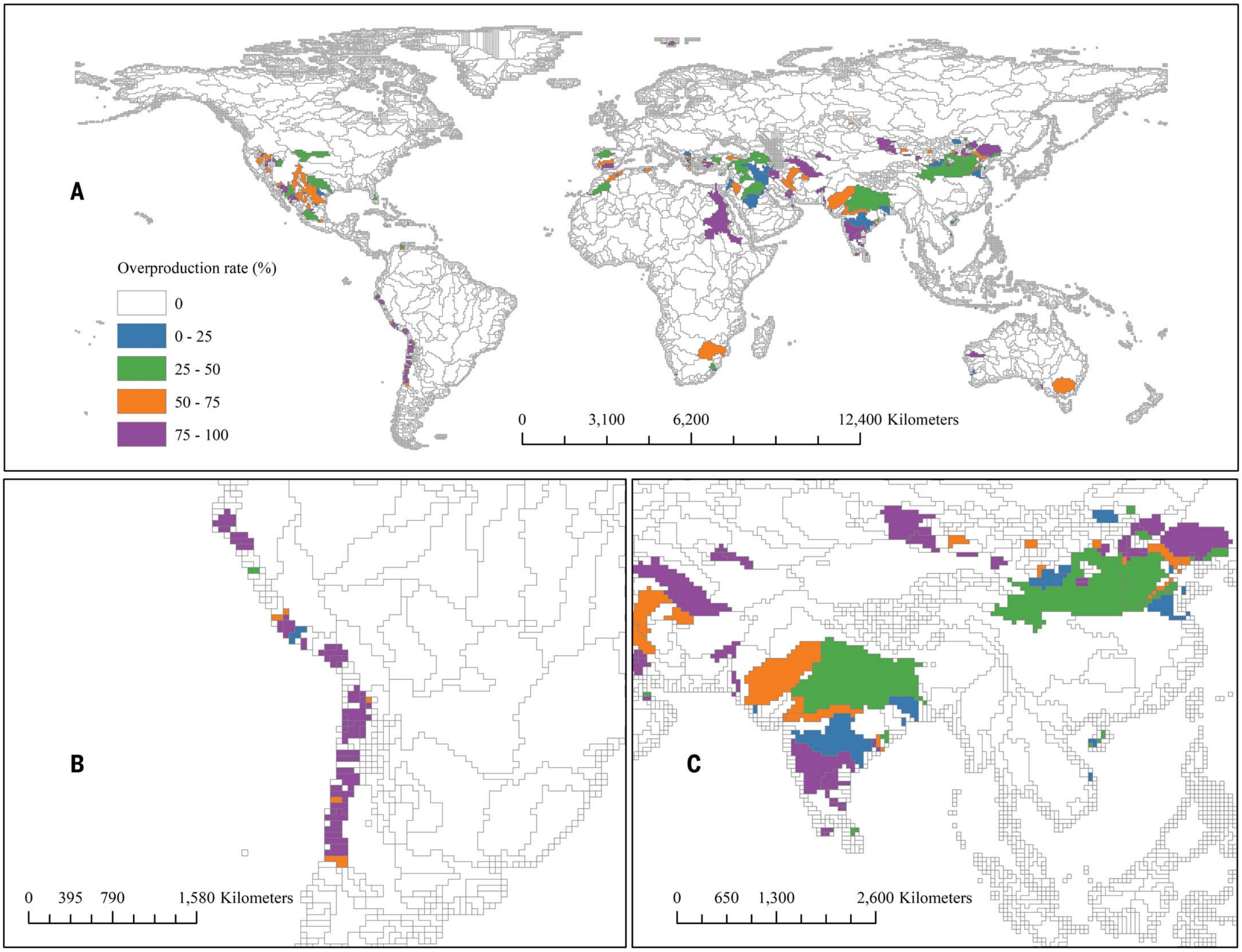

Fig. 2. Rate of overproduction of geological resources at watershed level during 2010. (**A**) The overproduction rate (%) in each watershed for global watersheds. (**B**) The zoomed-in view of mines within watersheds located in Chile and Peru. (**C**) The zoomed-in view of mines in watersheds in India and northern China.

Sustainability of water consumption for geological resource production

Constraints on water use depend not only on how much water is needed for geological resource production but also on how much water is available in the region. We estimated the overproduction of geological resources, namely the proportion of production inducing water consumption beyond RCC, at global mining sites aggregated into watersheds for 2010 (Fig. 2). Mines in Chile and Peru had the highest overproduction rates (25 to 100%). The scarcity of surface and groundwater in these regions has led to the use of desalinated ocean water for geological resource production (*30*). A total of 215 watersheds where 132 mines were located, accounting for 6% of the total watersheds with mines, experienced geological resource overproduction; although overproduction rates vary, close to half of these watersheds (105 out of 215 watersheds) had more than 75% overproduction rates across 64 mining sites. Most of these mines with higher overproduction rates (>75% overproduction) mined copper (22 sites), gold (14 sites), iron (11 sites), and coal (8 sites).

Top 10 geological resources in water overconsumption for their production accounts for around 98% of the total water overconsumption: iron, coal, phosphate, copper, gold, nickel, zinc, bauxite, chromite, and manganese (Fig. 3; see fig. S1 for details of all geological resources). Copper shows the largest proportion of overconsumption (37% of current production exceeding water resource capacity in 2010) to the current production, whereas iron shows the largest volume of water consumption but a lower proportion of overconsumption (9% of current production exceeding water resource capacity in 2010). Considering the volume of water overconsumption, coal shows the largest volume (382 million m^3), followed by copper (260 million m^3). This implies that the current momentum of decarbonization through an energy shift from coal may have synergistic effects on the reduction in greenhouse gas emissions and sustainable water use; a massive reduction of coal production will be needed to make a difference in the context of water stress alleviation. Meanwhile, decarbonization technologies are expected to require copper, and their large-scale implementation will increase the future demand for copper (*31*, *32*), possibly increasing its overproduction beyond the sustainable capacity of regional water resources.

Potential for alleviating overproduction

Six major geological resources showed major overproduction relative to their current production

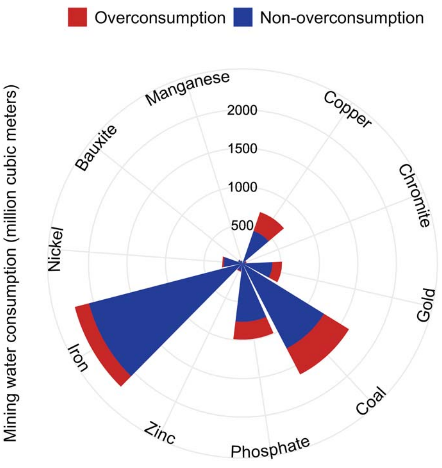

Fig. 3. Water consumption of the top 10 geological resources with the largest volume of water overconsumption. Overconsumption (red) is defined as the water volume consumed for geological resources production beyond the regional water availability (blue). The version covering all geological resources is available in fig. S1. The detailed data are available in table S11.

owing to the consumption of large water volumes. We found that countries with large geological resource production faced overproduction, whereas some countries with no overproduction had the capacity for additional production with respect to water resource availability (fig. S2 and table S5), indicating a large substitution potential for geological resource production to alleviate overproduction in other producing countries. Therefore, we analyzed the alleviation potential for substituting overproduction by countries with no overproduction in three defined scenarios: alleviation by substitution is limited by only production capacity (scenario 1), production capacity and market competitiveness (scenario 2), and production capacity and overproduction rate (scenario 3). Scenario 1 represents the maximum alleviation potential; others additionally consider more possible constraints in the context of economic competitiveness by prioritizing alleviation in countries with large volumes of overproduction (scenario 2) or high water stress (scenario 3) (see the detail of scenarios in table S6).

By adhering solely to the annual production capacity constraints, which are based on the water resources' carrying capacity, we succeeded in avoiding the overproduction of all six major geological resources in scenario 1; however, the production increase in substituting countries may not be feasible due to the limitations of facility capacity, labor, and other socioeconomic constraints for some geological resources, such as coal (166%), copper (217%), gold (101%), and phosphate (83%) (fig. S3). Conversely, the substitution potential decreased when we considered the economic competitiveness of goods produced in a country in scenarios 2 and 3. For example, some proportion of the overproduction in the current scenario (Business as Usual) will still remain in scenarios 2 and 3: 33 to 42% for coal, 30 to 32% for copper, 6 to 17% for iron, 64 to 77% for gold, 93% for phosphate, and 25 to 28% for nickel (table S7). These results indicate that the theoretical potential of substituting production with limitation by only production capacity (scenario 1) was sufficiently large to alleviate overproduction, but the feasible potentials when we considered the economic competitiveness of substituting countries (scenarios 2 and 3) were insufficient to cover the overproduction of all geological resources under the current situation. Detailed information on the major substituting countries in all scenarios is provided in table S8.

Future water consumption for geological resource production

We demonstrated that the current production of some geological resources already exceeds the production capacity under the constraint of sustainable water use (Fig. 4). This situation may worsen, given the projected increase in geological resource demand in the future. Coal will gradually increase water consumption until the midcentury. After the midcentury, water consumption for coal will increase in the three scenarios (middle of the road, SSP2; regional rivalry, SSP3; fossil-fueled development, SSP5), whereas a slight decrease of water consumption occurs in the sustainability (SSP1) and inequality (SSP4) scenarios (see the details of each scenario in fig. S4). In particular, SSP5 will result in a rapid increase after the midcentury owing to the economic growth and dependency on fossil fuels. Coal shows distinct temporal trends compared with metals (copper, iron, and nickel) because metals can be stocked in society and recycled after the lifetime of the embodied products. The three major metals' production is projected to cause a rapid increase in water consumption until the midcentury, then decline with the increased recycling of these metals in all scenarios, except for SSP3, which will reduce the demand for primary metals and associated water consumption. In the regional rivalry scenario (SSP3), the population in middle-income countries will continue increasing, although other scenarios will decrease the population in middle-income countries after the midcentury. The temporal change will differ between the SSPs, although, across scenarios, the water consumption for producing these metals is expected to reach a higher level in the future than the consumption in 2010. Considering the sustainability scenario (SSP1), water consumption associated with the production of these metals will increase by up to 241% for copper, 119% for iron, and 239% for nickel during the midcentury compared with those for their 2010 production (Fig. 4). This highlights that water constraint for geological resource production may become more severe in the future. In this case, the crucial point is that, owing to the changing climate, future changes in water availability and associated RCC will differ worldwide (*33*). Because we could not consider this aspect when estimating the future water consumption for geological resource production, our projections could be considered to contain uncertainty in the estimates in addition to the incompleteness of the coverage of global mines.

Discussion

Our results highlight that the environmental constraints, in particular, water scarcity, must be considered when discussing the sustainable production of geological resources, in addition to factors such as geological resources' abundance in the earth's crust, energy requirements in extraction and processing, and purely economic considerations, such as the availability of labor and other inputs. Both the magnitude and water consumption intensity for geological resource production determine the overproduction of geological resources. Overproduction varies by location, allowing for the potential to fully avoid overproduction of geological resources under the constraint of sustainable water use by shifting production from water-limited to water-rich regions. However, the feasibility of substitution will be restricted by several factors, including economic realities. Apart from the factors considered in this study, such substitution of geological resource production could be limited by the operational capacity of mining and production sites, including labor, quantity, and quality of deposits in substituting mining sites as well as production cost and market price of commodities. The detailed estimation of potential substitution with the consideration of these additional factors is a complex challenge but necessary in future analyses for governments and industries to plan sustainable geological resource production. An adequate regulatory framework and regular long-run planning of geological resource production are crucial for achieving sustainable water management in geological resource production. Appropriate allocation of the rights of water users (*34*) and consideration of relevant factors, including external cost of production activities, will be an effective option to avoid water constraints on future geological resource production.

Our findings indicate that increasing demand for major geological resources in the future, owing to economic and population growth, will increase water consumption associated with their production by around triple

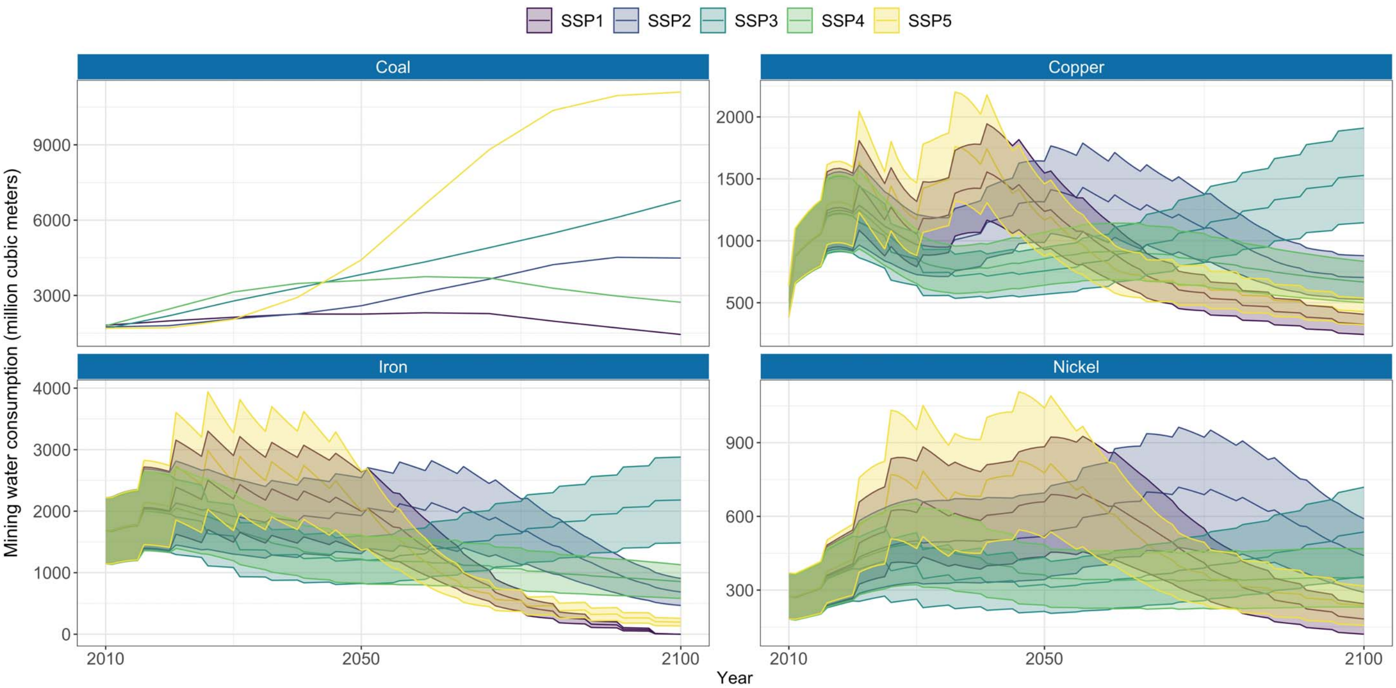

Fig. 4. Future water consumption associated with coal, copper, iron, and nickel production during 2010 to 2100 under different SSPs. Note that the shaded area in the plot denotes the range of future water consumption as the uncertainty of the estimation based on the standard deviation of water consumption intensity. Owing to the unavailability of data, the uncertainty of water consumption for coal production could not be estimated. SSP1, sustainability; SSP2, middle of the road; SSP3, regional rivalry; SSP4, inequality; SSP5, fossil-fueled development.

that of the present and may worsen the overproduction of geological resources. Although some scenarios demonstrate the decrease in water consumption for metal production owing to recycling metal stocks in society, the effects can be observed only after the midcentury, as it will take some time until stocks become available for recycling (*14*). This highlights that the improvement of water intensity for geological resource production and changing the location of geological resource production are crucial solutions to reduce the pressure of the overproduction of geological resources from a short-term perspective. At the same time, the advancement of recycling technologies and systems will also contribute to sustainable geological resource use from a long-term perspective. In addition, the demand for some metals, for example, copper and nickel, is expected to rapidly increase in response to the deployment of renewable energy technologies for decarbonization (*32*). Some previous studies have already suggested that such an increasing demand for metals for renewable energy technologies will exceed the capacity of production facilities (*35*) and the reserve of metals (*31*). Our results of increasing water consumption of metal production in the future confirm and complement these concerns on the future availability of metals.

As a first attempt to explore the relationship between geological resource production and water use, we highlighted the potential influence of the RCC of water use on geological resource production. Although the primary constraints on geological resource supply are often related to extraction capabilities and funding, our findings suggest the possibility that water use can pose a limiting factor in regional water availability and aquatic ecosystem conservation. However, the results and conclusions of this study have some methodological limitations. The limitations listed in the following paragraph should be overcome in future studies to obtain more robust results.

One of the primary objectives of this study was to illustrate the global picture of the current pressure of geological resource production on regional water resources. The mining datasets were derived from the SNL database, a comprehensive database covering global mines. However, the coverage of global mines is imperfect, as shown in tables S4, S9, and S10. There is potential for updating this analysis with comprehensive and up-to-date information on global mining sites (*36*), and site-specific production and commodity-level information need to be disclosed and obtained in parallel. Moreover, the intensity of water consumption for geological resource production has been derived from extensive literature reviews; however, we could not fully consider the effects of site-specific conditions of water use, including the effects on the water flows by geological changes for mining. Water for geological resource production is recycled or reused, and desalinated water is used in some production sites located in water-stressed areas. In addition, different water flows (e.g., evapotranspiration, product incorporation, and water transfers) are relevant to geological resource production (*37*), whereas the discrimination of water flows will be needed when considering countermeasures. In fact, some of the geological resources industry have developed their own framework for water accounting that enables tracing and management of relevant water flows for mining (*38*). However, such a good practice still needs time to be widely adopted by global production sites. For a more accurate estimation, the location-, technology- and water flow–specific water intensity for geological resource production should be pursued, although collecting location- and technology-specific data is currently challenging.

Regarding the estimation of the geological resource production capacity in the watershed, we assigned the RCCs for all water users in proportion to the amount of the total human water consumption for each use. This was a simplified assumption; however, it may have affected the estimation of the overproduction of geological resources. A completely acceptable allocation method remains undevised; therefore, several viable options for allocating RCCs to each water user should be tested in the future. For future projections of water consumption for geological resource production, we estimated only the global amount of water consumed to produce major geological resources without assessing geological resource overproduction owing to the lack of reliable data on the geographical distribution of geological resource production and water availability and consumption.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S11
Tables S1 to S19
References (*40*–*79*)
MDAR Reproducibility Checklist

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