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PERSPECTIVE

Effects of global shocks on the evolution of an interconnected world

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Abstract As the world grows more interconnected through the flows of people, goods, and information, many challenges are becoming more difficult to address since human needs are increasingly being met through global supply chains. Global shocks (e.g., war, economic recession, pandemic) can severely disrupt these interconnections and generate cascading consequences across local to global scales. To comprehensively evaluate these consequences, it is crucial to use integrated frameworks that consider multiple interconnections and flows among coupled human and natural systems. Here we use the framework of metacoupling (human–nature interactions within as well as across adjacent and distant systems) to illustrate the effects of major global shocks on the evolution of global interconnectedness between the early 1900s and the 2010s. Based on these results we make a few actionable recommendations to reduce the negative impacts of an ongoing global shock, the COVID-19 pandemic, to promote global sustainability.

Keywords Coupled human and natural systems · COVID-19 · Global interconnectedness · Global sustainability · Metacoupling

INTRODUCTION

Coupled human and natural systems (e.g., social-ecological systems, human–environment systems) around the world are interconnected through processes such as human migration, tourism, and the trade of commodities for global markets, among many others (Liu et al. 2021). These processes generate many displaced impacts on both humans and nature to the point that sustainability in one place may be determined by factors in others far away (Meyfroidt et al. 2010; Lenzen et al. 2012; Zhang et al. 2017; Fuchs et al. 2020). For instance, losses of food production in one sector (e.g., crops, livestock, aquaculture, fisheries) due to geographically localized shocks create challenges not only within the same sector and geographic region, but also across sectors and regions (Cottrell et al. 2019). Global shocks, such as the COVID-19 pandemic, exacerbate or amplify these effects, although their consequences (some of which are not necessarily negative) are highly variable depending on the degree of interconnectedness (Barbero et al. 2021; Dudek and Śpiewak 2022). Thus, it is crucial to evaluate the influence of these global shocks on the evolution of global interconnectedness.

Using the metacoupling framework (Liu 2017), here we evaluate the impacts of major shocks on the dynamics of global interconnectedness between the early 1900s and the 2010s. Metacoupling includes three types of couplings: human-nature interactions within a coupled human and natural system (intracoupling), among adjacent systems (pericoupling), and among distant systems (telecoupling) (Liu 2017) (Fig. 1). Intracoupling refers to the interrelationships among human and nature components within a system (Millennium Ecosystem Assessment 2005; Ostrom 2009; Binder et al. 2013; Liu et al. 2016), while explicitly specifying spillover effects [e.g., off-site effects or spatial externalities (van Noordwijk et al. 2004)] beyond system boundaries (Anselin 2003; Halpern et al. 2008). Pericoupling and telecoupling are umbrella concepts that encompass human-nature interactions (e.g., disease spread, species invasions, trade, migration, technology transfer) among adjacent and distant systems, respectively (Liu et al. 2013; Liu 2017). Depending on the direction of the interactions (e.g., flows of people, species, materials, energy,

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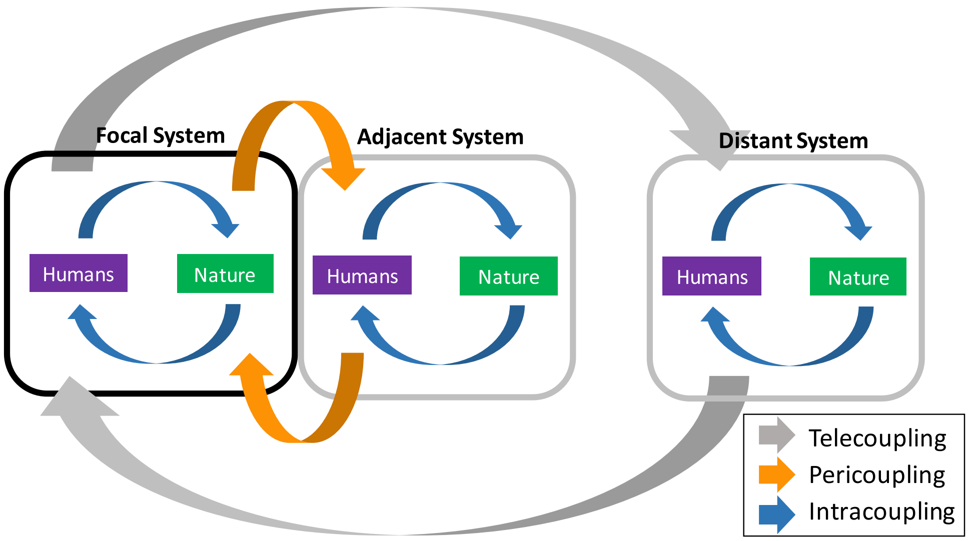

Fig. 1 Conceptual diagram representing the metacoupling framework. Blue arrows represent flows (e.g., of people, species, materials, energy, information, financial capital) within (i.e., intracoupling) a focal coupled human and natural system. Yellow and gray arrows represent these flows but between systems that are adjacent (i.e., pericoupling) and distant (i.e., telecoupling) to the focal coupled human and natural system, respectively. The framework also considers the impacts of the effects of all these flows on spillover coupled human and natural systems

information, financial capital), a system can be treated as sending, receiving or spillover (Hull and Liu 2018). Spillover systems affect or are affected by the interactions between sending and receiving systems (Liu et al. 2018a). The couplings influence each other (Herzberger et al. 2019; Carlson et al. 2020). They also have a variety of ecological and socioeconomic effects (Yang et al. 2013; Carter et al. 2015).

Although the relative contribution of intra-, peri- and telecouplings to global interconnectedness is dynamic over space and time (Liu 2020b), the magnitude of the last two has drastically increased in recent decades due to technological advancements in telecommunications and transportation networks, which reduce the cost of the flows of people, materials and information (Hummels 2007). Such advancements may increase the magnitude and speed of the flows, making the world ever more interconnected. However, as global shocks impact the flows of people, organisms, materials and information, they may modify the relative contribution of intra-, peri- and telecouplings to the global interconnectedness. Thus, it is crucial to evaluate the spatio-temporal dynamics of intra-, peri- and telecouplings in response to global shocks.

IMPACTS OF GLOBAL SHOCKS ON METACOUPLED SYSTEMS

Conceptually, the temporal dynamics of global interconnectedness can be understood as changes in the magnitude of intra-, peri- and telecoupling processes. Using these changes as a guide, here we hypothesize some of the fluctuations in global interconnectedness that may occur in response to a global shock (Fig. 2). While such changes represent overall tendencies, they are far from comprehensive, given the high complexity of metacoupled systems (Liu 2017). Initially, a focal system is dominated by intracoupling processes (e.g., local production with low trade with adjacent systems and even lower trade with distant systems; Fig. 2A). Due to its isolation, such a system is less vulnerable to shocks elsewhere (e.g., war, pandemic), although it is also more vulnerable to the effects of local shocks (e.g., drought, flood). As the world grows more interconnected through processes such as trade, tourism, and migration (Fig. 2B), the relative magnitude of intracouplings may be reduced, while those of peri- and telecouplings increase. When a shock occurs, peri- and telecoupling processes (e.g., trade, tourism) are disrupted, thus, the social, economic and environmental consequences of the shock tend to be more drastic in highly interconnected systems than in those that are more isolated. In addition, due to the disruption of the movement of people and materials, over the short and medium terms there may be a tendency for the magnitude of telecoupling to decline [although some telecouplings, particularly those related with the flow of information, may actually increase (Maghyereh and Abdoh 2022)], while the magnitude of intracouplings may increase (e.g., low availability of global commodities induces reductions in consumption and/or shifts to locally produced commodities). In addition, the magnitude of pericouplings may increase, as geographically closer suppliers start to fill the void left by geographically distant suppliers, even though such outcome is

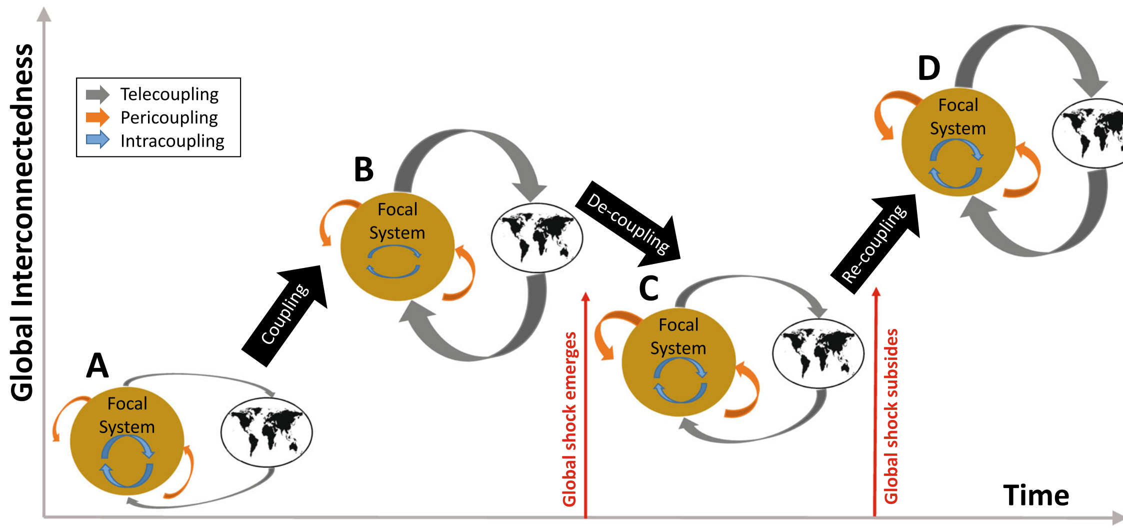

Fig. 2 Hypothetical changes in global interconnectedness due to the influence of shocks on intra-, peri- and telecouplings. Different intra-, peri- and telecoupling processes (e.g., economic growth, international trade, tourism, migration) induce couplings of coupled human and natural systems across different scales, thus increasing global interconnectedness. In contrast, global shocks (e.g., war, pandemic, economic recession) may reduce these couplings [although some couplings, particularly those related with the flow of information, may increase (Maghyereh and Abdoh 2022)]. Re-coupling starts to occur after the shocks subside. Relative magnitudes of intra-, peri- and telecouplings are represented by the thickness of their arrows. While the changes shown represent overall tendencies, they are far from comprehensive, given the high complexity of metacoupled systems

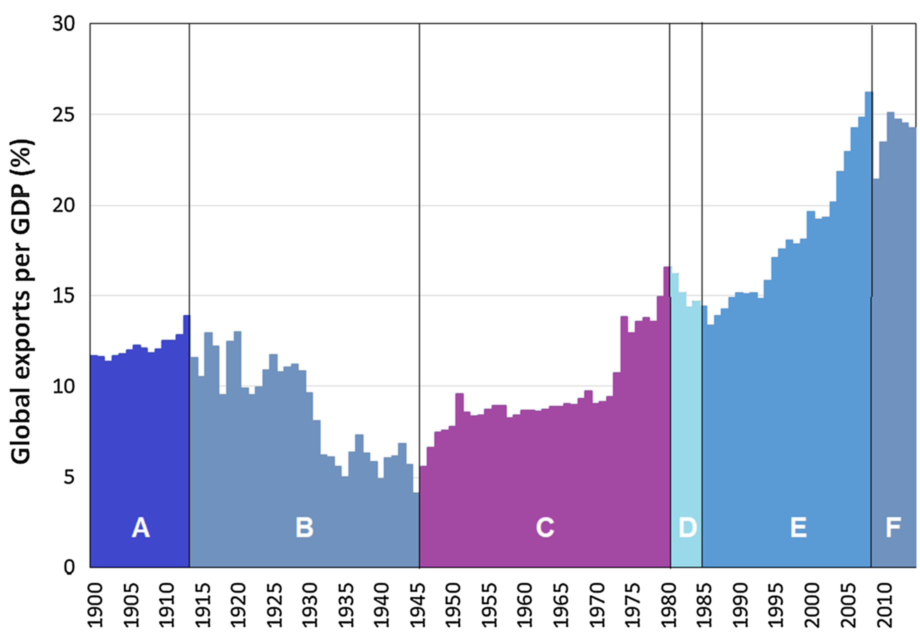

Fig. 3 Temporal dynamics of the global economic interconnectedness measured as the value of global merchandise exports per global Gross Domestic Product (GDP) (Fouquin and Hugot 2016). Highlighted in different colors are time periods characterized by particular global processes (**A** Belle Epoque; **B** Two World Wars, economic depression and the Spanish flu pandemic; **C** Post-war; **D** Economic recession of the early 1980s; **E** Establishment of the World Trade Organization and growth of e-commerce; **F** Great Recession of the late 2000s–early 2010s)

context dependent given the different conditions needed for supply chain formation (Jayaram et al. 2004) (Fig. 2C). As the shocks subside, a new normal appears in which peri- and telecouplings are, once again, enhanced while intra-couplings are either maintained or reduced (Fig. 2D).

Some of the hypothetical dynamics described in Fig. 2 have been observed throughout the 1900s to early 2010s. Figure 3 provides a general illustration of the temporal changes in global interconnectedness (represented as global exports per Gross Domestic Product). Time period A corresponds to the "Belle Epoque", a period characterized by an increase in trade, which brought economic prosperity to Western Europe and North America (Kowal 2020), while also causing environmental degradation in distant places. For instance, many bird species [e.g., egrets (such as *Ardea alba*) in South America] were pushed to the brink of extinction because their plumage was used to produce women's hats (Franco 1997; Souder 2013).

The Belle Epoque ended with the advent of World War I (1914–1918) (start of Time period B in Fig. 3), a global shock that caused social, economic and environmental consequences not only in the countries involved, but also in many other regions throughout the world (and a decoupling sensu Fig. 2B). For instance, due to World War I, the trade of plumage ended, allowing the populations of bird species affected by this trade to recover (Franco 1997; Souder 2013). Time period B exhibited an overall reduction in global interconnectedness (Fig. 3), as it was subjected to not only World War I, but also the Spanish flu pandemic (1918–1920), the Great Depression (1929–1933), and World War II (1939–1945).

After nearly two decades of economic depression and war, the world entered a period of economic growth (Green 1996), and experienced the creation of global institutions (e.g., the United Nations, the World Bank, World Health Organization). During this period the degree of global interconnectedness started to increase (Time period C; Fig. 2) until the early 1980s (Time period D; Fig. 2), which experienced a reduction due to a strong economic recession caused, among other things, by the 1979 energy crisis triggered by the Iranian revolution (Kose et al. 2020). After this recession, the world experienced the largest increase ($> 10\%$) in global interconnectedness (Time period E; Fig. 2). This period was characterized by the creation of the World Trade Organization (in 1995), which marked the biggest reform of international trade since World War II, and also by the exponential growth of the internet (thus of e-commerce). Yet such economic growth and the fast and unprecedented increase in global interconnectedness was disrupted by the great recession of the late 2000s—early 2010s. This disruption was mainly caused by the loosening of regulation and supervision of financial markets and institutions in developed countries, particularly the USA (Kose et al. 2020). This period also experienced a reduction in global interconnectedness (Time period F; Fig. 2).

While the different global forces (e.g., economic growth, international trade, tourism, migration) and shocks (e.g., war, pandemic, economic recession) behind the coupling, decoupling and re-coupling processes (Fig. 2) observed throughout history (e.g., time periods A–F; Fig. 3) exerted an influence on global interconnectedness, their effects were not homogeneous across space, as different regions and countries (Fig. 4) displayed different degrees and temporal dynamics of interconnectedness. For instance, while Africa, Eastern Europe, Oceania and Latin America demonstrated low levels of intracoupling and high levels of pericoupling, as compared to telecoupling, Asia, Western Europe and North America showed high levels of intracoupling and low levels of pericoupling as compared with telecoupling (Fig. 5). Individual countries selected from each of these regions (Fig. 4) exhibited similar temporal patterns (Fig. 6).

Consistent with what is expected during coupling (Fig. 2), during time period A (the "Belle Epoque"), Western Europe showed a relative increase in telecoupling, particularly due to an increase in exports to North America. But in this period, other regions displayed no clear trends (Africa, Eastern Europe, Oceania, Latin America) or even relative reductions (Asia and North America) in telecoupling (Fig. 5). Selected countries (Fig. 4) within these regions exhibit similar patterns (Fig. 6).

Also consistent with what is expected during de-coupling (Fig. 2), time period B (two World Wars, economic depression and the Spanish flu pandemic) presented quite drastic changes in some regions, such as a substantial relative reduction in telecoupling with a concomitant relative increase in intracoupling in Asia (Fig. 5), associated with a reduction in pericoupling in Oceania (Fig. 5). But contrary to this pattern, due to a decrease in commerce between the UK and Western Europe during WWII, the UK exhibited a reduction in intracoupling with concomitant increases in peri- and telecoupling (Fig. 6).

As is expected during re-coupling (Fig. 2), time period C (post-world wars) showed a substantial relative increase in telecoupling in Africa, Eastern Europe and Asia, as they expanded their interconnectedness with distant regions such as North America (Fig. 5). Selected countries (Fig. 4) within these regions showed similar patterns (Fig. 6). Oceania experienced drastic trends of relative increase in pericoupling during this period, and a reduction in telecoupling (Fig. 5), as its economy (particularly Australia's economy; Fig. 6) progressively became more interconnected with that of Asia (especially China) (Sampson 2021).

Likewise, consistent with what is expected during de-coupling (Fig. 2), period D (economic recession of the early 1980s) showed relative increases in pericoupling in Africa and Eastern Europe, and in intracoupling in Asia and North America, at the expense of telecoupling (Fig. 5). The patterns shown by selected countries (Fig. 4) within these regions were similar, although not as pronounced as those of the entire regions (Fig. 6).

The establishment of the World Trade Organization and the growth of e-commerce brought relative expansions in telecoupling in Africa and Latin America, while Western Europe and North America experienced relative increases

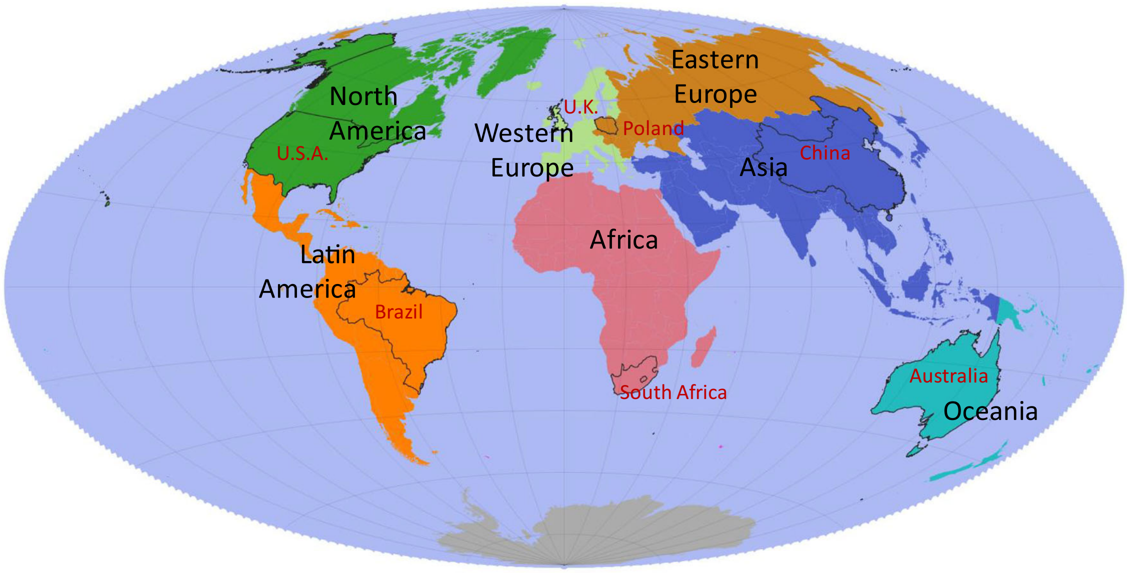

Fig. 4 Map of the globe depicting the different regions used to evaluate regional interconnectedness. Intracoupling is defined as the interconnectedness within each region, pericoupling as the interconnectedness among neighboring regions (e.g., North America–Latin America; Oceania–Asia), and telecoupling as the interconnectedness among distant (non-neighboring) regions (e.g., North America–Western Europe; Latin America–Asia). Also shown are individual countries selected from each region. These countries were selected as they constitute important exporters of commodities to global markets

in intracoupling and Oceania in pericoupling (Fig. 4). Selected countries (Fig. 4) within these regions exhibited similar patterns, with the notable exceptions of China and Poland, which showed an increase in telecoupling and pericoupling, respectively (Fig. 6). The cases of China and Poland are mostly driven by their gradual trade liberalization approaches, but while Poland increased its trade mainly with Western Europe (Berg and Sachs 1992), China increased it with the rest of the world (Ianchovichina and Martin 2001).

The Great Recession of the late 2000s—early 2010s does not seem associated with any changes in the trends of intra-, peri- and telecoupling in most regions, with the exception of Western Europe which showed a relative increase in telecoupling (Fig. 5). Other regions exhibited a stabilization in the relative magnitude of telecoupling, such as Africa, Asia and North America, while others continued their trends from period E, such as Oceania, Latin America and Eastern Europe (Fig. 5). Selected countries (Fig. 4) within these regions showed similar patterns (Fig. 6), with the exception of South Africa, which experienced a reduction in pericoupling due to a contraction in trade with the European Union and an expansion in telecoupling due to a switch in export markets toward Asian countries (Stein 2016).

As has been demonstrated throughout history (Fig. 3), the evolution from coupling to de-coupling and then to re-coupling (Fig. 2) may take from a few years to decades, and modify the relative magnitudes of intra-, peri- and telecoupling, generating different social, economic and environmental outcomes. However, these changes are heterogeneous across space and time (Figs. 5 and 6), depending on the type of interactions involved and the degree of interconnectedness of coupled systems. As such, global shocks may induce negative consequences over the short term (e.g., economic recession, reduction in public health), but may also cause some positive outcomes over the long run (e.g., diversification of production systems) that may increase the sustainability of different coupled systems throughout the world.

EFFECTS OF THE COVID-19 PANDEMIC ON GLOBAL INTERCONNECTEDNESS

Due to the current unprecedented degree of global interconnectedness, the COVID-19 pandemic rapidly became a global shock that influenced every sector of society on every place on Earth, including remote areas in the Arctic (Kapsar et al. 2022). This shock created numerous social, economic and environmental challenges, as it had drastic effects on human health, livelihoods and environmental conditions, among many others (Chakraborty and Maity 2020; Donthu and Gustafsson 2020; Harris et al. 2020; Velavan and Meyer 2020; Zambrano-Monserrate et al. 2020). It also increased previously existing vulnerabilities [e.g., food insecurity (Smith and Wesselbaum 2020), social inequality (Patel et al. 2020)]. Thus, the pandemic has

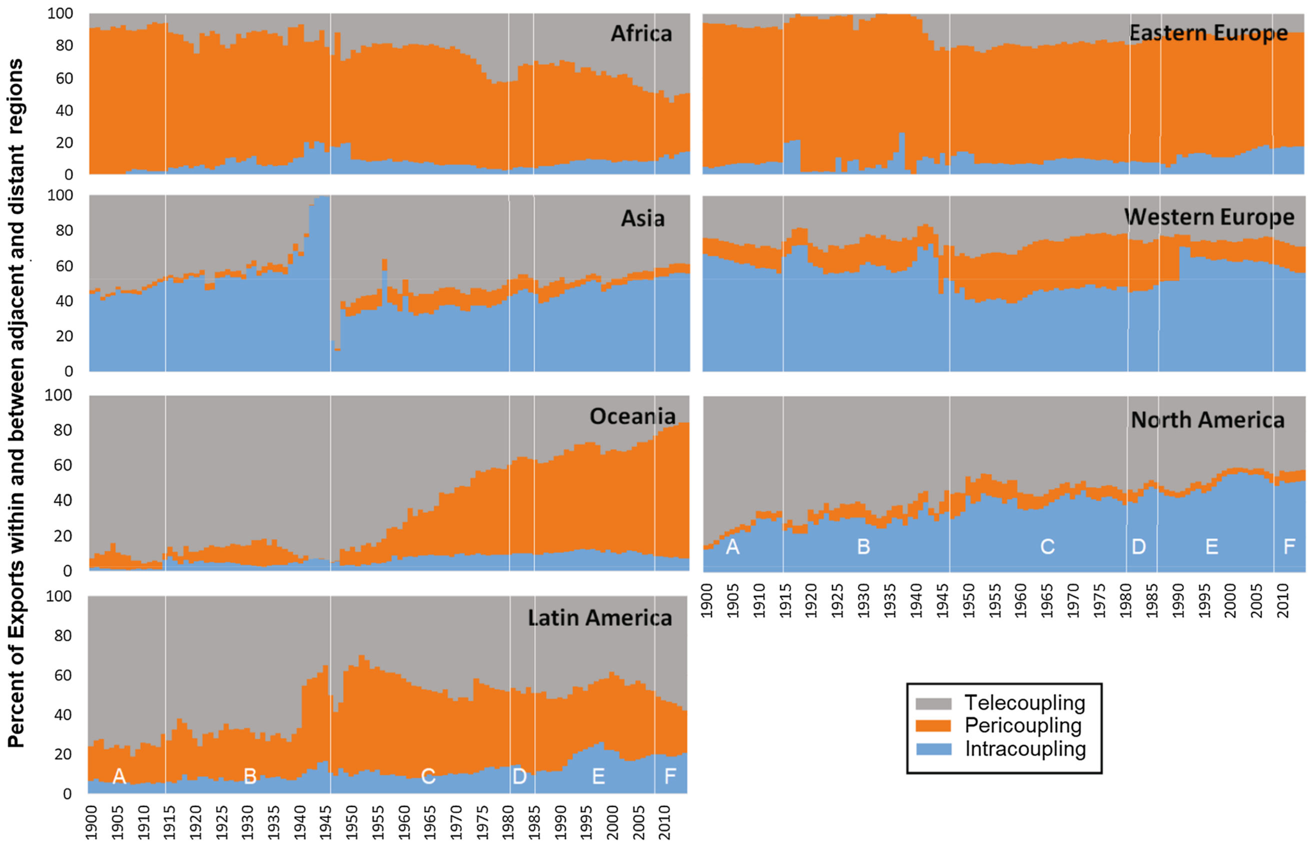

Fig. 5 Temporal dynamics of the relative contribution of intra-, peri-, and telecoupling to regional interconnectedness (see Fig. 3 for the geographic extent of each region), measured as the value of regional (i.e., aggregated per region) merchandise exports within (intracoupling), and between adjacent (pericoupling) and distant (telecoupling) regions. Aggregated export data for each region were obtained from (Fouquin and Hugot 2016). The vertical lines delimit different time periods characterized by particular global processes (**A** Belle Epoque; **B** Two World Wars, economic depression and the Spanish flu pandemic; **C** Post-war; **D** Economic recession of the early 1980s; **E** Establishment of the World Trade Organization and growth of e-commerce; **F** Great Recession of the late 2000s–early 2010s)

potentially affected the relative contributions of intra-, peri- and telecoupling to global interconnectedness (Barichello 2020; Chin et al. 2020; Erokhin and Gao 2020; Qiu et al. 2020).

The COVID-19 pandemic shares many similarities with previous global shocks. For instance, similar to the Spanish Flu of 1918, it has caused drastic negative consequences on public health at the global scale, facilitated by current transportation networks connecting all peoples around the world. In addition, with most governments at national and sub-national scales throughout the world taking drastic and unprecedented actions (e.g., lockdowns, travel bans) to reduce contagion, the COVID-19 pandemic exhibits some similarities with the impacts of world wars. While war may increase the flows of some goods and people in the areas directly associated with the conflict and adjacent systems (e.g., war supplies, troops, refugees escaping war zones), it may reduce the flow of goods among distant coupled systems and may generate cascading effects in other parts of the world beyond the war zones (Liu et al. 2022). As a consequence, this pandemic has caused large disruptions in labor supply (thus affecting supply chains) (Guerrieri et al. 2020), in the tourism industry (Sharma and Nicolau 2020) and in international trade (Gruszczynski 2020). Therefore, despite some observed increases in the flow of information (Maghyereh and Abdoh 2022), like previous global shocks (Fig. 3), the COVID-19 pandemic caused an overall reduction in global interconnectedness (Shrestha et al. 2020). The pandemic also exerted negative impacts on the global economy, which declined about 4.4% in 2020 (International Monetary Fund 2020), with a rebound of around 6.1% in 2021, and a projected growth of 3.6% in 2022, which is lower than anticipated in January, 2022 due mainly to the effects of the war in Ukraine (International Monetary Fund 2022).

The COVID-19 pandemic is also causing changes in consumption patterns (e.g., reduction, diversification), with consequences on the international trade of agricultural commodities (Aday and Aday 2020). This sector is particularly vulnerable to the pandemic because while the world's total food production has doubled over the past three decades (FAOSTAT 2020), food exports have

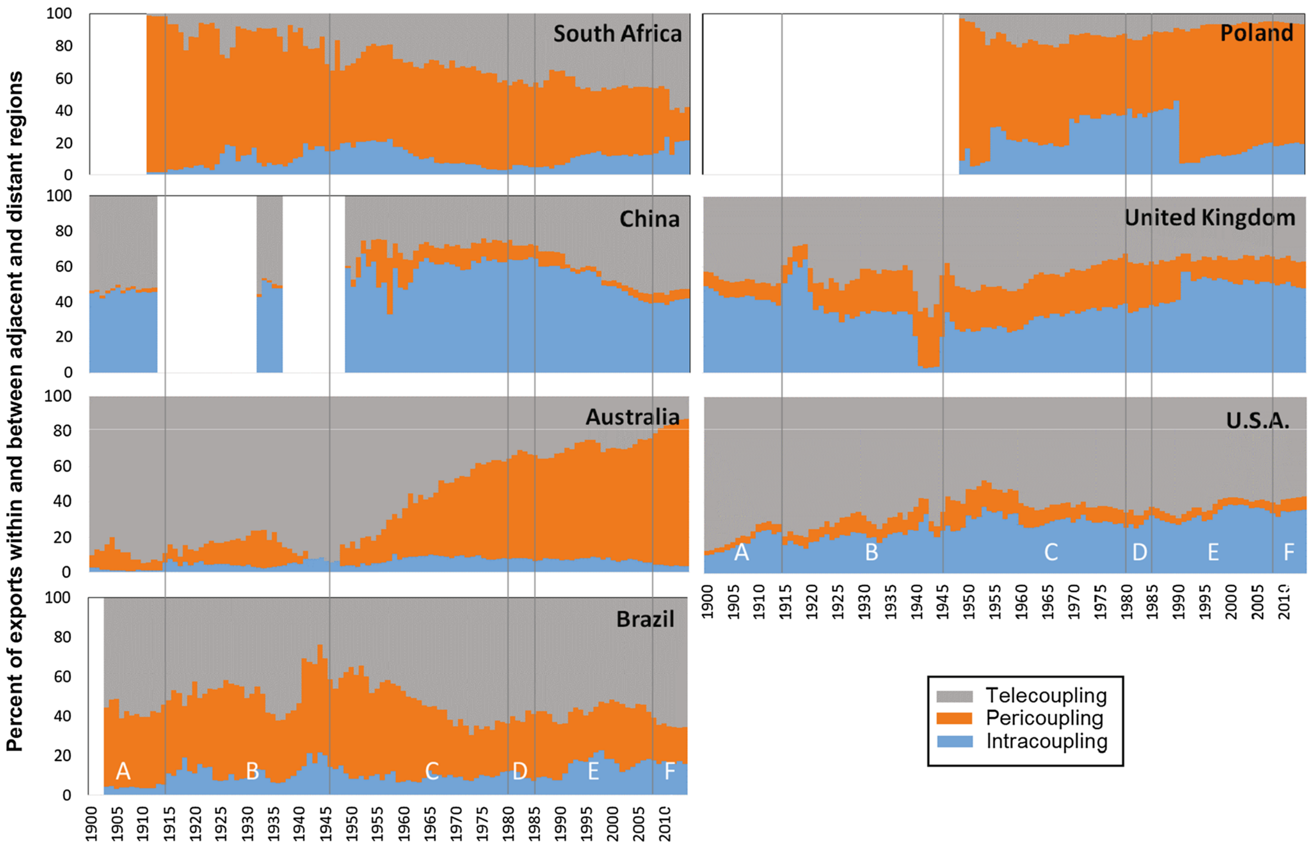

Fig. 6 Temporal dynamics of the relative contribution of intra-, peri-, and telecoupling to the economic interconnectedness of one country for each region described in Fig. 4, measured as the value of merchandise exports to countries located in the same region (intracoupling), in adjacent regions (pericoupling), or in distant regions (telecoupling). Export data for each of these countries were obtained from (Fouquin and Hugot 2016). The vertical lines delimit different time periods characterized by particular global processes (**A** Belle Epoque; **B** Two World Wars, economic depression and the Spanish flu pandemic; **C** Post-war; **D** Economic recession of the early 1980s; **E** Establishment of the World Trade Organization and growth of e-commerce; **F** Great Recession of the late 2000s–early 2010s). White (i.e., empty) areas denote time periods with no, or insufficient, data available to quantify intra-, peri- and/or telecoupling

increased tenfold (UNcomtrade 2019). With travel restrictions and lockdowns, many consumers shifted their consumption habits by reducing and/or diversifying their food sources, although this choice is not always available, particularly in places with limited food supply even before the pandemic. The net result is that the pandemic reduced the spread of production processes across different suppliers and manufacturers, particularly of high premium products (i.e., those that cost over 20% than the average category price) (OECD 2020), while also boosting local supply chains (Duguma et al. 2021). Thus, the pandemic reduced the relative contribution of peri- and telecouplings while increasing that of intracouplings in many parts of the world (Sarkar et al. 2020; Duguma et al. 2021). Such changes have multiple feedback effects [e.g., changes in the perception of risk, which influence responses to the pandemic (Breznau 2020); changes in environmental quality, which influence the diffusion of pandemic-causing viral infections (Coccia 2020); effects of pandemic-related policies, which influence social and political outcomes of global interconnectedness (Naumann et al. 2020)], which may further magnify or reduce intra-, peri-, and telecouplings, and their effects.

Besides the similarities with previous global shocks, some differences are also apparent. For instance, while previous global shocks caused rural–urban migration in some countries [e.g., to facilitate rebuilding of Western Europe after World War II (Nigg 1999)], the COVID-19 pandemic caused some short-term urban–rural migration, particularly for people exposed to higher food-insecurities (Smith and Wesselbaum 2020), as was reported in South Africa (Posel and Casale 2021). The USA has also seen some movement among economically affluent urban dwellers to suburban areas in response to the pandemic (Lerner 2020).

Similarly, while global shocks such as world wars are associated with immediate environmental degradation [e.g., air pollution (Hopke 2009)] the travel restrictions and lockdowns imposed in response to the COVID-19 pandemic exhibited positive environmental outcomes over the short term [e.g., improvement in air and water quality due to reductions in human activities (Chen et al. 2020; Naderipour et al. 2020; Saadat et al. 2020; Smith et al. 2020; Zhang et al. 2020)]. Yet, it has been suggested that the pandemic may have overall negative long-term environmental consequences due to reductions in conservation funding (given economic losses) and an increase in consumption of wild meat (given the disruptions to food supplies), particularly in developing countries (Lindsey et al. 2020). The latter is of particular concern, as wild meat consumption and unsafe wildlife trade practices are responsible for increasing the risk of zoonotic diseases (Aguirre et al. 2020), thus, making the world more vulnerable to the emergence of future pandemics.

Although the long-term consequences of the COVID-19 pandemic on all sectors of society are not fully understood, it is clear that it constitutes an unprecedented shock that is generating disruptions with cascading effects. As these effects are projected to last for several years into the future (Gillingham et al. 2020; Malliet et al. 2020), it is crucial to evaluate them within the context of a metacoupled world. Evaluating the effects of the pandemic using the metacoupling framework may reveal actions that enhance the sustainability of increasingly interconnected coupled human and natural systems worldwide (Liu 2018).

TOWARDS A SUSTAINABLE METACOUPLED WORLD

Even though global shocks tend to reduce pericouplings and telecouplings, they rebound after the shocks subside (Figs. 5 and 6). If these historical trajectories hold, we expect that the effects of COVID-19 will follow a similar pattern. In fact, large trade and investment treaties and agreements have been signed, such as the Regional Comprehensive Economic Partnership, a free trade agreement between the ten member states of the Association of Southeast Asian Nations (McCarthy 2020; Petri and Plummer 2020). However, the ways in which the world recouples (Fig. 2) are of paramount importance as they may provide some opportunities for global sustainability.

As a highly interconnected world becomes more vulnerable to global shocks such as the COVID-19 pandemic, it is more important than ever that all people fully understand the social, economic and environmental costs of their consumption habits. Consumption is the major driving force behind metacoupling (Liu 2020a), while many human activities, such as divorce (Yu and Liu 2007), in turn increase consumption. It is also the main factor shaping the future trajectories of the world (Liu 2017). Understanding the true costs will not only help making better governance decisions but will also allow implementing a more just and equitable compensation for the true costs of consumption at local, regional and global scales. This may also provide opportunities for diversifying global supply chains and to make them less geographically fragmented (i.e., lower spread of production processes across geographically distant suppliers and manufacturers). Consumers can then be brought closer to producers. Therefore, if society at-large obtains an understanding of the metacoupling framework, this will not only improve research, such as identification of knowledge gaps (Liu and Yang 2013), but also assist with the production of new knowledge (Schaffer-Smith et al. 2018; Dou et al. 2020; Xu et al. 2020a; da Silva et al. 2021), and the development and adoption of more effective sustainability policies (Liu et al. 2018b). Such an understanding may come from the incorporation of the framework into education curricula, from K-12 to graduate school levels, with a direct identification of individual coupled human and-natural systems, the flows within and between those systems, and the causes and effects of those flows. A widespread understanding that all regions in the world are metacoupled will also increase transparency of not only the benefits but also the costs of human actions, an important step toward effective policymaking (Munroe et al. 2019). Furthermore, such understanding may also help with the creation of coordinated governance processes even among distant systems (Oberlack et al. 2018). To this effect, we make a few suggestions below.

First, it is vital to map the flows of people, materials and information to unmask their direct and indirect social, economic and environmental impacts within, as well as in adjacent and distant systems (Xu et al. 2020b). Examples of this include the development of new tools for monitoring the effects of supply chains on biodiversity (Beck-O'Brien and Bringezu 2021). Such information then needs to be freely distributed in a decentralized way throughout the world through searchable databases on the internet, as well as clearly stated at the point of purchase (e.g., in the labels of goods). The free distribution of knowledge about the flows among systems will help inform the public about the social, economic and environmental impacts of their consumption choices across a metacoupled world.

Second, it is crucial to incorporate into the prices of goods and services the economic, social and environmental costs, not only in sending and receiving but especially in spillover systems. This will properly and fairly compensate the social, economic and environmental costs incurred by the flows of people, goods, and services (e.g., international trade, tourism) in a metacoupled world. The internalization of the environmental costs of solid waste (Matheson 2019) and certification schemes focusing on sustainability in which the added costs are covered by higher prices to consumers (Lambin and Thorlakson 2018) constitute a few examples of such incorporation. Incorporating these costs will contribute to reducing inequality in the distribution of the benefits and burdens of the consumption of goods and services among sending, receiving and spillover systems, within and across administrative boundaries.

Third, as there are both synergies and tradeoffs involving intra-, peri-, and telecoupling processes affecting sustainability [e.g., (Zhao et al. 2020)], it is imperative to maintain a balance among them. Enhancing one may either enhance or reduce the others, thus affecting the vulnerability to global shocks such as COVID-19. The challenge is to find the optimal balance as they differ depending on their particular conditions. For instance, local food production (intracoupling) may reduce transportation costs (thus energy expenditures and CO_2 emissions), help incentivize the diversification of foodstuffs and their production systems, and reduce the impacts on distant systems (Fuchs et al. 2020). Yet, food supplied from distant systems to areas with high endemic biodiversity (telecoupling) may help reduce the environmental impacts of local food production in the receiving systems (Chung and Liu 2022), although the international trade of food, such as soybeans, may also have negative effects on receiving systems (Sun et al. 2018). Governments at sub-national and national levels, in partnership with non-government entities at national and supra-national levels, may contribute to finding and implementing a proper balance (Meemken et al. 2021). However, it is important to recognize that while there are no silver bullets, the actions that reduce the dependence on geographically spread production processes may not only reduce the vulnerability to global shocks, such as the COVID-19 pandemic, but could also influence sustainability (Bang and Khadakkar 2020).

Fourth, as governments debate the implementation of economic stimulus programs to help cope with the economic recession caused by the pandemic, it is crucial that investments in environmental conservation/restoration are also included in these programs (Andrijevic et al. 2020). While some scholars addressing the recovery from prior shocks (e.g., the Great Recession of the late 2000s–early 2010s) have called for major investments on the environment (Omri et al. 2015), they tend to be oriented towards actions within country boundaries (Tienhaara 2014). Thus, it is crucial to consider the effects of such investments not only within but also across country boundaries, particularly on spillover systems which tend to bear much of the costs and receive few, if any, of the benefits (Dou et al. 2018). Such consideration may be implemented through bi-national or multi-national agreements that include investments in environmental conservation/restoration that cross country boundaries (e.g., the collaboration between the United States Environmental Protection Agency and the Environment and Climate Change Canada in support of the Great Lakes Water Quality Agreement—https://binational.net/).

Fifth, over the longer term, it is crucial to generate new technologies, products, markets and cooperation towards more resilient, robust and sustainable supply chains in the current era of multiple global shocks. Such new developments will contribute not only to the diversification of products, but also of production systems (Nerini et al. 2020), thus reducing their vulnerability to global shocks. A notable example on this regard was provided by the development and distribution of COVID-19 vaccines at unprecedented rates, supported by global cooperation. Increased multi-national cooperation, particularly technological facilitation mechanisms and logistic coordination among developed and developing countries at various levels will be crucial. The metacoupling framework can help with the identification of weak links and hotspots of vulnerability, thus helping to reconfigure them to strengthen the weak links while removing vulnerability hotspots.

CONCLUDING REMARKS

The integrated framework of metacoupling provides a lens to analyze the dynamic impacts of global shocks. As the world becomes more interconnected, vulnerability to global shocks increases. Such is the case of the COVID-19 pandemic, whose fast and unprecedented geographic progression was facilitated by peri- and telecouplings. In turn, the health challenges brought by the pandemic induced a global decoupling in which peri- and telecoupling processes such as trade and tourism were weakened or broken (e.g., through policies controlling the movement of people and reducing their demand for global commodities). This disruption induces changes in consumption due to lower accessibility of global commodities, causing shifts to alternative locally produced commodities. Such shifts enhance local and regional supply chains and move them geographically closer to the consumer. The long-term consequences of these shocks depend on the collective responses of the world's population. Thus, while global shocks bring negative outcomes and risks, they may also bring new opportunities for global sustainability. These include changes in consumption patterns, commodity supply diversification, and implementation of sound environmental conservation and restoration policies that consider not only individual coupled human and natural systems, but also adjacent and distant ones worldwide. Depending on the short-, medium-, and long-term responses to global shocks, these shocks may potentially present opportunities for building more resilient and sustainable societies in a metacoupled world.

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