Global Public Goods: A Survey

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This survey investigates the increasing importance of global public goods (GPGs) in today's interdependent world, driven by ever-growing, cross-border externalities and public good spillovers. Novel technologies, enhanced globalization, and population increases are among the main drivers of the rise of GPGs. Key GPGs include curbing climate change, instituting universal regulatory practices, eradicating infectious diseases, preserving world peace, discovering scientific breakthroughs, and limiting financial crises. The survey presents a compact theoretical foundation for GPGs, grounded in the provision of public goods. Because countries may be contributors or noncontributors to a particular GPG, coalition formation and behavior play a role, as do strategic interactions between a contributor coalition and other countries. In the survey, recurrent themes include strategic considerations, alternative institutional arrangements, GPGs' defining properties, new actors' roles, and collective action concerns. The four properties of GPGs – benefit nonrivalry, benefit nonexcludability, aggregator technology, and spillover range – influence the GPGs' supply prognoses and the need and form of provision intervention, which may affect the requisite institutional changes. Three representative case studies illustrate how theoretical insights inform policy and empirical tests. Regional public goods are shown to involve a question of subsidiarity and different actors compared to GPGs.

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1. *Introduction*

Global public goods (GPGs) possess partially or fully nonrival and nonexcludable benefits that affect a large swath of the planet.[1] Given myriad combinations of benefit nonrivalry and nonexcludability, GPGs may correspond to pure or impure public goods that impact much of the world's population. Quintessential GPGs include identifying virulent pathogens, ameliorating global financial crises, adopting universal regulatory practices, protecting essential ecosystems, allocating geostationary orbits, diverting earthbound planetesimals, preserving cultural heritage, reversing ozone layer depletion, and curbing climate change. These and other GPGs (e.g., eradicating infectious diseases, developing disease treatment regimes, fostering cybersecurity, preserving biodiversity, reducing transnational terrorism, maintaining world peace, discovering scientific breakthroughs, and addressing refugee flows) represent some of the world's most pressing problems. Handling these GPG problems may require efforts by a large number of countries that involve large transaction costs and, at times, institutional innovations.

Even though the study of GPGs encompasses elements of public goods provision (Bergstrom, Blume, and Varian 1986 and Cornes and Sandler 1984a, 1985a, 1996) and collective action, some novel features are of particular importance in the context of GPGs. GPGs concern collective action on a larger geographical scale than generic public goods and, thus, must address a greater extent of heterogeneity in terms of provision capabilities (Chen and Zeckhauser 2018). For GPGs, unlike public goods, there are layers of actors – individual citizens, each country, and countries collectives – whose interactions are relevant. GPGs generally involve countries or institutions as the agents, while public goods involve individuals as the agents. With countries as

[1] A good's benefits are fully nonrival when one user's consumption does not detract from the consumption opportunities available to others from the same unit. Benefits are nonexcludable when the good's benefits are available to all – payers and nonpayers alike – once the good is provided (Cornes and Sandler 1986, 1996).

the agents, sovereignty is a key GPG consideration with respect to provision and agreement. Coalition formation (i.e., voluntary cooperation by a subgroup of countries) is more germane for GPGs than for public goods to account for agent heterogeneity. Coalition analysis must investigate the adoption of technology or the presence of leakages as noncoalition countries free ride or offset the provision efforts of the coalition.[2] Alternative institutions – e.g., public-private partnerships, nongovernmental organizations (NGOs), and multilateral organizations – are important actors with respect to GPGs, but not with respect to public goods. The design of multilateral institutions can address free-riding concerns; e.g., a multilateral financial mechanism can be devised to share cost burdens among countries for environmental GPGs (Chan 2019). Such institutions can escape neutrality concerns that characterize interior solutions for public goods (Warr 1983) as new sources of funding are introduced. Decisions on cooperative arrangements normally must be made unanimously so that fairness becomes a concern for GPGs as countries' divergent interests must be reconciled. Globalization is an essential driver for GPGs, which raises issues not relevant for the traditional analysis of public goods.

Even though economists have taken a real interest in public goods since Samuelson (1954, 1955) spotlighted them, the notion of GPGs did not capture the attention of economists and other social scientists until Kindleberger (1974).[3] Kindleberger (1974, 1983) ties GPGs to key market-promoting activities at the global level such as opening trading systems, establishing well-defined property rights, and instituting standards of weights and measures. In his seminal study of the great depression, Kindleberger (1974) equates some GPGs to maintaining markets during shortages and finding essential lenders during severe liquidity shortages to correct economic instabilities. He also stresses the need for international public goods provision in the

[2] On technology adoption and leakages, see Barrett (1994a, 1994b, 2006b), Buchholz, Dippl, and Eichenseer (2017), Buchholz and Konrad (1994), Carraro, Eyckmans, and Finus (2006), Finus (2001), Harstad (2007), Hattori (2005), and sections 4-5.

[3] Cauley and Sandler (1974) simultaneously introduce GPGs to denote public goods with global benefit spillovers.

absence of a supranational government (Kindleberger 1986).

Modern-day globalization, or the increase in worldwide cross-border flows, is a driving force behind the growing importance of the study of GPGs (Kaul and Conceição 2006, Kaul et al. 2003, Kaul, Grunberg, and Stern 1999a, 1999b, and Sandler 1997, 1998). Borders are ever more porous to pollutants, diseases, propaganda, ideas, computer viruses, knowledge, and other externalities, given high-speed communication grids, computer networks, advanced transportation systems, and modern shipping vessels. There are other drivers that elevate the importance of GPGs in today's increasingly interdependent world (Cornes 2008, Ferroni and Mody 2002, Raffer 1999, and Sandler 2004). First, advances in technologies create novel GPGs – e.g., nuclear waste sequestration, the internet, satellite-based communication networks, supersonic air travel, and ozone-depleting chlorofluorocarbons. Second, economic growth and population expansion in many parts of the world place stresses on the planet that require actions to address environment-based GPGs, such as climate change. Third, novel monitoring technologies allow humankind to spot some global public bads (GPBs) and GPGs (e.g., the accumulation of atmospheric greenhouse gases, the melting of the planet's icecaps, the health of the world's forests, the state of the stratospheric ozone shield, and the spread of deserts). Fourth, the balkanization of countries transforms some national public goods into transnational public goods with consequences that extend to neighboring countries and well beyond (e.g., transnational terrorism and civil wars). Fifth, the integration of financial and goods markets can allow localized instabilities to become transnational and even global concerns, which when adequately addressed generate GPGs. A case in point is the 2007–2008 global financial crisis with its roots in the US subprime mortgage market that eventually required the development of improved financial practices in the United States and elsewhere (Asian Development Bank 2017). Sixth, high-speed communication links facilitate worldwide dissemination of ideas, threats, knowledge, misinformation, panics, and best practices that may benefit or harm the global community.

An understanding of how the world can better provide GPGs is essential to improve global welfare and address exigencies. There are many factors that inhibit the proper allocation of resources to providing GPGs so that recipient countries' summed marginal benefits are not equated to the goods' marginal provision costs. In particular, the global community represents an anarchic system in which countries generally act independently to maintain their autonomy, especially with respect to security concerns, such as maintaining world peace (Mendez 1999), eliminating transnational terrorism (Gaibulloev and Sandler 2019), or curbing nuclear weapon proliferation (Gartzke and Kroenig 2009, 2014). Thus, at-risk countries may view a rogue nation, which operates outside of accepted behavioral norms, as a threat to all, but do little to weaken the rogue, hoping that others will confront it (Peinhardt and Sandler 2015). By their nature, GPGs often require a large number of countries to coordinate actions; such large numbers frequently inhibit an effective collective response owing to strong free-riding incentives (Olson 1965 and Sandler 1992). To eradicate infectious diseases through immunization necessitates achieving herd immunity for which even a single country's inaction can greatly diminish the efforts of the collective (Barrett 2003a and section 9). Despite the growing interdependency of countries in myriad activities, there is no movement toward global governance, except in terms of regulatory practices regarding transportation and communication where such standards result in little loss of autonomy and high payoffs (Zacher 1996). Hence, we must consider countries' strategic behavior, which necessitates a game-theoretic foundation to understanding the provision of GPGs.

Adequate GPG provision can be further stymied by strategic incentives to delay contributions or to take actions that displace more provision burdens onto less strategic countries

(Buchholz and Konrad 1994, 1995). This is particularly worrisome when the coalition size and its contributions are too small to offset induced additional free riding by noncoalition countries.[4] GPG provision may also be inhibited by insufficient country-specific benefits or joint products that motivate countries' actions. Other roadblocks to GPG provision may stem from unresolved uncertainty (e.g., Barrett 2006a, 2006b, Barrett and Dannenberg 2014, Congleton 2006, and Sandler 2004), no influential leader nation (Arce 2001and Boadway and Hayashi 1999), equity worries (Buchholz, Haupt, and Peters 2016, Fehr and Gächter 2000a, 2000b, Fischbacher and Gächter 2010, Kosfeld, Okada, and Riedl 2009, and Posner and Weisbach 2010), or no requisite institutional arrangement (Finus and Tjøtta 2003 and Gollier and Tirole 2017).

Despite these and other roadblocks, the world community garnered notable successes with respect to some GPG challenges. For example, smallpox was eradicated in 1979, while the Montreal Protocol and its amendments are responsible for the continued replenishment of the stratospheric ozone layer (Barrett 1999, Benedick 1991, and Sandler 2017a). Moreover, the world community devised best banking and financial practices to limit financial crises and to speed recovery when crises occur (Asian Development Bank 2017, Kawai 2017, Rana 2004, and Wyplosz 1999). Notably, countries agreed on rules of passage to avoid accidents at sea and adopted flight practices in intercontinental air corridors to promote aviation safety. With the World Health Organization's guidance, countries work in unison to inhibit the spread of infectious diseases – e.g., Ebola and severe acute respiratory syndrome (SARS). Those containment efforts involve vigilant surveillance, quarantine efforts, and outbreak reporting, all of which represent GPGs. Another GPG success is tied to an increasing network of weather satellites that can gauge the strength of hurricanes to warn those in the storms' paths. For other

[4] See, in particular, Barrett (2007b), Buchholz and Eichenseer (2017), Buchholz, Haslbeck, and Sandler (1998), Carpenter (2007), Carraro and Siniscalco (1993), and Finus and Caparrós (2015a).

GPG cases – most notably in curbing greenhouse gas emissions – far less success has been achieved to date.[5]

The purpose of this survey is to investigate the growing importance of GPGs in today's interdependent world, driven by increasingly prevalent cross-border externalities. In so doing, we identify key considerations that impact collective action outcomes with respect to providing GPGs. Essential properties of GPGs are related to the need for corrective action and form of such actions that may include alternative institutional arrangements such as matching contributions,[6] treaties, clubs, networks, or coalition formation.

The proposed survey stresses seven recurrent themes. First, GPGs are shown to be a growing influence on world welfare, thus necessitating that those goods be adequately provided. Second, GPGs are associated with diverse collective action concerns that may differ markedly among goods. These varying differences are related, in part, to asymmetries implied by countries receiving GPG spillovers (Chen and Zeckhauser 2018 and Finus and McGinty 2019). Third, strategic behavior and, thus, noncooperative *and* cooperative game theory plays a major role in the success or failure of GPG provision (Finus and Caparrós 2015a, 2015b). Fourth, the provision of GPGs requires institutional frameworks beyond the use of international treaties that assist some environmental GPGs. Fifth, because the properties of GPGs may vary greatly, institutional arrangements must be tailored to each good. At times, clubs, which charge congestion-internalizing tolls, may be the preferred institutional mechanism as in the case of satellite-based communication networks, while, at other times, contribution-matching arrangements may be appropriate (e.g., in financing UN peacekeeping operations). Sixth, the growing prevalence of GPGs results in the appearance of new actors – e.g., public-private

[5] On the difficulties in addressing climate change, see, e.g., Aichele and Felbermayr (2013), Barrett (1990, 1999), Esty (2008), Nordhaus (1991, 2007), Ostrom (2009), Tirole (2012), and section 7.

[6] On matching contributions see Boadway, Song, and Tremblay (2007), Buchholz, Cornes, and Rübbelke (2011, 2012), Guttman (1978, 1987), and section 4.

partnerships and transregional networks – that bolster provision. Seventh, knowledge gained from overcoming collective action problems with specific GPGs can inform best practices regarding other transnational public goods with more confined spillover ranges, such as regional public goods.

The remainder of the review contains ten sections. Section 2 presents requisite background primarily focused on the four properties of GPGs, alternative types of GPGs, and the notion of subsidiarity. Sections 3-5 present theoretical considerations, commencing in section 3 with a highly stylized game-theoretic model of GPG provision. Section 4 generalizes the baseline model to account for non-normalized marginal costs, alternative aggregator technologies, leader-follower behavior, matching contributions, and joint products. Issues involving coalition formation are investigated in section 5. Institutional considerations with respect to real-world institutions are considered in section 6, which considers how the United Nations, the World Health Organization, and other institutions approach the provision of GPGs in practice. Sections 7-9 briefly present three GPG case studies – climate change, biodiversity preservation, and global health provision – to apply earlier-derived insights. Regional public goods are briefly examined in section 10, while concluding remarks complete the study in section 11.

2. *Background Concepts*

To set the stage for this GPG survey, we indicate some essential background, commencing with four basic properties of GPGs. These properties are necessary for distinguishing alternative types of GPGs that possess different strategic considerations, supply prognoses, and, thus, policy recommendations. Two key properties of GPGs involve the degree of nonrivalry and nonexcludability of benefits, the first and second properties of publicness, both of which imply that independent provision decisions by countries do not achieve Pareto-optimal levels (Batina and Ihori 2005, Cornes and Sandler 1986, Finus and Rundshagen 1998a, and Samuelson 1954, 1955). Complete nonrivalry of GPG benefits indicates that one country's consumption or use of the provided good does not reduce, in the least, from what other countries can utilize, so that there is *zero* marginal cost in extending the good's consumption to additional countries. For instance, one country's derived benefits from a thickened stratospheric ozone layer from reduced ultraviolet exposure does not diminish those potential benefits for all other countries. This zero marginal cost of consumption dictates that all countries should receive a nonrival GPG's benefits even if benefit exclusion were possible.[7] To practice exclusion for nonrival GPGs means that consumption is denied to some countries whose derived positive marginal benefits are less than the exclusion price charged. Inefficiency results because it costs society nothing from accommodating all benefit-recipient countries, so that practicing exclusion reduces net social benefits. The dilemma to the world community concerns how to finance the nonrival GPG if a charge cannot be applied to cover provision costs.

GPGs' benefits are nonexcludable if, once provided, their benefits are available to all countries regardless of their payment, which then results in free-riding or easy-riding worries.[8] The stratospheric ozone shield's benefits are nonexcludable as is limiting greenhouse gases, preserving biodiversity, controlling infectious diseases, eliminating a rogue nation, or curbing transnational organized crime. When a GPG's benefits are both nonrival and nonexcludable, then it is purely public.

Generally, GPGs do not possess fully nonrival or wholly nonexcludable benefits. At times in the literature, four extreme cases of global private and public goods are denoted (see,

[7] Olson (1965) indicates that nonrival goods result in all-inclusive consumption groups.
[8] Easy riding means that a country does not equate the sum of marginal benefits (over all recipients from a unit of provision) to the marginal provision costs, thus underproviding the GPGs (Cornes and Sandler 1984a, 1985a). Free riding means contributing nothing.

e.g., Kaul, Grunberg, and Stern 1999b). Global private goods possess rival and excludable benefits; impure GPGs offer excludable and nonrivalrous benefits (e.g., curbing organized crime activity or deploying peacekeeping forces); global commons contain nonexcludable and rivalrous benefits (e.g., open-seas fisheries);[9] and pure GPGs display nonexcludable and nonrival benefits. Most impure GPGs do not display either nonrivalry or nonexcludability in an extreme form; i.e., impure GPGs may possess partially rival or partially excludable benefits. As such, impure GPGs encompass most GPGs. Consider limiting the diffusion of transnational terrorism for which greater border vigilance can partly limit such attacks at home, while transferring some intended attacks abroad to less protected countries. In addition, acid rain is partly rivalrous because greater airborne sulfur and nitrogen depositions in upwind countries mean fewer deposits in downwind countries (Murdoch, Sandler, and Sargent 1997). Greater efforts to surveil financial practices in one part of the world takes such surveillance resources away from other countries, thereby making them more vulnerable to financial crises that may have global consequences.

An important class of GPGs consists of global club goods (GCGs), whose benefits are excludable but partly rival (Buchanan 1965, Cornes and Sandler 1996, and Sandler and Tschirhart 1980). For GCGs, excludability implies a negligible exclusion costs. GCGs abound and include INTELSAT (a global satellite-based communication network in geostationary orbit), the Suez and Panama Canals, the global air-traffic control network, satellite launch facilities, the space station, the global internet, crisis-management teams, and biohazard facilities, each of whose use is excludable. GCGs experience crowding (congestion) costs or diminished benefits as consumption is extended to each additional user country or member. An optimal toll charges *each unit* of utilization for the sum of its marginal crowding costs imposed on the membership.

[9] On global and local commons, see Barrett (2003b, 2006b), Cornes (2016), Cornes and Sandler (1983), Endres (1997), Ostrom (1990), and Sandler and Sargent (1995). Commons imply public external costs and private provision benefits, while GPGs imply public external benefits and private provision costs (Sandler and Arce 2003).

Under reasonable assumptions (e.g., constant scale economies), those tolls can finance the optimal provision of the club good (Sandler 2013 and Sandler and Tschirhart 1997). Countries reveal their heterogeneous preferences for the GCGs through their utilization rates and thus pay more in total tolls when they use the club good more intensively than other countries. Since the benefits of GCGs are partially rival, there is a positive congestion-based marginal cost for extending user privileges, so that exclusion is not welfare diminishing as in the case of excludable, nonrivalrous goods (Cornes and Sandler 1996).

The third property of publicness involves the range of benefit spillovers. Quite simply, GPGs possess global or near-global spillovers, reaching to the far corners of the planet, thereby distinguishing them from other public goods. For example, INTELSAT ties the world into a communication network with coverage except at the poles. Discovering a vaccine to immunize against Ebola or other infectious diseases protects the people of all countries. Smaller ranges of benefit spillovers result in transregional, regional, subregional, transnational, and national public goods (Arce and Sandler 2002 and Kanbur, Sandler, and Morrison 1999).

2.1 *Aggregator Technologies*

The fourth property of GPGs concerns the technology of aggregation (or aggregator technology), which indicates how countries' contributions to the GPG determine the overall level of the good that is available for consumption or use.[10] Until 1983, a summation aggregator was routinely assumed for all public goods, so that each contributor's provision adds equally at the margin to the level of the public good. With a summation GPG, each country's provision is a perfect substitute for those by other countries, thereby encouraging free riding and underprovision. In

[10] Hirshleifer (1983) and Cornes and Sandler (1984a) first indicate that individual contributions to a public good may have to be transformed by some function into the amount available for consumption. In his seminal article, Hirshleifer refers to the aggregator technology as a "social composition function." Also, see Cornes (1993) and Vicary and Sandler (2002).

the case of greenhouse gas accumulation, the overall level of those atmospheric gases equals the sum of the countries' emissions. Similarly, the amount of peacekeeping efforts consists of the aggregate troops and equipment contributed by the peacekeeping countries. The transmission capacity of an external satellite network equals the summed component satellites in orbit. Summation aggregators are generally associated with Prisoners' Dilemmas, where a contributor's provision costs exceed the contributor's provision benefits so that not contributing is a dominant strategy.

For a weighted-sum aggregator, each country's provision is assigned an empirically determined weight prior to being summed to ascertain the total level of the GPG available for use or consumption by a recipient country. These weights may be dependent on spatial or locational factors, say, in terms of prevailing winds for airborne pollutants. Each weight contains two indices – one for the producer and one for the recipient countries, thereby allowing for a determination of how much each country receives from the set of producer countries. Weighted-sum GPGs include efforts to reduce acid rain or ambient pollutants. Even the control of the spread of an infectious outbreak may abide by weighted sum because prophylactic actions may be location-specific in their effectiveness. The location of global infrastructure – e.g., a network of canals and waterways – affects countries' ease of passage differently. A weighted-sum aggregator limits the degree of substitutability and can be tied to a variety of game forms (Sandler 1998, 2004).

For a weakest-link GPG, the smallest individual contribution fixes the aggregate level of the public good. Surveillance of financial crises or a disease outbreak is only as good as the smallest effort if the world is not to be blindsided. The same holds for quarantining an infectious disease. For global air travel, the least adequate component of the air-traffic control system can affect the integrity of the whole system. A less extreme form of weakest link is weaker link for which the smallest contribution has the greatest influence on the GPG's aggregate level, followed by the second smallest contribution, and so on (Cornes 1993). Weaker-link GPGs may include inhibiting the spread of financial instability or forestalling the diffusion of a pest, where efforts beyond the smallest have an influence on the GPG's level. Weakest-link public goods result in matching contributions because provision beyond the smallest has no effect. The underlying weakest-link GPG game form is that of assurance (Sandler 1992, 1998). For weaker-link GPGs, there is less need for matching behavior.

In general, the threshold aggregator requires the overall provision of the public good to meet or surpass some level before benefits are generated (see, e.g., Bagnoli and McKee 1991). Establishment of an early-warning system for tsunamis requires some threshold or minimum grid of sensors to provide reasonable protection. Deployment of crisis-management teams worldwide to react to terrorist threats (e.g., skyjackings or ship hijackings) also necessitates surpassing a threshold to ensure a sufficient response time. Threshold GPGs are associated with coordination games where leadership may be helpful to attain the required effort level (Sandler 1998).

Although there are myriad alternative aggregator technologies, we consider just two additional ones. The aggregate provision for a best-shot GPG solely hinges on the largest contribution by a country. For instance, any country with the means to divert an earthbound comet or to eliminate a troublesome rogue country does so for all. In these two circumstances, additional efforts by other countries is redundant and wasteful. Finding the cure to a particular disease is also a best-shot GPG. For best-shot GPGs, countries must coordinate their actions by making way for the best-equipped country so that a coordination game applies. Better-shot GPGs are a softer variant of best shot for which the largest contribution by a country has the greatest influence on the good's overall level, followed by the second largest contribution, and so on. Examples include uncovering a treatment regime, where second-best regimes may be better tolerated by some patients. Campaigns to limit the diffusion of transnational terrorism or drug trafficking may have some effectiveness even if they are not the largest action.

[Table 1 near here]

Table 1 displays the seven highlighted aggregators along with select examples of each. In addition, the table links each aggregator technology to three general types of GPGs – pure public, impure public, and club goods. GCGs have the best provision prognosis because a toll scheme can finance provision and induce countries to reveal their preference.

Why are the aggregator technologies so essential for understanding GPGs?[11] There are numerous considerations. First, these aggregators are integrally connected to the underlying game structure that characterizes GPGs. As such, aggregators can influence the provision prognosis and the type for remedial policy. Consider a weakest-link GPG where all countries possess the same endowments and tastes. In this extreme scenario, there is no incentive to free ride because contributing nothing by *any* single country brings the overall level of the GPG to zero! Problems arise when countries have different incomes or capacities to contribute so that some cannot afford or match the desired contribution despite identical preferences. In this case, efforts are required to "shore up" the poorer countries and such actions confront free-riding incentives as well-to-do countries wait for other rich countries to do the shoring up (Sandler 2016). The larger the number of rich countries, the greater the free-riding concern. Second, the aggregator technologies influence the direction of transfers to improve the level of GPGs.[12] For instance, the provision levels of weakest-link GPGs improve when income is evenly distributed for identical tastes because countries then have the ability to match efficient contribution amounts (Jayaraman and Kanbur 1999 and Sandler 1997). Third, leadership can assume a key

[11] The underlying literature includes Arce and Sandler (2002), Barrett (2006b, 2007b), Buchholz and Rübbelke (2017), Caparrós and Finus (2019), Kanbur, Sandler, and Morrison (1999), and Sandler (1997, 1998, 2004).
[12] Such transfers for weakest-link and best-shot GPGs involve corner solutions so that the number of contributors changes. As such, neutrality does not apply (Bergstrom, Blume, and Varian 1986, Warr 1983, and section 4).

role for some aggregator-associated game forms (Arce 2001). Fourth, in a global context, aggregators may offer a need for some institutions – e.g., multilateral organizations such as the United Nations – to build up capacity, to arrange monitoring, to provide leadership, or to achieve thresholds. In the case of monitoring, the United Nations established the Cooperative Program for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) in 1977 to measure the transport matrices for sulfur and nitrogen oxides emissions. Fifth, aggregator technologies indicate the importance of country heterogeneity in supplying GPGs. Rich countries are essential in providing best-shot and better-shot GPGs for which concentrated action is required.

[Table 2 near here]

Table 2 draws on the relevant literature[13] and the above discussion to gather together some provision prognoses and policy recommendations for GPGs based on their underlying aggregator technology. As a general rule, summation GPGs are more plagued than other aggregator-based GPGs from free riding and, thus, the need for grants (or outright gifts) or loans by multilateral organizations, other institutions, and donor countries. The mistaken notion that GPGs generally abide by Prisoners' Dilemmas can be dispensed with when coordination, assurance, and other strategic aspects of nonsummation aggregators are recognized.

2.2 *Joint Products*

In his seminal work on collective action, Olson (1965) introduces "selective incentives" as a means for overcoming free riding associated with collective or public goods. Quite simply, selective incentives' contributor-specific benefits may motivate an agent to provide the public

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[13] The literature includes Arce (2001), Arce and Sandler (2002, 2003), Bagnoli and McKee (1991), Barrett (2003b, 2007b), International Task Force on Global Public Goods (2006), Kaul and Conceição (2006), Sandler (1997, 1998, 2004, 2015), and Segasti and Bezanson (2001).

good. When jointly produced private benefits are added to the contributor's share of the tied public benefits, the contributor may come to view received net benefits to be positive. With time, public goods with selective incentives became equated with *joint products* where a public activity simultaneously gives rise to multiple outputs whose publicness may vary. Consider a military alliance for which allies' defense spending deters potential aggressors (an alliance-wide pure public good), protects an alliance's exposed borders (an impure partly rivalrous public good), and generates ally-specific private goods (e.g., national prestige, coastal protection, and riot control) (Sandler and Hartley 2001). Andreoni (1988, 1989, 1990) applies joint products in his work on charitable giving for which a warm glow of the giver inspires more general altruism, a pure public good. In the case of foreign assistance, warm glow and other contributor-specific gains (e.g., prestige, military bases, trade agreements, or foreign-policy concessions) may motivate the GPG of relieving world poverty (Anand 2004, Kanbur, Sandler, and Morrison 1999, Raffer 1999, and te Velde, Morrissey, and Hewitt 2002).

With joint products, there are at least three goods in the country's utility function. Suppose that these goods are a private numéraire good, a jointly produced pure public good, and a jointly produced contributor-specific good. The presence of three goods means that the joint products may be Hicksian substitutes or complements, so that – holding utility constant – an increase in the price of the private good will increase (decrease) the demand for the country-specific good that is jointly produced with the country's public good contribution. In the case of gross complements, Cornes and Sandler (1984a, 1994) show that increased contributions by others to the public good may induce a contributor to raise its own contributions in order to get more of the complementary contributor-specific output.[14] Thus, joint products may curtail the

[14] Technically, gross complementarity hinges on the relative values of the cross and direct compensated price effects for the jointly produced goods.

substitutability between contributors' public good provision by resulting in a positive relationship between a country's contributions and those from other countries. In a sense, contributor-specific benefits foster property rights to the jointly produced public good, because the former private benefits can only be acquired by contributing to the joint product activity. This is especially germane for GPGs that often contain donor- or country-specific benefits tied to public benefits. Joint products are necessary to explain the production of public bads, provided that the country's gain from, say, polluting is greater than its losses from generating pollution (Cornes and Sandler 1996, pp. 242-3). The existence of joint products also means that neutrality of income redistribution does not hold, thereby allowing income policies to affect the level of the public good. For GPGs, income redistribution may be in the form of foreign assistance.

Joint products are important for institutional design in the global community, which is a recurrent theme with respect to GPGs. That is, institutions promoting GPGs can be designed to emphasize country-specific benefits. In the United Nations, the five permanent members of the Security Council get to decide the deployment of UN peacekeeping missions, thus bestowing to these countries a valuable country-specific benefit. This benefit then motivates them to assume a larger portion of total UN peacekeeping costs than other UN members. For joint product GPGs, the extent of suboptimality depends on the ratio of excludable (including country-specific) benefits to total benefits. As this ratio approaches 1, the activity is more private; as this ratio approaches 0, the activity is more globally purely public. This ratio may be endogenous to the choice of the institution – see section 6.

2.3 *On Subsidiarity*

In a classic article, Olson (1969) introduces fiscal equivalence for which the political jurisdiction matches the range of benefit spillovers for the public good (or externality), known as the economic domain. A mismatch between the political jurisdiction and economic domain implies inefficient provision. If the economic domain exceeds the political jurisdiction, then too little of the public good is anticipated as marginal benefits of spillover recipients outside of the jurisdiction are ignored. If, on the contrary, the political jurisdiction extends beyond the spillover range, then too much of the public good is anticipated as financing burdens are placed on those not receiving benefit spillovers. For transnational public goods, the notion of fiscal equivalence, a within-country concepts, gives rise to the subsidiarity principle for which the public good spillover range determines the jurisdictional or institutional reach (Kaul, Grunberg, and Stern 1999a and Sandler 1997). Thus, multilateral organizations with a global mandate should allocate resources to GPGs. For example, the UN Environmental Programme helps coordinate countries' efforts regarding climate change or ozone shield depletion, while the World Health Organization coordinates efforts regarding global pandemics and other infectious diseases. Based on subsidiarity, regional institutions address regional public goods, such as regional infrastructure projects. Some deviation from strict adherence to subsidiarity is necessary if economies of scale or scope warrant expanding the political jurisdiction owing to cost savings (Sandler 1997, 2006, 2010).

3. *The Baseline Model*

Analogous to firms in oligopolistic competition, sovereign countries strategically react to the decisions of the other countries and choose their best responses when they independently decide their contributions to a GPG. Hence, the theory of voluntary public good provision (as pioneered by Bergstrom, Blume, and Varian 1986 and Cornes and Sandler 1984a, 1985a, 1986) provides the cornerstone for our presentation of the major theoretical insights relevant for understanding

GPG supply in the real world.[15] To present this theoretical approach, we use a very stylized model for which there are *n* countries that are characterized by their initial endowments or incomes, w_i (measured in units of the private numéraire good) and their utility functions, $u^i(c_i, G)$, where c_i denotes country i's private good consumption and G is GPG supply.[16] That all countries equally benefit from public good supply G reflects that the public good's nonrivalry and nonexcludability are features of our baseline model.[17]

The part of its endowment that country i does not spend on private good consumption is this country's GPG contribution, $g_i = w_i - c_i \geq 0$. In the baseline model, the technology of aggregation is a summation technology, i.e., $G = \sum_{i=1}^{n} g_i$, so that each country's GPG contribution adds equally to the level of the GPG. The marginal rate of transformation between the private and the public good, i.e., the GPG productivity, is then constant and equal to one for each country, and $G + \sum_{i=1}^{n} c_i = \sum_{i=1}^{n} w_i$ holds for any feasible allocation. Other aggregator technologies are considered in section 4.

In the framework of this highly stylized model, we now apply the Aggregative Game Approach (AGA) of Cornes and Hartley (2007)[18] to determine the Nash equilibriums of noncooperative GPG provision by sovereign states. This approach makes apparent mechanisms and effects necessary for understanding GPGs and conducting some comparative statics exercises. The AGA is based on the fact that country i, which actively contributes to the GPG,

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[15] For comprehensive treatments of public good theory, see Batina and Ihori (2015) and Cornes and Sandler (1996).

[16] The utility functions are assumed to have the standard properties: they are twice partially differentiable, strictly monotone increasing in both variables, and quasi-concave.

[17] Global public bads (GPBs) and commons are encompassed in this model because reducing the level of a GPB or restricting the depletion of global commons can be interpreted as provision of a GPG.

[18] Cornes (2016) shows how the AGA can be applied to various environmental public goods and especially to environmental GPGs.

only attains an equilibrium position of the voluntary contribution game if a marginal change of its public good contribution, $g_i > 0$, does not increase its utility. Similar to a price-taking agent in microeconomics household theory, country i's marginal rate of substitution, $m_i(c_i, G)$, at an equilibrium position, (c_i, G), must equal the marginal rate of transformation between the private good and the GPG, which in our baseline model is assumed to be one. In a c_i-G diagram, these potential equilibrium positions of country i, at which the indifference curves have the slope –1, correspond to the (income) *expansion path*, $e_i(G)$.

The location of the expansion path $e_i(G)$ indicates how much a country appreciates the GPG: the more a country values the GPG, the closer its expansion path lies to the G-axis.[19] A country's preference intensity for the GPG can be traced back to two different causes – to objective factors based on the range of cross-border spillovers (e.g., different degrees of exposure to terrorist attacks, contagious diseases, fake news, refugee outflows, or environmental harm) and to subjective factors like citizens' and politicians' diverging safety and environmental concerns.

By means of expansion paths, GPG supply, $\hat{G}$, in a Nash equilibrium of voluntary public good contributions is characterized by

$$(1) \quad \hat{G} + \sum_{i \in C} e_i(\hat{G}) = \sum_{i \in C} w_i \, ,$$

where C denotes the set of contributing countries. As the position of each country $i \in C$ lies on its expansion path $e_i(G)$, the country's private good consumption in the Nash equilibrium is given by $\hat{c}_i = e_i(\hat{G})$. For a noncontributing or free-riding country i, its private consumption is

[19]A greater preference intensity for the GPG means that $m_i(c_i, G)$, which is the reciprocal value of country i's marginal willingness to pay $\rho_i(c_i, G)$ for the GPG, becomes smaller at any (c_i, G), so that indifference curves become flatter. The assertion on the expansion paths then follows from the convexity of indifference curves.

$\hat{c}_i = w_i$, so that we instead have $e_i(\hat{G}) \geq w_i$. If we assume that both the private good and the GPG are strictly non-inferior for each country $i = 1,...,n$, a Nash equilibrium then exists and is unique (see Bergstrom, Blume, and Varian 1986 and Fraser 1992).

For the case of two countries, figure 1 depicts how the Nash equilibrium is determined by horizontal aggregation of the expansion paths. In figure 1, equilibrium public good supply $\hat{G}$ is found at the point of intersection between the function $\Psi(G) := G + e_1(G) + e_2(G)$ and the vertical line that represents the aggregate endowment $W = w_1 + w_2$ of the two countries. For private consumption of country $i = 1,2$, we have $\hat{c}_i = e_i(\hat{G}) < w_i$, which indicates that both countries are contributors to the GPG.

[Figure 1 near here]

This baseline model directly provides some findings, which are well-known from standard public good theory and which are also of much relevance in the specific context of GPGs as shown throughout the ensuing applications.

(F1): *The Nash-equilibrium level of GPG supply is suboptimal. The divergence of GPG supply between the Nash equilibrium and a Pareto-optimal allocation is greater as the number* k_C *of contributing countries increases.*

That the Nash equilibrium is not Pareto optimal follows because the sum of marginal rates of substitution between the public good and the private good over the k_C contributing countries, i.e., $\sum_{i \in C} \rho_i(\hat{c}_i, \hat{G}) = k_C$, exceeds one if there is more than a single contributing country. According to Samuelson's rule (Samuelson 1954, 1955), this sum must be $\sum_{i \in C} \rho_i(\hat{c}_i, \hat{G}) = 1$ for a Pareto-optimal allocation, where $\rho_i(\hat{c}_i, \hat{G}) = 1 / m_i(\hat{c}_i, \hat{G})$. The difference between these two equations becomes larger when the number k_C of contributing countries increases, which indicates that the suboptimality of the Nash equilibrium is aggravated as benefit recipients grow in number (Sandler 1992, pp. 49-54). Some additional considerations show that the GPG will be usually undersupplied in the Nash equilibrium as compared to Pareto-optimal allocations (e.g. Cornes and Sandler 1996, pp. 158-63).[20]

Finding 1 reflects the deep "social dilemma" occurring in the context of public good provision. Unlike the case of private goods (and perfectly working markets), isolated actions by utility-maximizing agents do not result in a Pareto-optimal allocation for public goods so that collective action is required to attain optimality. Yet, especially when many countries are involved, international cooperation curing or even ameliorating the suboptimality of GPG provision is difficult to achieve, which figures prominently throughout the survey.

(F2): *If income increases in some contributing country i, more of the GPG will be supplied in the noncooperative solution and utility of all countries will increase.*

This finding follows immediately since a rise in income increases the right-hand side of eq. (1). In order to re-establish identity between both sides of eq. (1), the left-hand side also must increase. The non-inferiority of the GPG implies that the countries' expansion paths are increasing, resulting in a higher GPG supply. The simple intuition behind F2 is that – given non-inferiority of the GPG and a constant GPG price – a country wishes to consume more of the GPG when its income rises. Because the other contributing countries then move outward along their expansion paths where their private consumption also increases, they also benefit from the increase of income in a single contributing country. This spillover, which occurs in the strategic

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[20]For example, Cornes and Sandler (1996) show that eliminating the income effect on the public good with the help of a quasi-linear utility function ensures that the deviation between the Nash equilibrium and the Pareto optimum increases with group size. Some exceptional cases are considered by Buchholz and Peters (2001).

context of voluntary public good provision, however, dampens the rise of the GPG level as compared to the situation in which the country with the higher income stood alone. For environmental GPGs, F2 moreover qualifies the view that economic growth leading to higher incomes will necessarily be harmful to the environment.

A comparative statics finding that is analogous to F2 refers to changes of preferences:

(F3): *If preferences for the GPG in some country i get stronger, GPG supply in the Nash equilibrium and the utility of all countries except country i will increase.*

Using the fact that stronger preferences for the GPG in country i shift this country's expansion path closer to the G-axis, finding F3 can be substantiated in quite the same way as F2 with help of eq. (1).

At first glance, one might suspect that a redistribution of income to countries that have more interest in the GPG could increase GPG supply in the Nash equilibrium. However, this expectation is not fulfilled, which is also a straightforward implication of eq. (1).

(F4): *A redistribution of income that does not alter the set of contributors leaves GPG supply in the Nash equilibrium and the utilities of all countries unchanged irrespective of the preferences of the donor and the recipient countries.*

This finding follows since a redistribution of income among contributing countries does not change both sides of eq. (1) so that after the redistribution the condition is satisfied for the same GPG level $\hat{G}$ (and the same levels of private consumption in each country) as before. The reason for this famous "Warr neutrality" (Becker 1974, Cornes and Sandler 1984a, and Warr 1983) is that the countries adapt their contributions to the GPG to their changes of income: The income-receiving country contributes more after the redistribution, while the income-losing country contributes less to the GPG so that their changing contributions precisely offset one another. In a GPG context, this means that sources of funding for these GPGs must come from new sources and not be repurposed for existing financing. The appearance of new agents at the global level – e.g., charitable foundations and public-private partnerships – with new funding sources can escape this neutrality concern. Neutrality is dependent on our very restrictive assumptions, some of which are relaxed in section 4.

4. *Generalization of the Baseline Model*

Although the extensions and ramifications of the baseline model that we consider apply to public goods in general, most of them have been developed with special reference to GPGs.

4.1 *Contributors and Noncontributors and the Exploitation Hypothesis*

Not every country contributes to a GPG in the noncooperative Nash equilibrium[21] – e.g., most developing countries contribute nothing to climate protection, while large industrialized countries contribute the most to climate protection. A key question concerns identifying GPG contributors and their contributions (e.g., Bergstrom, Blume, and Varian 1986 and Andreoni 1988).

(F5): *At the Nash equilibrium, high-income countries are more likely to be contributors and make larger contributions to the GPG than low-income countries. The same holds for countries with a strong preference for the GPG.*

To examine the effects of countries' income on their GPG contributions in the Nash equilibrium, we initially assume that all countries possess the same preferences and thus the same relevant expansion path, denoted by $e(G)$. From eq. (1), all contributing countries must have the same private consumption equilibrium level, $\hat{c} = e(\hat{G})$. High-income countries with

[21] For mechanisms by which contributors and free-riders are identified, see Andreoni and McGuire (1993). Shrestha and Feehan (2003) focus on this identification with international public goods.

$w_i > \hat{c}$ are contributors, making the GPG contribution, $\hat{g}_i = w_i - \hat{c}$, which increases with income. Low-income countries with $w_i \leq \hat{c}$ are noncontributors.

In terms of the effect of different preferences on the countries' GPG contributions, we assume that all n countries have the same income, w, and are ranked according to the location of their expansion paths, i.e., $e_1(G) \geq \ldots \geq e_n(G)$ for all G. Based on section 3, countries with higher ranks exhibit a stronger preference for the GPG. Since in the Nash equilibrium all contributing countries have private consumption, $\hat{c}_i = e_i(\hat{G})$, all high-preference countries with $e_i(\hat{G}) < w$ are contributors, making the GPG contribution, $w - e_i(\hat{G})$ (which is increasing in i or the preference intensity for the GPG). All low-preference countries with $e_i(\hat{G}) \geq w_i$ are noncontributors.

Finding F5 shows that, metaphorically speaking, there is "exploitation" of the rich countries by the poor, which is a seminal result in the theory of GPGs (Olson 1965, Olson and Zeckhauser 1966, and Sandler 2015). Similarly, there is exploitation of countries that are more interested in GPG provision by less interested countries (Buchholz and Sandler 2016). The impacts of income and preferences may counteract each other so that, e.g., a country with low income but strong preferences for the GPG contributes more than a country with high income but low preferences.

When noncontributors are taken into account Warr neutrality ceases to apply, and income transfers may yield an increase in public good supply (Bergstrom, Blume, and Varian 1986).

(F6): *If income is shifted from a noncontributing country to a contributing country, GPG supply in the Nash equilibrium and utility of all countries, except the donor country, will increase while utility of the donor country falls.*

This income transfer raises the aggregate income of the initial contributor group, captured by the right-hand side of eq. (1). Because expansion paths are increasing owing to non-inferiority, GPG supply and private consumption of all initially contributing countries (and clearly also of all initial noncontributors except country i) must increase to restore equality in eq. (1). All initial noncontributors remain noncontributors after the redistribution, while some initial contributors may become free riders. The donor country *i* loses utility because as a noncontributor its marginal willingness to pay, $\rho(w_i, \hat{G})$, in the original Nash equilibrium is smaller than one, the transfer-induced increase of GPG is smaller than its lost private consumption.

Cornes and Sandler (2000) establish that since some Nash equilibrium, tied to an initial income distribution, may dominate another income distribution's equilibrium, a Pareto-improving redistribution from noncontributors to contributors is possible under special assumptions. For a summation aggregator, those circumstances involve a large number of noncontributors possessing a high marginal valuation for the GPG and contributors displaying a sizeable GPG response to their augmented income.

4.2 *Weighted-Sum Technologies and Pareto-Improvements through Redistribution*

GPG productivity generally differs among countries based on technological capabilities and locational factors as described by Cornes (1993), Buchholz and Konrad (1995), Ihori (1996), and section 2.[22] We now generalize the baseline model by assuming that country *i*'s GPG productivity may be some constant, $a_i \neq 1$, which varies among countries. Country *i*'s individual expense for the GPG, $z_i = w_i - c_i \geq 0$ (measured in units of the private good), is then transformed into this country's GPG contribution (measured in units of the GPG), $g_i = a_i z_i$. The reciprocal

[22] For climate protection, a general empirical assessment of differences in greenhouse gas abatement costs is provided by Gillingham and Stock (2018).

value $1/a_i$ of a country's contribution productivity can be interpreted as its "price" of GPG provision. In the case of a summation aggregator, we thus have $G=\sum_{i=1}^{n} g_i = \sum_{i=1}^{n} a_i z_i$, so that any feasible allocation is characterized by $G+\sum_{i=1}^{n} a_i c_i = \sum_{i=1}^{n} a_i w_i$.

Country *i* is at a Nash equilibrium position at some (c_i, G) if its marginal rate of substitution between the private good and the GPG equals a_i. By $e_i(\hat{G}, a_i)$, we denote the corresponding expansion path, which connects these potential equilibrium positions, along which country *i*'s indifference curves have slope $-a_i$. GPG supply, $\hat{G}$, in the Nash equilibrium of this generalized model is characterized by

(2) $\hat{G}+\sum_{i\in C} a_i e_i(\hat{G}, a_i) = \sum_{i\in C} a_i w_i$,

and private consumption of a contributing country is $\hat{c}_i = e_i(\hat{G}, a_i)$. Based on eq. (2), we can now infer the effect of an income transfer from some contributing country to another (Buchholz and Konrad 1995, Ihori 1996, and Jayaraman and Kanbur 1999).

(F7): *A redistribution of income from a country with a low GPG productivity to a country with a high productivity increases GPG supply and the utility of all countries in the Nash equilibrium.*

This finding follows because an income transfer Δ from some country *j* with contribution productivity a_j to country *k* with greater productivity a_k increases the right-hand side of eq. (2) by $(a_k - a_j)\Delta$. Equality in eq. (2) can only be re-established when public good supply, private consumption of every contributing country, and utility of all countries (including the noncontributors) increase. Moreover, Buchholz and Sandler (2016) show that countries with high GPG productivities are more likely to be contributors, other things constant.

4.3 *Unilateral Action and Leadership*

In the context of GPG provision, unilateral action by a country may involve an increase of a country's GPG contribution or an improvement of its technology of GPG provision. Given the strategic context of voluntary public good provision, the effects of unilateral actions on GPG supply in both cases are dampened through countervailing actions by other countries.

A country that deviates from the Nash equilibrium by making an extra GPG contribution to show goodwill or to set a good example often becomes worse off after its unilateral action.[23] But even when such an additional contribution is made, its net effect on total GPG supply is partially evaporated through a strategic response.

(F8): *If the private good is non-inferior, additional GPG contributions by a country are partially crowded out through reduced contributions by the other countries.*

The additional GPG contribution works like an implicit income transfer to the other contributing countries. Given that the private good is non-inferior, other countries will react by increasing their private consumption and hence reducing their GPG contributions. In other words, the GPG contributions of different countries are strategic substitutes. A related finding applies to unilateral advancements in the contribution technology by some country (Buchholz and Konrad 1994).

(F9): *In the Nash contribution game, country i might be unwilling to develop and use a more cost-effective contribution technology even if the transition to the new technology is completely costless.*

Consider some country *i* that has the possibility to switch to a higher productivity without

[23] There are various motives for unilateral action and taking a leadership role, see, e.g., Brandt (2004) and Schwerhoff (2016).

incurring any investment costs. On its own, this country would then clearly apply the cheaper contribution technology. Yet, in the strategic context of voluntary GPG provision, country *i* observes offsetting reactions by the other countries, which will reduce their GPG provision as the technology-adopting country raises its GPG supply and hence lowers its private consumption. If the decline of country *i*'s private consumption and of the other countries' GPG contributions is sufficient[24] and more than offsets utility gained from the net increase of GPG supply, country $i's$ utility falls so that it loses interest in developing and applying the more cost-effective technology (Buchholz and Konrad 1994).[25] This negative effect, however, becomes weaker if there are technological spillovers among countries (Buchholz, Dippl, and Eichenseer 2017, Foucart and Garsous 2018, and Stranlund 1996).

However, a country is more in favor of adopting a technological improvement in its GPG provision if the new technology is freely available *and* adopted by others. Then additional countries are inclined to provide more of the GPG so that the strategic offset of reduced GPG provision disappears. The same effects also result if – independent of the technological choice in country *i* – sufficiently many other countries simultaneously switch to technologies with a higher GPG productivity.[26]

To gain a strategic advantage, a country can downplay its interest in the GPG as others respond by contributing more (e.g., Endres 1997). Smaller interest in GPG provision can result from the application of an adaptation technology that makes a country less vulnerable against underprovision of the GPG; i.e., Ebert and Welsch (2012) explore the strategic implications of

[24] This outcome is expected if the other countries are numerous and severely restrict their GPG contributions as a response to country *i*'s unilateral action, which happens if their expansion paths favor the private good.
[25] This can be alternatively established with the help of eq. (2) in light of country *i*'s increased productivity and changes to its expansion path as it moves closer to the *G*-axis in figure 1.
[26] A free-rider problem also occurs at the innovation stage, which may reinforce free-riding at the contribution stage, see Gersbach, Oberpriller, and Scheffel (2019). For a discussion of the effects of technological spillovers on GPG provision under different assumptions, consult Hattori (2005).

various adaptation technologies of an environmental public good to counter underprovision. Additionally, a country could feign weaker preferences for the GPG. In the political process, this can be brought about by "strategic delegation," by which citizens appoint politicians less interested in the GPG than themselves to make the decision on that country's GPG contribution (e.g., Buchholz, Haupt and Peters 2005 and Hattori 2010).

In a different scenario, well-known from duopoly theory, leadership results from an ex ante given asymmetry of roles in the contribution game; i.e., a country (the "leader") chooses its GPG contribution first, anticipating the Nash reaction of another country (the "follower").[27] In the basic version of this leader-follower or Stackelberg game, GPG supply will be even lower than in the Nash game so that the underprovision problem is aggravated (Sandler 1992, p. 57 and Varian 1994). This negative outcome, however, may not hold when the leading country makes not only a decision on the level of its GPG contribution, but also on its contribution technology (Buchholz and Eichenseer 2019), because a leader has more incentive to apply a more productive contribution technology than a Nash player. Following a similar reasoning in a model with endogenous timing in terms of leadership, it can be shown that the option for one country to switch to a less costly contribution technology may make that country the leader (Hattori and Kitamura 2013).

4.4 *Matching and Conjectural Variations*

A country is not only able to strategically influence its own willingness to contribute to the public good but also that of other countries, thereby altering the noncooperative Nash equilibrium in its favor. This can be done by "matching," i.e., committing to add some own

[27] For a discussion of neutrality of income redistribution in the Stackelberg model (and its similarities and differences to neutrality in the Nash case), see Buchholz, Konrad, and Lommerud (1997) and Cornes and Sandler (1996).

GPG contributions to those of other countries.[28] A paradoxical outcome results (e.g., Bergstrom 1989):

(F10): *If a contributing country unilaterally matches another initially contributing country, the matching country gains at the expense of the matched country.*

If some country i matches some other country *j*'s GPG contribution with the matching rate s_i (and the GPG productivity of all countries is one), then country *i* augments any GPG contribution of country *j* by $s_i g_j$. This changes matched country *j*'s marginal rate of transformation between the private good and the GPG to $1+s_i$, thereby making the private good relatively more expensive. Henceforth, country *j*'s Nash equilibrium position is on the expansion path $e_j(G,1+s_i)$, which favors GPG provision compared to the original expansion path. Matching country *i* remains on its original expansion path. Following the same reasoning as applied above in other scenarios, the Nash equilibrium under matching must result in a larger GPG supply, a smaller GPG contribution, a larger private consumption, and greater utility for the matching country *i*. By contrast, the matched country *j* has a lower utility since its lost private consumption is more detrimental than the resulting increase in GPG supply.[29] This outcome also occurs if country *i* matches the GPG contributions of more than a single country.

The matched country, however, benefits from unilateral matching if the matching country can commit itself not to reduce its GPG contribution in the original Nash equilibrium (Buchholz, Cornes, Peters, and Rübbelke 2015). This condition is automatically fulfilled when the matching country is a noncontributor in the initial Nash equilibrium (Buchholz and Liu 2019 and Liu

[28] The idea of matching public good contributions goes back to Guttman (1978, 1987). For applications to international public goods, see, e.g., Falkinger, Hackl, and Pruckner (1996) and Rübbelke (2006). An experimental test of matching mechanisms is provided by Falkinger, Fehr, Gächter, and Winter-Ebmer (2000).

[29] In the new Nash equilibrium, country *j* not only pays for the entire increase of public good supply but also indirectly for country *i*'s increase of private consumption (Buchholz, Cornes, Rübbelke, and Peters 2015).

2019). When other countries are "matching back," the negative effect on their utility may vanish (Buchholz, Cornes and Rübbelke 2012 and Liu 2019).

(F11): *Multilateral matching may make all countries better off.*

A Pareto-optimal Nash equilibrium can only be implemented through reciprocal matching under very special conditions, especially in terms of the income distribution (Buchholz, Cornes, and Rübbelke 2011).[30]

Similar effects as in the case of multilateral matching are triggered if there are "positive conjectural variations;" i.e., if the countries anticipate parallel reactions by other countries. They then expect that increases of their own GPG contributions lead to an increase of the other countries' contributions, which works as an implicit coordination device and may bring about a Pareto improvement (Cornes and Sandler 1984b, 1985b).[31] If, instead, the other countries react as Nash players by reducing their contributions to some country's increased contribution (see finding F8), public good supply in the corresponding "consistent conjectural equilibrium" becomes smaller than the Nash equilibrium, thus exacerbating underprovision (Sugden 1985 and, with special reference to environmental GPGs, Gelves and McGinty 2016).

4.5 *Impure GPGs with Joint Products*

Many GPGs involve joint products, which mean that a country's GPG contribution is not only a sacrifice but also entails country-specific benefits (see section 2). Bolstering a country's healthcare system to prevent contagious diseases makes the world safer and at the same time lifts

[30] In a two-stage game where matching rates are chosen in stage 1 and GPG contributions in stage 2, a Pareto-optimal solution may result as a subgame-perfect equilibrium (Boadway, Song, and Tremblay 2007 and Danziger and Schnytzer 1991).

[31] Related to positive conjectural variations are normatively oriented approaches in which countries act as "Kantian maximizers," asking themselves what action they should choose to maximize their utility under the hypothetical assumption that all countries act in a similar way (Bilodeau and Gravel 2004, Cornes and Sandler 1985a, and Roemer 2010).

the well-being of the country's people, or curbing greenhouse gas emissions through a reduced use of fossil fuels addresses climate change and helps improve local air quality. Impurity of a GPG results not only from such technologically given private joint products (e.g., Pittel and Rübbelke 2008, 2017), but also from psychological co-benefits as people often feel a "warm-glow-of-giving" (Andreoni 1989, 1990) from doing something good – e.g., for the conservation of species or climate protection.

That a GPG with joint products is impure for some country *i* is captured by assuming that this country's utility function is $u^i(c_i, G, z_i)$, where z_i denotes country *i*'s ancillary country-specific benefit. Given joint products of a GPG, many important effects that we observe in the pure public good model no longer hold. To make this clear, we note that country *i*'s impure GPG preferences can be equivalently represented by the pure GPG utility function $\overline{u}^i_{w_i}(c_i, G) := u^i(c_i, G, w_i - c_i)$, so that the treatment of an impure GPG can be traced back to that of a pure GPG. Since the auxiliary utility function depends on the initial endowment, w_i, an income redistribution usually does not leave country *i*'s expansion paths unchanged so that the argument leading to neutrality in finding F4 is no longer applicable.[32] In particular, according to Andreoni (1989, 1990), an income transfer from a country with small to a country with large private co-benefits of its GPG contribution will decrease GPG supply in the Nash equilibrium.

Other effects are also different for GPGs with joint products (Cornes and Sandler 1984a, 1994) in response, e.g., to additional GPG contributions of other countries. Joint outputs of a GPG may turn countries' private consumption into an inferior good, which implies that the GPG contributions of different countries are not strategic substitutes but strategic complements (Buchholz and Sandler 2017 and Ebert and Welsch 2011). In the latter case, an increase in a

[32] Conditions for neutrality of income redistribution for impure public goods are discussed by Yildirim (2014).

country's GPG contribution triggers other countries to raise their GPG contributions. In a military alliance, increases in one ally's conventional forces on its border may lead other allies to augment their conventional forces along their borders so that they are not viewed by an enemy as more vulnerable (Sandler and Hartley 2001). Foreign aid to alleviate world poverty may also induce strategic complements as countries raise their aid to maintain their prestige as others augment their aid.

(F12): *If the GPG is impure, added contributions by one country may trigger crowding-in of other countries' GPG contributions*.

4.6 *Uncertainty*

Uncertainty in GPG provision may take various forms. There is strategic (or "social") uncertainty when a country does not know the GPG contributions of others (Sandler, Sterbenz, and Posnett 1987). Moreover, there is "private" uncertainty when a country does not know the GPG productivities (Gradstein, Nitzan, and Slutsky 1993 and Keenan, Kim, and Warren 2006), the countries' income levels (Barbieri and Malueg 2016), or the GPG-derived benefits (Boucher and Bramoullé 2010).

Under certain conditions enhanced uncertainty can mitigate the free-rider problem. A country's voluntary GPG contribution is increased if, through an increase in risk, the country's expected marginal value of the GPG is affected more than its expected marginal value of the private good (Caplan 2016). Such a positive effect is also more likely when a country's utility function exhibits "prudence" (Kimball 1990), where the third derivative of a country's utility function $u^i\left(c_i, G\right)$ with respect to *G* is positive (Sandler, Sterbenz, and Posnett 1987).

4.7 *Weakest-Link and Best-Shot Aggregator Technologies*

For a weakest-link GPG, we let G_i^S denote the GPG level that a country demands on its own, given a constant rate of transformation a_i between the private good and the GPG. Country *i'*s autarkic GPG demand is the solution to maximizing $u^i(w_i - \frac{G}{a_i}, G)$. The Nash-equilibrium level of a weakest-link GPG is then determined by the "pivotal" country with the smallest G_i^S, and each country spends G_i^S / a_i for the GPG. Because demand for a non-inferior GPG is increasing in income, the contribution productivity, and GPG preferences, a country is more apt to be pivotal if it has low income, low GPG productivity, and weak GPG preferences.

Neutrality of income redistribution does not apply in the case of weakest-link GPGs (Vicary 1990 and Jayaraman and Kanbur 1999):[33]

(F13): *Given a weakest-link and non-inferior GPG, an income transfer to the pivotal country increases the GPG and utility of all countries except maybe the donor country.*

This finding follows because the pivotal country's GPG supply becomes larger through the transfer (or another country with an initially larger GPG demand becomes pivotal).[34] All other countries, except the pivotal one, also gain since after adjusting their contributions they are still below their optimal autarkic demand. The donor country may benefit from making the transfer if its marginal willingness to pay for the GPG in the original Nash equilibrium is large and the transfer entices the pivotal county to increase greatly its GPG contribution.

For a best-shot GPG, the pivotal country has the largest G_i^S, which then determines the GPG level in the Nash equilibrium. The pivotal country is likely to have high income, high GPG productivity, or a great preference for the GPG. An income transfer to the pivotal country

[33] Vicary and Sandler (2002) explore the effects of matching and highlight the difference between transfers in cash and in-kind for case of weakest-link GPGs.
[34] This argument requires that there is a single pivotal country; otherwise, the transfer had to go to all pivotal countries.

increases GPG supply and may also lead to a Pareto improvement.

5. *GPG Coalitions*

Collective action is needed to overcome the anticipated underprovision of GPGs. Because a "grand coalition" of all GPG spillover recipients, and thus full Pareto efficiency, is rarely anticipated in the real world, such action is likely to assume the form of a limited group of countries. Such a coalition determines a GPG provision that is efficient for its members, given the strategic reactions of the Nash-playing noncoalition countries.[35] Forming a coalition usually is based on negotiations among the coalition members. In the realistic case where countries are not identical so that a "focal point" for the negotiations (Schelling 1960) is missing, the result of these negotiations is not unambiguously determined.

(F14): *When countries are heterogeneous, the coalition's level of GPG supply and its pattern of burden sharing among members depend on factors such as, e.g., the possibility of monetary transfers among countries.*

If lump-sum transfers among countries are not feasible, the "conventional wisdom" that the marginal costs of GPG supply have to be identical across countries at an efficient solution is no longer true (Chichilnisky and Heal 1994), so that the outcome of negotiations is not first-best efficient. In any second-best allocation without transfers, the countries' marginal costs of GPG provision are positively correlated with their marginal valuation of the private good.[36] Given increasing marginal costs of GPG supply and decreasing marginal utility of private consumption, poor coalition members then will contribute less to a GPG than their rich counterparts, *ceteris*

[35] For an overview of the problems related to coalition building, see Finus and Caparrós (2015b). On the theoretical issues related to the process of bargaining over GPGs, see Caparrós (2016) and Hovi, Ward and Grundig (2015).
[36] This follows from a modified Samuelson rule where the sum of the country-specific ratios between the respective marginal willingness to pay for the GPG and the marginal costs of GPG provision must equal one (Chichilnisky and Heal 1994, Sandmo 2003, 2007, and section 3).

paribus. Whether GPG supply is larger or smaller in the efficient solutions with and without transfers is not, however, clear a priori (Sandmo 2007, p. 13).

Apart from the problem whether transfers between countries are or not possible, public good supply normally cannot be expected to be the same in the infinitely many Pareto-optimal allocations (e.g., Cornes and Sandler 1996). Traditionally, an obvious candidate for singling out a specific Pareto optimal allocation is the Lindahl mechanism, which rests upon country-specific cost shares for GPG supply at which coalition members desire the same GPG amount. The Lindahl equilibrium, which has attracted attention also in the context of GPG provision (Groot and Swart 2017, Sandler and Murdoch 1990, and Uzawa 2003), incorporates the ability-to-pay and the benefit principle, both associated with fair burden sharing in public good provision (e.g., Peinhardt and Sandler 2015, pp. 75-8). However, the Lindahl equilibrium does not necessarily result in a Pareto improvement over the Nash equilibrium because poor countries and those with a low preference for the GPG may be harmed (Buchholz, Cornes, and Peters 2006). To circumvent this concern, Chen and Zeckhauser (2018) devise the "Cheap-Riding Efficient Equilibrium" (CREE) as an alternative solution concept, which uses the Nash equilibrium as the starting point for finding cost shares that harmonize the coalition members' GPG demands. Through income transfers among countries, any CREE can be transformed into a standard Lindahl equilibrium.

Negotiations among countries often fail, e.g., due to information asymmetries. But even under ideal conditions for successful negotiations, pre-bargaining (strategic) actions of countries may have adverse consequences.

(F15): *Moves by countries prior to coalition formation may result in lower post-bargaining GPG supply, ending in inefficient negotiated outcomes.*

If, e.g., a benevolent country unilaterally increases its GPG contribution, then this action reduces its utility in the noncooperative outcome (see finding F8), thus changing the threat point for the Nash bargaining process by which the coalition is formed.[37] Consequently, the bargaining solution will be shifted along the transformation curve to the harm of the unilaterally acting countries. If not all efficient solutions on the transformation curve exhibit the same GPG supply, the danger arises that, through the unilateral move, GPG supply becomes smaller after bargaining (Hoel 1991), especially when the unilateral-acting country possesses a greater preference for the GPG than other countries.

In the Hoel (1991) setting, Pareto optimality of the bargaining solution is preserved; in other scenarios, some countries' pre-bargaining moves may even undermine efficiency. For instance, countries may lack an incentive to apply a more-cost effective technology for GPG provision, given the anticipated bargaining solution when making their technology decision (Buchholz and Konrad 1994).[38] As the GPG is then produced by a too costly technology, the ensuing outcome clearly is not efficient. Such adverse effects may also result from any pre-bargaining action of a country that affects its marginal benefit of GPG provision in subsequent periods, and thus its bargaining position. As a consequence, GPG supply without bargaining could be smaller than with bargaining.[39] To avoid such inefficiencies, coalition building must be extended to the stage of technology choice so that the contract between countries becomes complete (see Battaglini and Harstad 2016 in a dynamic setting). Analogous observations have also been made in the context of strategic delegation (e.g., Buchholz, Haupt, and Peters 2005). In case of uncertainty, e.g., about the costs of GPG supply, a country's unilateral increase of its GPG contribution may even reduce the probability that bargaining will consummate an agreement at all and lead to coalition formation (Konrad and Thum 2014).

[37] The same effect occurs if a small coalition wants to expand and, thus, enter negotiations.
[38] In the noncooperative scenario, this has been observed by finding F9.
[39] In a dynamic game with contracts of different duration, see Beccherle and Tirole (2011) and Harstad (2012).

Intuitively, one might suspect that coalition formation should always be favorable both for the coalition members and GPG provision. In the strategic context of GPG supply, this is not necessarily the case.

(F16): *Due to the reactions of noncoalition countries, cooperation of a limited coalition does not necessarily improve utility of the coalition members and achieve a higher GPG supply than the Nash equilibrium.*

If a group of "willing" countries forms a coalition, their collectively determined GPG contributions increase, while those of the noncoalition outsiders are reduced in the ensuing Nash equilibrium. These outsiders may even become complete free riders (Buchholz and Eichenseer 2017 and Vicary 2018). If this crowding-out by the noncoalition countries is strong enough, then cooperation is unprofitable for the coalition members, especially when the group of outsiders is large and the coalition is small (Buchholz, Haslbeck, and Sandler 1998). At the same time, the noncoalition countries benefit from coalition building, where something like an "exploitation of the coalition by the outsiders" occurs (Boadway and Hayashi 1999).

Due to this effect, coalition formation by some group A of countries may reduce the willingness of the remaining group B to build its own coalition.[40] The disincentive of coalition formation by group A on coalition building by group B may be so strong that – in the Nash equilibrium of the ensuing Chicken Game – GPG supply even becomes lower than in the situation where group B stands alone and group A is absent. This less desirable outcome becomes more likely if the members of group A are greatly interested in the GPG or possess a high GPG productivity. Paradoxically, a stronger taste for the GPG or technological progress may thus reduce GPG supply in the Nash equilibrium of the coalition-formation game. In the

[40] For details on the coalition formation game and the resulting subgame-perfect equilibria, see Buchholz and Eichenseer (2017), Foucart and Wan (2017), and Hattori (2015).

game of coalition formation even a Prisoners' Dilemma situation may occur, unfavorable for GPG supply (Hattori 2015).

Regarding GPG supply, things may even get worse if a coalition does not act as a Nash player but is the leader in a Stackelberg game with the noncoalition countries as followers. A coalition can attain such a leadership position when it uses a multilateral matching mechanism (see F11) as the instrument for internal cooperation[41] (Buchholz, Cornes, and Rübbelke 2014). Then the possibility of "harmful cooperation" arises, which means that GPG supply in the Stackelberg equilibrium with a leading coalition becomes smaller than in the Nash equilibrium without the formation of a coalition.

Even a profitable coalition that strives for a larger GPG supply than in the Nash equilibrium confronts considerable risk that its members may not fulfill their agreed-upon GPG contributions so that the coalition is not self-enforcing. Since the seminal articles by Barrett (1990) and Carraro and Siniscalco (1993), this problem of coalition stability, well-known from oligopoly theory, plays a focal role in the theory on GPG provision. According to the most common definition, a coalition is called "internally stable" if no country wants to leave and "externally stable" if no country wants to join.

(F17): *Generally, GPG coalitions that are stable cannot be expected to provide much welfare gains over the noncooperative outcome.*

The reason is that stable coalitions either are small or if they are large, the gains from cooperation are small. This "paradox of cooperation" is mainly considered in a one-shot game in which each coalition member balances whether it will be better off if it stays or leaves the

[41] A general analysis of the links between coalition building and matching in the case of GPGs is provided by Liu (2018).

coalition (Barrett 1994a).[42] In this setting where there are many remaining coalition countries after a single country exits, no large reduction of GPG supply is usually anticipated. That reduction, moreover, will not hurt the defaulting country by much if GPG supply has initially been high, which reflects a highly profitable original coalition.

In coalition theory, there are many contributions that describe various ways to avoid this stability dilemma: A large, and possibly the grand coalition, may become stable if, e.g., a minimum number of countries are able to commit to their cooperative GPG contribution and to lure the remaining countries into the coalition by means of transfers or side payments (Carraro and Siniscalco 1993). Coalition stability may also be enhanced when countries exhibit a preference for equity (Lange and Vogt 2003) or reciprocity (Buchholz, Peters, and Ufert 2018 and Nyborg 2018), or when the benefits of GPG supply are uncertain and countries are risk averse (Boucher and Bramoullé 2010).[43] Additionally, coalition formation can be advanced for heterogeneous countries when country-specific costs and benefits of GPG provision are negatively correlated and very skewed in the case of a summation technology (Finus and McGinty 2019) or asymmetric in the case of a weakest-link technology (Caparrós and Finus 2019). Large coalitions may arise when noncooperating countries are punished, e.g., through various threat strategies in repeated games (e.g., Asheim and Holtsmark 2009, Barrett 1999, and Finus and Rundshagen 1998b), or through trade sanctions (e.g., Nordhaus 2015) with a focus on R&D incentives as a specific form of issue linkage (Helm and Schmidt 2015). In addition, cooperation of large coalitions could be sustained through more modest requirements on GPG supply (Finus and Maus 2008), through specific membership rules (Finus and Rundshagen

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[42] For most of the literature on coalition stability, the remaining countries are assumed to continue their cooperation after a country has departed. If, instead, a core-theoretic e.g., Chander and Tulkens 1995) stability criterion is applied according to which cooperation collapses after a country exits, the stability of even large coalitions can clearly be achieved more easily.

[43] For some qualification of this result, see Kolstad (2007) and Ulph, Pintassilgo, and Finus (2018), which take learning about GPG provision costs and benefits into account.

2009), through the establishment of a deposit-refund system (Gerber and Wichardt 2009), or through the availability of specific adaptation technologies (Bayramoglu, Finus, and Jacques 2018). These escapes to the paradox of cooperation through coalition formation indicate that institutional design factors can be essential for the success of cooperation for GPG provision. However, there is no escaping the realization that forming stable self-enforcing coalitions is an enormous challenge for GPGs as the lack of progress to date on climate change underscores.

6. *Institutional Considerations*

Institutional design can be engineered based on the theoretical insights regarding impure public goods, matching behavior, aggregation technologies, and leadership, developed in sections 3-5. When countries independently provide a GPG, a suboptimal level generally results. In the absence of coalition formation, the overall suboptimal level of the GPG cannot be raised through redistributing income among the set of contributors if the GPG is pure and a summation aggregator applies (Warr 1983). Somehow GPG funding must be obtained from initial noncontributors to raise GPG provision (see section 3). In addition, increased contributions by a country are partially crowded out through decreased contributions by other countries. Crowding-out is also germane to a cooperative coalition as noncoalition countries reduce their GPG in response to greater provision by coalition members. Thus, some institutional arrangement is required to secure a more appropriate level of the GPG while ameliorating or even reversing the crowding-out or leakage concern.

There are at least four types of institutions that promote the provision of GPGs. First, multilateral organizations provide a wide range of GPGs that include world peace, world health, global financial stability, reduced world poverty, and international crime prevention. Essential multilateral institutions include the United Nations, the World Health Organization, International

Monetary Fund, World Bank, and INTERPOL. These institutions not only provide GPG funding, but also coordinate actions by countries and other participants (e.g., the National Institutes of Health). To take advantage of economies of scope stemming from the sharing of administrative costs, multilateral organizations often supply multiple GPGs. Ideally, these organizations must use side payments, sanctions, and reduced uncertainty to thwart actions by members to reduce post-bargaining GPG supply. Second, international treaties are frequently employed to address international environmental concerns. Prime instances include the Montreal Protocol on Substances that Deplete the Ozone Layer, the Kyoto Protocol to the United Nations Framework Convention on Climate Change, the Convention of International Trade in Endangered Species (CITES), and many others. International environmental agreements work best when they limit transaction costs of assigning property rights by removing scientific uncertainty, reducing asymmetric information, fostering compliance, and other concerns (Libecap 2014). Third, countries can form clubs for GCGs that possess excludable benefits. Such clubs include international airports, the Suez Canal, INTELSAT, or INTERPOL databases to screen international passengers (see section 2). Fourth, international regimes can provide myriad GPGs that foster maritime commerce, reduce radio interference, and promote international mail flows, which are the jurisdiction of the International Maritime Organization, the International Telecommunication Union, and the Universal Postal Union, respectively (Zacher 1996). Countries abide by these regimes because the associated GPG benefits from increased commerce and communication far outweigh any regime-induced loss of autonomy. Often, the required rules mimic those already adopted within the country (Zacher 1996).

6.1 *Institutional Engineering*

The properties of many GPGs are not immutable and may be endogenously determined through institutional design. The design goal is to affect the properties of the GPGs to encourage more optimal provision levels. An apt example is to institute an exclusion mechanism to transform the GPG into a club good that can be supported through congestion-internalizing tolls. For example, the World Health Organization can exclude nonpayers from its expert consulting services. Even the underlying aggregator technology can be institutionally adjusted by design. A threshold participation level can be set before the GPG is provided. In the case of the Montreal Protocol on ozone-depleting substances, a sufficient number of ratifying countries was mandated before the treaty went into effect (Beron, Murdoch, and Vijverberg 2003 and Congleton 1992). A threshold of ratifiers was also set for other international environment agreements. In some instances, a threshold of provision can be set to limit the impact of free-riding induced leakages to augment GPG supply. Peacekeeping operations (PKOs) can be withheld until sufficient troops, police, observers, and equipment are accumulated to have an effect on quelling the conflict or keeping peace. Instituting a weighted-sum aggregator may require the collection of sufficient information so that countries know their weights. In section 10.2, we indicate that monitoring stations in Europe allowed potential signers of the Helsinki and Sofia Protocols to learn their roles as exporters and importers of sulfur and nitrogen oxides depositions. This information resulted in the construction of a transport matrix that induced countries that were net importers or large self-polluters to sign the treaties (Murdoch, Sandler, and Sargent 1997). Thus, pre-treaty action made for a weighted-sum aggregator that encouraged participation and provision of the public good of reduced air pollution by reducing uncertainty.

There are numerous instances where multilateral organizations and treaties resorted to instituting multilateral matching to increase GPG provision. A prime instance concerns the way that the United Nations currently funds its PKOs throughout the world. Until 1974, expenses for UN PKOs were either covered by voluntary contributions with shortfalls made up by the UN regular budget. This was a recipe for disaster because PKOs provide purely public goods to the world community. Not surprisingly, voluntary contributions did not attract sufficient funding and this put a real drain on the UN regular budget (Sandler 2017b). In the early 1960s, a financial crisis ensued because of huge shortfalls to fund the expensive UN Operation in the Congo (ONUC). As a response, UN PKOs virtually stopped during 1965–1973, except for two small missions. On December 11, 1973, the UN General Assembly Resolution 3101 established assessment accounts that instituted a matching formula to fund PKOs, based on UN members' income and status (e.g., permanent Security Council member) (Sandler 2017b). Following the institution of the assessment account in 1974, the United Nations acquired the means to engage in a large number of PKOs to pursue world peace. Even though countries are assigned different assessments or matching rates, GPG free riding is curtailed.

For the Montreal Protocol, the Multilateral Fund is supported by rich countries to assist poor countries meet the required cutbacks in their use of chlorofluorocarbons use, which deplete the stratospheric ozone layer. Even though the contributions to the fund are voluntary, rich countries can anticipate that other rich countries will contribute through a moral obligation. Such contributions are side payments that foster coalition stability. Periodic reports of the Multilateral Fund indicate which rich countries are meeting their implicit obligations. In a recent article, Chan (2019) argues that similar multilateral burden-sharing arrangements should be used for a host of transnational environmental public goods.

6.2 *Some Further Design Principles*

Multilateral organizations and treaties can bolster country-specific *complementary* benefit to entice select countries to take a greater interest in supporting the provision of the GPG.[44] For instance, the World Bank can offer greater recognition to donor countries and allow them to support those recipient sectors – e.g., health or governance – that donors view as having a larger spillover influence on their welfare. Multilateral organizations can assign a leadership role to countries for which their specific benefits are complementary. For example, the United Nations has for some PKOs assigned a leadership role to a strong country in close proximity to the conflict – e.g., the United States in the Haiti conflict and Australia in the Papua New Guinea conflict. In those instances, country-specific complementary benefits arise from reduced refugee flows, greater foreign direct investment, more reliable resource supply, more post-conflict investments, and enhanced trade (Sandler 2017b). With complementary country-specific benefits, leadership may induce other countries to raise their GPG contributions as well (Sandler 1996).

Multilateral organizations and treaties have a long history of exploiting rich countries' interests to get them to assume greater costs for GPGs. For many international environmental treaties, much larger burdens are placed on rich countries that include financing the provision efforts of poor countries and sharing new technologies with them. Given that environmental protection is income elastic, such exploitation is an effective way to supply environmental GPGs. In other instances, this exploitation may be directed at countries with strong preferences or superior productivity in supplying the GPG. By their nature, multilateral organizations can implement means for funding GPGs. Nonvoluntary funding arrangements that assign specific shares of the GPG costs to member countries must be considered as fair and equitable in order to be acceptable for all countries involved. The importance of fairness principles for public good

[44] See Amin (2016), Bodansky (2012), Buchholz and Sandler (2017), Cornes and Sandler (1994), Heugues (2014), and Wagner (2016).

provision has been highlighted by a great number of experiments showing, in particular, that many peoples' preferences not only have a prosocial and altruistic component but also a strong need for reciprocity (see, e.g., Fehr and Gächter 2000a, 2000b). Cooperative actions encourage cooperation by others, while noncooperative actions induce noncooperation by others. Reciprocity, in general, plays a central role in international relations and receives much attention in the context of public good provision, especially in connection with climate protection (Buchholz and Peters 2005, Carattini, Levin, and Tavoni 2019, and Cramton et al. 2017).[45] Whether GPG provision leadership by some countries is regarded as meaningful crucially depends on the belief that other countries reciprocate. Unilateral increases of GPG contribution by a group of countries induce positive conjectures so that other countries in aggregate match some of the leader's efforts (Buchholz and Sandler 2017 and Cornes and Sandler 1984b). A related institutional principle involves designing assessment schemes to correspond to the underlying aggregator technology of the GPG. For weakest-link GPGs, an assessment scheme must lean on rich countries to assume the financial burdens; for weighted-sum GPGs, an assessment arrangement should lean on high-productivity countries to carry the financial burden (see sections 2 and 4).

Neutrality concerns can be addressed by seeking funds from new participants, such as charitable foundations. For instance, the Gates Foundation allocates philanthropic funds from private sources that primarily support health-related GPGs (see section 10). Consequently, the foundation is not drawing its funds from contributing countries. Such outside funding raises not only the amount of weakest-link GPGs by bolstering poor countries' efforts, but also the level of best-shot GPGs by funding capable countries' actions. Multilateral organizations and treaties

[45] A review of applications of behavioral, and especially experimental, approaches to the climate change issue is provided by Brekke and Johansson-Stenman (2008).

often rely on a core coalition of countries to supply the GPGs. The prognosis for the supply of GPGs improves if this coalition is large and heterogeneous to curtail leakages. Also, countries that disproportionately affect GPG supply must be in the coalition and use side payments.

7. *GPG Case 1: Climate Change*

As our first GPG case study, we investigate actions to limit climate change by curbing man-made greenhouse gas (GHG) emissions. We choose climate change because it represents a supremely challenging GPG to supply. To address the problem adequately requires a large stable coalition, but such coalitions are very difficult to put together beyond a small number of countries, which for climate change cannot have much of an effect. Climate change arises from a greenhouse effect as sunlight-generated infrared radiation becomes partly trapped in the earth's atmosphere, thus increasing the earth's mean temperature. Atmospheric GHG can be man-made or nature induced (e.g., from volcanoes). Since 2010, the National Academy of Sciences of the United States supports man-made GHGs as the prime cause of climate change from atmospheric accumulation of these gases (Peinhardt and Sandler 2015, p. 267). According to the Environmental Protection Agency (EPA) (2019), there has been a 37% increase in radiative forcing (a net warming influence) between 1990 and 2015. Earth's global mean temperature in 2017 was approximately 1.1°C greater than the pre-industrial period in 1750 (World Meteorological Organization (WMO) 2018). This temperature rise is halfway to the maximum temperature increase of 2°C, targeted by the Paris Agreement on climate change to limit potential dire consequences.

Primary GHGs include carbon dioxide, methane, and nitrous oxide, which were 145%, 257% and 122% of their pre-industrial levels, respectively, in 2016 (WMO 2018). Other GHGs include sulfur hexafluoride, chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons (refrigerant substitutes for chlorofluorocarbons), and others. The production of GHGs is tied to a host of human activities that involve fossil fuels use, deforestation, wet rice agriculture, refrigerants, coal mining, fertilizers, and livestock. Virtually every country adds to the accumulation of GHGs and climate change, with large industrial countries adding the most, particularly China, the United States, Japan, India, and the Russian Federation. Climate change is associated with a host of concerns: melting icecaps, rising sea levels, devastating storms, droughts, forest fires, ocean acidification, flooding, lost coral reefs, and lost species. Climate-induced changes can result in mass migrations and may spark conflicts over resources (Gleditsch 2012).

Curbing climate change is the quintessential pure GPG with a global spillover range (Bayramoglu, Finus, and Jacques 2018, Sandler 1997, and Sinn 2008). Actions by a country to curb its GHG emissions limit the atmospheric concentration of GHGs worldwide as mixing takes place in the atmosphere. A summation aggregator applies because the cumulative atmospheric reductions of GHG stocks are the sum of all countries' reduced GHG emissions – i.e., each reduced ton of GHG emissions is a perfect substitute for one another. Moreover, reduced GHG emissions yield benefits that are nonrival and nonexcludable to all countries. For example, limiting climate-change-induced species losses enrich the genetic heritage of all countries. Reducing the risk of extreme weather events by curtailing climate change can benefit all countries even though countries more prone to, say, hurricanes receive more potential gain. Benefit publicness does not require that countries evaluate their derived benefits identically.

7.1 *Climate Change Treaties*

Three international treaties are relevant for the control of climate change. The United Nations Framework Convention on Climate Change (UNFCCC) was framed in May 1992 prior to the

Earth Summit in Rio during June 1992, when the UNFCCC was opened for signatures.[46] The framework convention entered into force on March 21, 1994 after receiving the mandated 50 ratifying states' signatures. Like other UN conventions, the UNFCCC initiated a study period for the climate-change problem by tasking signatory countries to establish their GHG emissions and removal levels, so that a subsequent protocol could be framed that required ratifying countries to take specific actions to curtail their GHG emissions if warranted based on scientific information (UNFCCC 1991).

On December 11, 1997, the Kyoto Protocol was framed and opened for signatures. To enter into force, 55 UNFCC ratifying countries had to sign the agreement. A key feature of the treaty was differentiated abatement levels assigned to the ratifiers. Notably, developing countries (non-Annex-I countries) did not have to reduce their GHG emissions from 1990 levels during the first commitment round that ran from 2008 to 2012. This pass was intended to promote fairness because most of the atmospheric stock of carbon had come from industrial countries. Although this exemption was well-meaning and increased treaty ratifiers, it was extremely myopic since some of the fastest growth in GHG emissions came from countries such as China, Brazil, and India, which had no cutback responsibility under the protocol (Sandler 2004, table 10.3). GHG reductions assigned to developed Annex I countries – 37 countries and the European Union – varied by countries, with an average reduction of 5% from 1990 emission levels. Some Eastern European (Annex I) countries had little or no reduction requirements. The Kyoto Protocol entered into force on February 16, 2005.

The overall impact of the Kyoto Protocol was disappointing. Despite the protocol, GHG emissions increased by 50% since 1990 rather than the planned 5% decrease (Harvey 2012). Many factors contributed to this dismal outcome including the failure of the United States, the

[46] For treaty facts and details, see United Nations (2019).

largest GHG polluter at the time, to ratify the agreement because of the free ride given to the developing countries. Other major polluters – Canada, Australia, Japan, and the Russian Federation – eventually dropped out of the agreement or did not want to agree to a second commitment period with penalties for first-period shortfalls. Without any real enforcement mechanism, other countries did not achieve their pledged cutbacks. As noted earlier, some large developing countries greatly increased their GHG emissions. Although the Kyoto Protocol was intended initially to constrain countries that collectively accounted for over 50% of GHG emissions, the protocol eventually only constrained countries with a mere 15% of GHG emissions (Gollier and Tirole 2017 and International Institute for Sustainable Development 2012). By the end of the first commitment period, the Kyoto Protocol controlled only a modest set of polluting countries and a decreasing percentage of global GHG emission (Esty 2008).

Barrett (1999, 2003b) highlight some flaws with the Kyoto Protocol. Most notably, the protocol effectively limited only a subset of countries so that the strategic reaction of nonsignatory (free-riding) countries could greatly limit or offset the emission cutbacks of the cooperators (section 5). Another flaw concerns the treaty's failure to protect against leakages, whereby GHG-intensive activities shifted to the territories of nonsignatory countries since no trade penalties were imposed on leakages (Barrett 1999). Such leakages could actually increase overall GHGs emissions. In addition, the protocol did not permit side payments to augment coalition size and GPG supply (Carraro and Siniscalco 1993 and Hovi, Ward, and Grundig 2016). The theoretical literature on stable and effective coalitions to provide GPGs underscores the importance of side payments (section 5). Even though the coalition of signers was heterogeneous, Finus and McGinty (2019) indicate that the *positive* covariance between signers' marginal abatement benefits and their marginal abatement costs meant that the climate change coalition was unstable in the absence of side payments or transfers. This prediction is consistent with the failure of the Kyoto Protocol. Rather than mandating a continual abatement commitment like the Montreal Protocol on ozone depleters, the Kyoto Protocol required new negotiations after the first commitment period, which encouraged new strategic reactions and raised transaction costs (Barrett 1999 and section 5). During the Doha Climate Change Conference of the Parties in the late 2012, new cutback guidelines were not consummated for the second commitment period. In particular, developing countries would not assume a reduction commitment that some rich countries had requested. Essentially, strategic moves prior to the formation of a new coalition, required for the second commitment period, resulted in an inefficient bargaining outcome and no agreement (section 5). Thus, the Kyoto Protocol was basically dead (Harvey 2012). Though dead, the protocol can be viewed as initiating a process of negotiations that resulted in the next treaty.

The third key international treaty regarding climate change is the Paris Agreement, framed on December 11, 2015 and ratified on November 4, 2016 after 55 UNFCCC countries, accounting for 55% of global GHG emissions, signed. Key elements of the Paris Agreement include country-determined emission reduction pledges, no Annex I designated countries, rich countries' assists (side payments), and national anthropogenic GHG inventories (UNFCCC 2015). With the Paris Agreement, developing countries have an implicit responsibility to reduce their GHG emissions, but the timing and the size of their commitments are left unspecified. If developing countries put off their reductions too long or offer little in the way of cutbacks, then the United States' and other countries' past reluctance to agree to large reductions may not be addressed. Already, the Trump administration has pulled out of the Paris Agreement. Although helpful in principle, the understanding that rich countries have a commitment to help developing countries meet their cutbacks could cost hundreds of billions of dollars, unlike the relatively cheap Multilateral Fund of the Montreal Protocol (Sandler 2017a). This funding commitment would give rise to a free-riding problem as rich countries strategize to shift assistance burden onto other rich countries. In practice, this commitment issue is an unresolved political problem.

Even though the Paris Agreement asks ratifying countries to assume large emission-reducing efforts during the initial commitment period, the realized efforts are likely to be Nash responses, which have failed to address the problem thus far. This Nash concern is particularly worrisome since national commitments are voluntary and there is no mechanism to punish shirkers. By requiring signatory countries to raise their pledged cutbacks over time, the Paris Agreement encourages a strategic motive to keep initial pledges as low as possible (Beccherle and Tirole 2011, Gollier and Tirole 2017, Sandler 2017a, and section 5). Such a perverse incentive is similar in nature to failures to invest in green-promoting technologies (Buchholz and Eichenseer 2019 and Buchholz and Konrad 1994, 1995). We must also note that the required national inventory reports of GHG emissions and sinks are apt to be beyond the capability of many developing countries unless assisted. Such assistance is costly and adds further to the burden or exploitation of the rich countries. There is a clear incentive for countries to underreport their GHG emissions and to overreport their GHG sinks in order to limit their pledges. Although the Paris Agreement addresses some of the flaws of the Kyoto Protocol – e.g., putting no emission reductions on all developing countries, the success of the agreement in keeping the temperature rise to 2°C is by no means assured. Things may change if major polluting countries come to recognize dire consequences of doing too little about climate change.

7.2 *Montreal and Kyoto Protocols*: *Collective Action Considerations*

There are myriad collective differences that influence the effectiveness of the Montreal and Kyoto Protocols that transcend treaty differences. Like addressing GHG emissions, actions taken by the Montreal Protocol and its amendments to protect the stratospheric ozone layer provide a GPG. A thicker ozone shield protects humans and all other species so that benefits are nonexcludable. The safety that the ozone layer affords to one country does not detract from the protection experienced by other countries, so that the shield's benefits are nonrival. The spillover reach of the ozone shield is global. Finally, actions to control ozone-depleting substances are cumulative, so that a summation aggregator applies. An interesting puzzle emerges because controlling climate change and safeguarding the stratospheric ozone layer possess the same four basic properties of publicness, yet the former has proven much more difficult to address than the latter. The answer to this puzzle hinges on contextual aspects of the two GPGs, not captured by the four dimensions of global publicness.

The ozone layer absorbs much of the harmful ultraviolet B radiation from the sun. A compromised or thinned ozone shield has many detrimental consequences: e.g., the extinction of species, the inducement of skin cancers, a greater incidence of cataracts, the disruption of the food chain, and damage to the human immune system. All of these global consequences stem amazingly from a three millimeters thick (if fully compressed) ozone layer that ranges from 10 to 25 miles above the earth.

In the early 1970s, scientists hypothesized that released chlorofluorocarbons (CFCs) (used as refrigerants, cleaning agents, and aerosol propellants) migrated to the stratosphere, where sunlight decomposed them into their constituent parts during frigid winter conditions. In the process, liberated chlorine combined with ozone, thereby thinning the ozone shield (Toon and Turco 1991). Subsequently, a similar ozone-depleting process was linked to bromide-based substances. Scientific evidence eventually supported the hypothesized destruction of the ozone layer, thereby removing the uncertainty regarding the cause of the ozone layer hole.

Benedick (1991) documents world action to address the thinning ozone shield that commenced with the Vienna Convention, framed in March 1985 and adopted in September

1988, which required further study of the harmful effects of CFCs. In January 1989, the Montreal Protocol was ratified and mandated progressive cuts in CFCs rising to 50% of 1986 levels (Barrett 2003b and UN 2019). Subsequent amendments to the Montreal Protocol resulted in accelerated phasing out of 15 CFCs and cutbacks in an ever-growing list of ozone depleters. Virtually every country eventually signed the Montreal Protocol and its amendments. By 1994, atmospheric concentration of gaseous chlorine started to decline and slowly the ozone layer began thickening so that the current generation reaped near-term benefits from its action. In fact, the ozone layer is anticipated to achieve its pre-damage thickness by 2050 (EPA 2018). This emerging recovery of the ozone layer reflects successful provision of a GPG.

There are a number of contextual considerations that worked in favor of reducing ozone depletion but worked against curbing GHG emissions. First, ozone-depleting emissions were concentrated in relatively few countries – the United States, Japan, the former Soviet Union, and the European Union – that accounted for the majority of CFC emissions, while a much larger number of countries added to GHG emissions. Thus, putting together a coalition to limit sufficiently free riding was more challenging for climate change. Second, the temporal profile of abatement costs and benefits favored addressing ozone depletion, where today's actions could obtain sizeable benefits for the current generation. Since the atmospheric residency of GHG emissions is at least 50 years, abatement efforts result in immediate costs and much delayed benefits (Nordhaus 1991). This benefit delay highlights the importance of the time discount rate, where a larger rate favors no action today (Nordhaus 2007). Third, uncertainties are more germane for climate change than for ozone shield depletion. The influences of the atmospheric stock of GHGs on earth's mean temperature, rainfall patterns, sea level rises, and icecap melting are not known with certainty.[47] That uncertainty encourages delays in R&D and the investment in green technologies (Battaglini and Harstad 2016, Konrad and Thum 2014, and Tirole 2012). Fourth, climate change may lead to losers and gainers, while ozone-shield thinning only results in losers. For climate change, gainers involve countries in the higher latitudes that may get warmer, longer, and wetter growing seasons. Such countries will either take a wait-and-see attitude or oppose actions to limit climate change. Fifth, major polluters – e.g., the United States – took a leadership role for curbing CFCs, while some major polluters – China, Japan, Canada, and the United States – did not assume a leadership role for reducing GHGs. Sixth, the costs associated with rich countries assisting poor countries differ markedly in supplying the two GPGS. The Multilateral Fund required a relatively modest pool of money to allow developing countries to adopt more ozone-friendly technologies, such as refrigerators using hydrofluorocarbons instead of CFCs. The likely assistance costs, required for poor countries to reduce their fossil-fuel dependency, are huge. Seventh, the producers of CFCs had discovered substitutes prior to the Montreal Protocol ratification so that CFC manufacturers stood to gain billions in profits as CFCs were phased out and the substitutes phased in (Benedick 1991 and Sandler 2004). Affordable substitutes for fossil fuels have been slower to develop. Eighth, relatively few activities added to ozone shield depletion, while many activities resulted in GHG emissions.

7.3 *Climate Clubs*

We learned in section 2 that clubs share a public good characterized by excludable and partly rival benefits. Excludability is needed so that the benefits of the shared club good do not spill

[47] Some of these changes may be discontinuous where a "tipping point" is reached for which change becomes catastrophic – e.g., the sudden collapse of the Greenland ice shelf (Barrett 2003b and Barrett and Dannenberg 2014).

over to nonmembers, thereby giving members a reason for joining. The partial rivalry gives rise to congestion that can be used to compute congestion-internalizing tolls. Controlling GHG emissions or climate change offers nonexcludable and nonrival benefits and, as such, is not a club good that can be allocated through a "climate club" used in a standard Buchanan (1965) sense.

Nordhaus (2015) appeals to climate clubs as a promising institutional avenue for addressing climate change (also see Hovi et al. 2019).[48] Nordhaus (2015, p. 1340) characterizes such clubs as "a voluntary group deriving mutual benefits from sharing the costs of producing an activity that has public-good characteristics." This suggests that he has a standard club good in mind and refers to the Sandler and Tschirhart (1980) survey on clubs. In fact, Nordhaus (2015) is really examining coalition formation in regards to a pure GPG – controlling climate change. He envisions a "top-down" approach where a small stable coalition of countries with a large carbon footprint forms. To attract other members, carbon-based tariffs are imposed on nonmembers. If these penalties outweigh the abatement costs (net of reduced damages) of joining the coalition, then the coalition grows in size. Nordhaus uses climate-change modeling data to show that the so-called climate club may grow in size and encompass many countries. We see a number of concerns. First, the ability to punish nonmembers requires powers that coalitions seldom have in practice, especially in the current anarchic international system. Second, these coalitions are not organizations sharing club goods so that the terminology is misleading. Third, the distinction between Nordhaus' top-down approach and the standard analysis of coalition formation, discussed in section 5, with side payments is not entirely clear. Side payments are an alternative means to allow existing coalition members to use their surplus to attract more members, especially when countries are heterogeneous. The main difference

[48] Hovi et al. (2019) do not equate climate clubs with Buchanan clubs.

seems to be that Nordhaus' club approach relies on negative incentives, while the coalition approach relies on positive incentives to avoid leakages. Often, positive inducers are easier than punishments for countries to impose.

8. *GPG Case 2: Biodiversity*

Biodiversity corresponds to "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part" (United Nations 1992, p. 3). Biodiversity requires not only the preservation and management of species, but also the protection of their ecosystems or habitats. The primary treaty safeguarding biodiversity is the Convention on Biological Diversity, signed on June 5, 1992 in Rio de Janeiro. This so-called "Biodiversity Convention," now ratified by 196 parties, indicates that host countries are responsible for protecting their biological diversity as they exercise sovereignty over their biological resources. Select key elements of the treaty are in-situ conservation, ex-situ conservation, host-country financial assistance, conservation incentives, and technical and scientific cooperation (United Nations 1992). In-situ conservation involves preserving gene pools within the host country's ecosystem, whereas ex-situ conservation concerns preserving gene pools outside their natural habitats. The latter may include zoos, wildlife preserves, or cryogenic storage. Article 8 of the treaty seeks to establish a patchwork of protected areas with rich biodiversity that include tropical forests, coral reefs, and marine habitats (e.g., the Arctic seas). Another crucial aspect of the treaty is rich developed countries' underwriting of host-developing countries' efforts to maintain biodiversity (see Articles 9, 11, 16, 18, 20, and 21 of the treaty).

At least four actions deplete a host country's biodiversity: harvesting, pollution, invasive species, and habitat destruction (Barrett 2003b, p. 350, 2006b). Harvesting of species is most problematic when it results in species extinction. Pollution can originate from within or beyond the host country's borders. Countries must be vigilant in inhibiting the introduction of invasive species, but, once introduced, the country must seek ways, if possible, to eradicate the unwanted intruders. Habitat destruction is driven by population growth and economic development. Article 11 of the treaty encourages host countries and treaty parties to develop economic and social incentives that favor biodiversity preservation. For instance, bioprospecting agreements with pharmaceutical companies may motivate a host country to maintain its gene pool (Amin 2016 and Eichner and Pethig 2006).[49]

There are a number of features that make biodiversity preservation a particularly fascinating type of GPG with both promoting and inhibiting factors. For illustration, we consider the preservation of tropical rain forests as habitats that house an amazingly rich array of species. The preservation of tropical forests provides joint products that vary in their degree of publicness and their range of benefit spillovers (Perrings and Gadgil 2003 and Sandler 1993). Country-specific outputs from tropical forests include soil erosion protection, timber, eco-tourism, nontimber products (e.g., fruits and nuts), nutrient recycling, flood control, crop pollination, and option value. These outputs are private among countries, but public and/or private within the host country. Timber and nontimber products are private and marketable, while crop pollination is public within its spillover range. Eco-tourism is a club good for which the host country can charge visitors from the host or other countries a congestion-internalizing toll to motivate and underwrite preservation. In short, such country-specific outputs provide preservation incentives to the host country. Next, region-specific joint products correspond to localized climate effects and watersheds. These regional public goods may motivate nearby countries to finance or

[49] Costello and Ward (2006) build a search model, where their calibrated parameters provide insufficient bioprospecting incentives for significant investments in biodiversity preservation. However, these authors note that as species vanish bioprospecting incentives may assume an enhanced importance.

support preservation efforts when such benefits are recognized. Finally, global joint products from tropical forests stem from biodiversity, carbon sequestration, inter-species linkages,[50] and bequest value to future generations.

Jointly produced GPGs represent the most worrisome outputs associated with tropical forests and are a prime motivator of the Biodiversity Convention because host countries are unlikely to internalize these GPGs' benefits when deciding preservation acreage. Country-specific jointly produced outputs offer key preservation incentives that can be bolstered by regional support to maintain co-produced region-specific benefits. If these country- and region-specific benefits are complementary to the associated global benefits, then more of the forest is preserved (Cornes and Sandler 1984a, 1994 and section 2). Consider eco-tourism which increases in value as the tropical forest's gene pool grows through larger forest tracts. This complementarity is at the heart of the Biodiversity Convention's pursuit of preservation incentives. The convention also supports foreign assistance of host countries by rich developed countries. As shown in section 4, such income redistribution can escape the neutrality concern when there are private (in this case country-specific) outputs produced along with the forest-derived GPGs. Also, we learned in section 4 that leadership and unilateral action by an interested country can increase GPG supply with joint products that display complementarity, as in the case of biodiversity.

Another special feature of tropical forest preservation and its concomitant biodiversity has to do with location of these forests and other biodiversity hotspots in developing countries. Generally, rich countries place greater value than poor countries on the GPG benefits of biodiversity, carbon sequestration, and bequest value. Consequently, there is an anticipated

[50] A particular inter-species linkage concerns songbirds that protect crops in the United States and Canada by feasting on insects. These songbirds migrate to Central and South America for the winter. If these songbirds' winter habitat is degraded through deforestation, then these birds' numbers will dwindle and crops will suffer in the temperate zone (Myers 1992, pp. 59-60).

exploitation of rich and more interested countries by the poor and less interested host countries when it comes to forest preservation (see section 4). Host countries are likely less interested because they are focused on survival and development.[51] This exploitation is part of the Biodiversity Convention's orientation to seek support from rich countries.

Sandler (1993) examines this exploitation in a generalized Nash bargaining model where rich countries bargain with poor host countries over the shrinking tropical forests. According to Sandler (1993, p. 232), the coalition of developed countries is more impatient than forested developing countries, since the rich coalition possesses the wherewithal now to exploit the genetic material of the tropical forests. Additionally, developed countries have a larger demand for environmental preservation, which is income elastic, than the host countries. The underlying Rubinstein (1982) bargaining model implies that the developed countries are motivated to strike an early agreement giving them a smaller share of a larger prize before the forest assets shrink further.

Yet another hallmark feature of tropical forest preservation hinges on the need for collective action at the local, regional, and global levels owing to the mix of national, regional, global public goods that are jointly derived from tropical forests. A similar mixture would stem from any efforts to preserve biodiversity. The need for collective action at three distinct jurisdictional levels requires coordination among component jurisdictions. A global institution is required to assume a leadership role so that component institutions work in sync. The Biodiversity Convention implicitly spells out this leadership role. The complementarity of these joint products favors leadership in bolstering the component GPGs of biodiversity.

Amin (2016) offers an interesting empirical analysis of the role of economic incentives in

[51] Although country-specific benefits make host countries more interested in forest GPGs, these benefits are unlikely to make host countries more interested than rich countries.

promoting biodiversity conservation in 48 sub-Saharan countries during 1990–2009. An ecoregion protection score, compiled by the Center for International Earth Science Information Network, is used as the dependent variable, measuring those countries' success in preserving their biodiversity. Amin's (2016) main independent variables are tourism development and international environment aid. For eco-tourism, the author relies on international tourist arrivals in the sample countries; for environmental aid, the author uses the flow of official development assistance, earmarked for biodiversity, climate change, and desertification.[52] Amin finds that both eco-tourism and foreign assistance have a significant positive influence on his measure of biodiversity, thus supporting the assumed complementarity of those actions, envisioned by the Biodiversity Convention.

9. *GPG Case 3: Global Health*

Our third GPG case study is characterized by some features that are not prominent in the two previous case studies. Global health again emphasizes the recurrent themes of this survey – e.g., a growing influence on world welfare, the need for diverse collective action, the presence of strategic behavior, the emergence of new agents, and the tailoring of institutions. Global health concerns offer a wide variety of GPGs with alternative publicness properties.

The potential global nature of infectious diseases is illustrated by past pandemics. The Black Death or the plague killed about a third of the European population during the fourteenth century (Zacher 1999, p. 266). The dissemination of the plague is linked to increased trade by land (the Silk Road) and sea from Central Asia. The so-called Spanish flu, an H1N1 virus, killed tens of millions of people during 1918–1920 due, in part, to stresses on the healthcare system caused by World War I (Centers for Disease Control and Prevention (CDC) 2019).

[52] Amin (2016) imperfectly accounts for simultaneity concerns by lagging these two controls.

Globalization prior to World War I increased trade and immigration and helped transmit the flu epidemic worldwide with cases even reported on Pacific Islands and in the Arctic. With modern air travel, infectious diseases can now go from Liberia, Africa to Dallas, Texas in a matter of days, as aptly illustrated by the Ebola death of Thomas Eric Duncan during early October 2014. He had contracted the disease before leaving Liberia for Texas.

Today, the world must remain vigilant to new pandemics – e.g., strains of virulent influenzas and antibiotic-resistant diseases – while addressing modern-day plagues – i.e., HIV/AIDS, tuberculosis (TB), malaria, hepatitis, and neglected tropical diseases. According to the World Health Organization (WHO) (2015), progress continues to be made against HIV/AIDS, TB, and malaria. Annual HIV infections fell from 3.1 million in 2000 to 2.0 million in 2014, while AIDS deaths fell by 24% during this same period. The incidence of TB fell by 1.5% each year on average during 2000–2014 (WHO 2015, p. 5). For malaria, the number of infections dropped from about 262 million to 214 million, with mortality declining by 60% during 2000–2015 (WHO 2015). These three epidemics are highlighted because much of health-related disbursement of overseas development assistance went to these diseases and bolstering healthcare facilities in developing countries. Without adequate health, populations in developing countries are an ideal host for infectious diseases that can spread to rich countries. One study shows that a significant increase in public-good aid went to international health public goods during 1980–1998 (te Velde, Morrissey, and Hewitt 2002, pp. 124-25).

The progress with respect to HIV, TB, and malaria demonstrates that global collective action achieved some success even though the mortality rates are still high. Perhaps, the most notable success in terms of global health was the certified eradication of smallpox in 1979, two years after the last recorded infection in 1977. Eradication of smallpox requires the achievement of herd immunity in all countries. Herd immunity, which varies by disease, refers to a sufficient portion of the population acquiring immunity, whereby new cases among non-immunized individuals stay in check and die out. Effort to eradicate a disease through an immunization drive represents a weakest-link GPG because even a single country, below the herd immunity threshold, poses a risk worldwide (Barrett 2003a, 2007a, 2010 and Sandler 1992). Despite continual efforts since 1988,[53] polio is still not eradicated because it remains endemic to Afghanistan, Nigeria, and Pakistan. In a fascinating game-theoretic article, Barrett (2010) indicates why polio has been harder to eradicate than smallpox even though herd immunity percentages are very similar for the two diseases. In large part, polio poses a tougher eradication challenge because the use of a live-attenuated vaccine in developing countries meant that vaccine-induced infections may occur years later. This was not true of the live-attenuated smallpox vaccine. Cost and administering considerations resulted in developing countries relying on the live-attenuated polio vaccine, despite its drawback.

9.1 *What Is Different about Health GPGs*?

There are many considerations that set health GPGs apart from other types of GPGs. One notable difference involves the diverse aggregator technologies that characterize health GPGs (Chen, Evans, and Cash 1999, Sandler and Arce 2002, Smith and Woodward 2002, and Sonntag 2010).[54] Weakest-link health GPGs are associated with infectious disease eradication, infectious disease quarantine, outbreak surveillance, and information sharing for which a single country's lax efforts can greatly or totally undo the efforts of others and, in so doing, put all countries at risk. In a less stark form, weaker-link health GPGs include maintaining sterilization, limiting

[53] Currently, a public-private partnership – the Global Polio Eradication Initiative – coordinates eradication efforts. Partners include the WHO, Rotary International, CDC, United Nations Children's Fund (UNICEF), and the Gates Foundation.
[54] Much of the Sonntag (2010) book is devoted to distinguishing the strategic aspects that are associated with weakest-link and best-shot health public goods.

pest diffusion, and collecting vital statistics for which efforts greater than the smallest can provide some of the good but the least effort has the largest marginal influence. Best-shot health GPGs correspond to finding a cure, developing a treatment regime, isolating a virus, or discovering a vaccine. Creating an antibiotic may be a better-shot health GPG insofar as other less effective new antibiotics may be better tolerated by some patients and thus of some use. The weighted-sum aggregator may apply to curbing the spread of AIDS, reducing some airborne pollutants, or eliminated a toxin from a shared environmental. In all three cases, spatial dispersion plays a role.

In general, there is a preponderance of weakest-link and best-shot health GPGs. For weakest-link health GPGs, there is a need to foster capacity by shoring up poor countries' provision efforts. This shoring up can come from rich donor countries, multilaterals, charitable foundations, or public-private partnerships to allow every country to attain an acceptable provision of the good. This is the role model used to eradicate smallpox and to eventually eradicate polio. The weakest-link aspects of eradication and other health GPGs motivate rich countries to take an interest to reduce their own exposure.[55] An end to smallpox meant that countries no longer had to assume vaccination risks. From section 4, income transfers from rich to poor countries can increase a weakest-link GPG and circumvent neutrality. For best-shot health GPGs, there may be a need to pool efforts to make the breakthrough if no country has the means to do it on its own. That pooling or transfer of income to rich countries can augment best-shot GPGs – see section 4. The US CDC takes actions to isolate new pathogens, develop vaccines, and coordinate surveillance efforts. In so doing, the CDC privileges the world to essential best-shot health GPGs. These weakest-link and best-shot GPGs affect the roles

[55] Shoring up weakest-link countries may present a free-riding problem when many rich countries can assume this role. Sandler (2016) offers some theoretical considerations in such scenarios.

assumed by various institutions and agents in the global health sector.

Another noteworthy feature characterizing health GPGs involves the many institutional arrangements that foster provision. For the global health sector, table 3 indicates six major categories of institutions, along with select examples in each category. Their primary purposes in providing health GPGs are also displayed. As indicated, multilateral organizations – e.g., the WHO, the World Bank, and the UN Development Programme (UNDP) – are ideally positioned to pool funds for best- and better-shot health GPGs, while fostering capacity for weakest- and weaker-link health GPGs. Multilateral institutions also participate in public-private partnerships – e.g., Onchocerciasis Control Partnership, Global Alliance for Vaccines and Immunization (GAVI), and Global Fund – to finance and coordinate provision activities. By overseeing fund disbursement and accounting, multilateral organizations limit asymmetric information, thereby reducing transaction costs. In the global health sector, public-private partnerships utilize component participants' comparative advantage in terms of intelligence, drugs, distribution networks, funding, and other tasks (Glassman, Duran, and Sumner 2013). Diverse participants include donor countries, recipient countries, private corporations, NGOs, and multilateral organizations. For instance, the Onchocerciasis Control Partnership joins efforts by Merck, the WHO, host countries to the disease, and donors to control river blindness, endemic to 34 countries in Africa, Latin America, and the Arabian Peninsula. Merck contributes dosages of Ivermectin to treat the disease. Such partnerships allow for multilateral matching on the part of donor and recipient countries, thereby escaping the Bergstrom paradox (section 4). The institutional category of networks are uniquely positioned to link diverse regions of the world to address best-shot and weakest-link GPGs – prime networks include the Global Environment Facility (GEF) to bolster environmental protection in poor countries and the Consultative Group for International Agricultural Research (CGIAR) to foster sustainable agriculture in poor countries. Healthy environments and adequate food supplies support the health and well-being of host populations. By attracting new sources of funds, these networks can circumvent neutrality concerns. Three additional categories of health sector institutions include charitable foundations, NGOs, and nation-based institutions. Prime examples of each are given in table 3, along with a short description of their main roles in providing health GPGs.

[Table 3 near here]

Yet another distinguishing feature of health GPGs concerns their potential for intergenerational spillovers,[56] whereby provision by the current generation may negatively or positively influence the well-being of future generations (Peinhardt and Sandler 2015 and Sandler 1999). Consider the overuse of antibiotics that can result in antibiotic-resistant TB that adversely impacts current and future generations. Similarly, expanded use of antiretroviral drugs to treat the AIDS epidemic in Africa may diminish the effectiveness of the drug with time. Some best-shot health GPGs – e.g., discovering vaccines, developing treatment regimes, and curbing microbial resistance – provide intergenerational public benefits. Those spillovers may exacerbate provision inefficiency because impacted generations cannot meet and bargain to an ideal provision level. For intergenerational health GPGs, the future generations are not present and so the current generation must be altruistic to them, which poses a problem insofar as later generations' preferences cannot be known today. For weakest-link health GPGs, the current generation is likely to be poorer than future generations so that provision shortfalls commence immediately, thereby passing along a small level of the good for subsequent generations. In contrast, the provision of best-shot health GPGs are apt to improve over time as future generations acquire knowledge and resources, thus resulting in ever-increasing breakthroughs.

[56] For environmental GPGs, spillovers often effect primarily the current generation as is true of many flow pollutants. Climate change is, of course, an exception with true intergenerational spillovers.

Kremer and Leino (2004) highlight another feature of health public goods: namely, many of these goods possess more local benefits at the national or regional levels. Often, these localized benefits are jointly produced with the global benefits – e.g., treating an infectious epidemic provides training to indigenous healthcare workers. Such complementary benefits can motivate or crowd-in host-country actions. When a disease is region- or geoclimatic-specific (e.g., some malaria strains), benefits from fighting the disease may have little global spillovers, leading to the need for nation- or region-based health institutions. As such, assistance from a regional, rather than a global, institution may be more appropriate. This is an appeal to subsidiarity by not necessarily equating health contingencies with GPGs and global-directed action. Nevertheless, Kremer (2006) recognizes that combating communicable diseases with wide spillover ranges are GPGs, as is vaccine-based eradication of polio or other global diseases.

A final distinguishing feature of health GPGs involves the wide variety of impure public goods owing to rivalry and excludability considerations.[57] For example, internet-based diagnostic procedures possess club good elements due to crowding and exclusion that provide subscription funding possibilities. Knowledge gained from clinical trials or research may be excludable. Elite hospitals that treat patients worldwide offer health private goods to those who can afford the best specialists.

9.2 *Infectious versus Non-infectious Diseases*

Healthcare concerns differ greatly between rich and poor countries. That difference is starkly

[57] Today, there is almost no literature that tests for the strategic interactions among governments with respect to health GPGs. A notable exception is by Kyle, Ridley, and Zhang (2017) who study how medical research funding in other countries for infectious and parasitic diseases respond to changes in US government funding for the same diseases. Their study finds that greater US funding significantly reduced research funding elsewhere on these diseases. This is a clear free-riding result, indicative of pure publicness. Also, those funding reductions are shown to be repurposed to other diseases. The article applies an interesting identification strategy using the composition of the US Congressional appropriations committee and NIH budgets to isolate influence of changes in US funding.

underscored by the so-called “90/10” gap involving the development of medicines, vaccines, and treatments for which *less than 10%* of US annual health-research spending is tied to the healthcare interests of 90% of the world’s population (WHO 2002, p. 23). The 90/10 gap means that there is an imbalance of best-shot health GPGs that primarily favors rich-countries diseases. Given differences in life expectancy, lifestyles, healthcare infrastructure, population age profiles, nutrition, education, immunization programs, and economic development, people in developed countries generally suffer from noncommunicable “old age” diseases, while those in developing countries typically suffer from infectious and parasitic diseases. With these differences, donor countries and their constituency face a difficulty in understanding the health GPG needs of poor countries.

The problem is compounded by the pharmaceutical companies whose research and development is motivated by profit. As a consequence, those firms want to develop medicines to treat cancers, heart disease, and hepatitis C. Pharmaceutical firms’ profits are higher when they develop treatment regimes rather than vaccines. With vaccines, one or two doses are sufficient to keep the disease at bay, so that per-patient revenue streams are low unlike the case for treatment regimes with a continual revenue stream. Pharmaceutical firms pursue drugs where there is high income elasticity and low price elasticity, which corresponds to life-saving medicines in rich countries.

The typical shortfall associated with public goods as countries act independently is especially worrying for health GPGs because of the vastly different threats posed by infectious and non-infectious diseases to poor and rich countries, respectively. Rich countries with the means to provide best-shot GPGs are not motivated to do so if they can protect themselves from a spreading infection.

10. *Regional Public Goods* (*RPGs*)

Until now, our focus has been on GPGs, but the spillover range of public goods may be more constrained, thereby giving rise to national public goods (NPGs), subregional public goods, RPGs, and transregional public goods. An RPG provides benefits to a well-defined region that can be based on propinquity (e.g., contiguity), geographic location (e.g., a continent), geology (e.g., watershed, coastline, mountain range, or plain), geoclimatic factors, culture (e.g., language), or politics (e.g., customs union membership) (Arce and Sandler 2002, Estevadeordal, Franz, and Nguyen 2004, Estevadeordal and Goodman 2017, and Sandler 2010). For our purposes, region is equated to geographic location. For RPGs, benefit spillovers may be fully or partly nonrival or nonexcludable. Moreover, a host of aggregator technologies apply, analogous to GPGs (Berg and Horrall 2008, Sandler 2006, and Tres and Barbieri 2017). At the regional level, reducing acid rain abides by a weighted-sum aggregator, monitoring financial stability corresponds to a weakest-link aggregator, suppressing a forest fire adheres to a threshold aggregator, ending a conflict follows a best-shot aggregator, and curbing a terrorist campaign indicates a better-shot aggregator. As before, these aggregators influence the extent of suboptimality, the need for policy, the role of agents, and the design of institutions with respect to allocative decisions. Recalling section 4, these three aggregators can result in income transfers that increase the amount of the RPG if engineered in the right direction – e.g., to countries with larger productivity weights in the case of a weighted-sum aggregator.

For GPGs, globalization is a driving force; for RPGs, regionalism is a driving force. Regionalism stems from enhanced region-based, cross-border flows and the subsequent requirement for augmented regional integration to bolster development through the provision of RPGs and the reduction of regional public bads (Acharya 2017 and Stålgren 2000). A prime instance is the need for interregional infrastructure that fosters connectivity in terms of communication, rail networks, highways, energy, and trade (Prasad 2017). Massive infrastructure projects in, say, Asia are currently tying together parts of the continent into waterways, power grids, and interstate highways (e.g., Belt and Road Initiative) to support not only greater regional integration, but also enhanced investment and trade flows (Asian Development Bank 2017).

Regional infrastructure connectivity is essential so that one nation's portion of a power grid, pipeline, air-traffic control network, or railway system can be seamlessly joined to those of other nations (Prasad 2017). Such linkages require conformability, which for a railway network means that the same track gauge, operating logistics, and signaling system are used throughout. For interstate highways, customs clearance must be sufficiently homogeneous to eliminate bottlenecks at border crossings. Additionally, road width and bridge heights must support a standard truck dimensions along the entire interstate highway.[58] Another connectivity consideration concerns the prevalence of weakest- and weaker-link aggregators. Given their network nature, interregional infrastructure projects are most inhibited by their least functional component – e.g., the narrowest part of an interregional canal has a disproportionate effect in transit times. Most infrastructure projects consist of regional club goods that allow the use of tolls to finance each component nation's network portion. Because regions contain nations with vastly different incomes and wealth, the initial financing of some countries' portions must be funded by a regional bank through loans, later repaid by transit tolls (Kanbur, Sandler, and Morrison 1999). In some regions, a dominant country may provide loans or grants so that the cross-region infrastructure is built. China is serving this purpose in Southeast Asia and other parts of Asia (Asian Development Bank 2017).

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[58] Berg and Horrall (2008) emphasize the need for policy harmonization in regional regulatory networks, and commissions (e.g., South Asian Telecommunication Regulators' Council and East Asia and Pacific Infrastructure Regulatory Forum). Regulatory networks promote data sharing, best practices, and benchmarking data.

10.1 *Which Is Easier to Address*, *RPGs or GPGs*?

Based on the standard theory of public good provision, RPGs should be easier to address than GPGs because the number of countries receiving spillover benefits is smaller (see section 3). In practice, however, there are a host of factors that either promote or inhibit the provision of RPGs compared to GPGs (Cook and Sachs 1999 and Sandler 2006). We first consider factors, beyond the fewer number of countries, that favor the provision of RPGs over GPGs. Spatial and cultural propinquity fosters RPG provision. At the regional levels, nations are in constant contact, thereby allowing nations to gain an understanding of one another that curtails uncertainty, fosters bargaining, and limits transaction costs, thereby promoting RPG provision. Regional propinquity increases repeated interactions, which means that potential short-run gains from reneging on RPG provision agreements may not justify long-term retribution. Regional interactions involve many different public goods that can result in complementarity and the need for joint provision. Regions experiencing economic growth, such as Southeast Asia, may be particularly well-positioned for supplying their RPGs (see section 4). The rise of regionalism created regional trading blocs that can offer loans to members to provide trade-promoting RPGs. These blocs can also coordinate RPG supply efforts among member states. Many RPGs possess favorable characteristics of publicness – e.g., complementary joint products, weighted-sum aggregators, weakest-link aggregators, and excludable benefits – in contrast to some essential GPGs (curbing climate change or ozone shield depletion). For many airborne regional pollutants abiding by weighted sum (e.g., acid rain), countries generally experience the greatest share of their own pollutants, thereby motivating them to curb emissions (Aakvik and Tjøtta 2011, Finus and Tjøtta 2003, and Murdoch, Sandler, and Sargent 1997). Weakest-link RPGs generate incentives either to match one another's provision or to shore up poor countries' efforts. The latter efforts can circumvent neutrality concerns (see section 4). Given fewer countries, shoring up weakest-link countries is easier to accomplish regionally than globally (Sandler 2016). At a regional level, the paradox of cooperation can be circumvented if two or three countries form a coalition and account for the bulk of the RPG provision so that the noncoalition members cannot undo the coalition's efforts (section 5). The sufficient efforts of just two or three coalition countries are much less apt to be sufficient for most GPGs. Also, at the regional level, there is apt to be more other-regarding preferences and less uncertainty that can support the stability of the coalition.

By contrast, some factors inhibit RPGs relative to GPGs. First, regional rivalries and past conflicts may block the provision of RPGs (Cook and Sachs 1999). Second, regions may lack a dominant leader country that champions and coordinates RPG provision. Third, there is a culture for donor countries to support global institutions and their GPG agenda. The World Bank, the United Nations, and other multilateral institutions have a rich history since World War II of supplying GPGs and RPGs that include peace, financial stability, regulatory standards, health, and environmental preservation. There is much less tradition to rely on regional institutions to provide public goods with more constrained spillover ranges. Nevertheless, this tradition is slowly emerging with the rise of regional banks, trading blocs, and other regional institutions. Fourth, many RPGs do not provide benefit spillovers to donor countries, thus limiting their interest and support.

There are actions that can offset these RPG inhibitors. Regional rivalries are ameliorated as countries are enlightened that they can all prosper from greater RPG integration. Public-private partnerships, networks, charitable foundations, and other new agents can assume a leadership role in championing and coordinating RPG provision, thus taking the place of a dominant country. The World Bank can redirect funds to regional development banks so that

RPG provision better reflects recipient countries' derived benefits. Donor benefit spillovers from RPGs can be better recognized by showing the complementarity between RPGs and GPGs as done in a World Bank (2001) development report (see also Ferroni and Mody 2002). Thus, regional financial stability – an RPG – bolsters global financial stability because a financial crisis starts in a vulnerable region and then spreads. Similarly, NPGs may be complementary to some RPGs and GPGs – e.g., better healthcare facilities at the national level supports the effectiveness of health RPGs and GPGs (World Bank 2001).

10.2 *Transboundary Air Pollution – The Case of Acid Rain*

For our region-based empirical illustration, we consider sulfur-based acid rain. Once released into the air from an emission source, sulfur combines in the atmosphere with water vapor and tropospheric ozone to form sulfuric acid. As this acid precipitates from the atmosphere, damage results to lakes, rivers, forests, and man-made structures. The two main sources of sulfur emissions are power plants and industry (Sandler 1997, p. 116). Three international environmental agreements are germane to curbing these sulfur emissions in Europe. The Long-Range Transboundary Air Pollution (LRTAP) Convention, ratified in March 1983, mandated scientific investigation and evaluation of sulfur emissions and deposition throughout Europe. Two protocols to the LRTAP Convention followed: the Helsinki Protocol of 1987 and Oslo Protocol of 1998. The Helsinki Protocol mandated that ratifiers reduce their sulfur emissions by 30% of 1980 levels by 1993 or as soon as possible; the Oslo Protocol mandated that some ratifiers further reduce their sulfur emissions by upward of 80% of 1980 levels.[59]

The Cooperative Programme for Monitoring and Evaluation of the Long-Range

[59] Cutback percentages depended on the signers' cost of abatement. Low-cost abaters were assigned greater cutbacks, while really high-cost abaters were allowed to return to 1980 emission levels. The Oslo Protocol tried to equate marginal costs of abatement among ratifiers to minimize abatement costs (Finus and Tjøtta 2003).

Transmission of Air Pollution in Europe (EMEP) set up observation stations throughout Europe to identify emission sources and downwind deposition sites for sulfur, nitrogen oxides, volatile organic compounds, and other pollutants. EMEP resulted in the identification of a *transport matrix* in which the columns indicate the amount of sulfur emitted by country *j* that falls on recipient countries, denoted by the *i*th row entries (Aakvik and Tjøtta 2011, Murdoch, Sandler, and Sargent 1997, and Vollenweider 2013). If each matrix entry is divided by the emitter's total sulfur emissions, then the resulting entry, α_{ij}, is the fraction of country *j*'s emissions deposited on country *i*. The normalized transport matrix indicates the weights for a weighted-sum aggregator, where country *i*'s reduced depositions equal: $\alpha_{ii}q_i + \sum_{j \neq i}^{n} \alpha_{ij}q_j$. In this expression, q_j denotes country *j*'s sulfur emission reduction. The α_{ii} captures self-pollution or the share of country *i*'s emissions that fall on its own soil. Once airborne, sulfur emissions are deposited downwind in a rival fashion: a ton of these emissions deposited on Germany cannot be deposited elsewhere. Ideally, the countries are ordered in the top row of the transport matrix from west to east according to the prevailing wind. EMEP estimated annual transport matrices for sulfur, nitrogen oxides, and other pollutants, thereby allowing ratifiers' adherence to LRTAP protocols to be examined.[60]

The first empirical evaluation of the Helsinki Protocol is by Murdoch, Sandler, and Sargent (1997) who estimate the determinants of sulfur emission reduction before and after the Helsinki Protocol went into effect in 1988. These authors derive a reduced-form estimating equation for sulfur emission cutbacks, based on a game-theoretic public good provision model

[60] Vollenweider (2013) tests the Gothenburg Protocol of 2005 for multiple pollutants (e.g., sulfur, ammonia, and fine particulates); Finus and Tjøtta (2003) investigate the Oslo Protocol of 1998 for sulfur; and Murdoch, Sandler, and Sargent (1997) also examine the Sofia Protocol of 1991 for nitrogen oxides. These articles find little in the way of cooperative behavior compared to the Nash equilibrium.

that allows for a weighted-sum aggregator. These authors find that *prior* to the framing of the protocol in 1985 that 10 of the 25 countries had already achieved the subsequently mandated 30% reduction. Another six countries had reached emission reductions of at least 23%. On average, mean reductions were almost 21% prior to the treaty framing. This suggests that the treaty basically encoded Nash-equilibrium reduction levels. This apparent lack of cooperation is further supported by Murdoch, Sandler, and Sargent's (1997, p. 294) estimates of the determinants of sulfur emission reduction. After the ratification of the Helsinki Protocol, countries responded more negatively to spillovers or reduced sulfur emissions of others, thereby indicating an even greater free-rider response. Moreover, treaty-based aggregate target reductions induced countries to respond with fewer voluntary cutbacks. This discouraging finding agrees with the theoretical prediction that coalitions may not accomplish much in the way of public good provision beyond Nash levels – see section 5.

A follow-up study examines the Helsinki Protocol as a two-stage game whereby countries first decide whether or not to participate (ratify) and then choose their emission reduction levels (Murdoch, Sandler, and Vijverberg 2003). These authors apply a full-information maximum likelihood estimator that accounts for the simultaneity bias associated with public good spillovers at both stages. Based on the underlying subgame perfect equilibrium, reduced-form estimating equations are derived for both stages with additional variables (e.g., forest cover and democracy) characterizing the participation stage to allow for identification. The spillover variable (i.e., reduced emission of others) provided a different strategic response in the two stages: at the ratification stage, the spillover coefficient was positive, consistent with strategic complements,[61] while at emission-reduction stage, the spillover coefficient was negative, consistent with strategic substitutes and free riding.

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[61] In the context of the Kyoto Protocol, Sauquet (2014) also finds spillovers resulting in strategic complements.

Reduction-stage free riding implied that treaty-induced cooperative gains were neither large nor optimal. Unlike earlier studies of the Montreal Protocol on ozone shield protection (Congleton 1992 and Murdoch and Sandler 1997), democracy did not foster ratification of the Helsinki Protocol, which was probably because autocratic countries in the east were the largest importers of sulfur depositions at the time of ratification, thereby making them highly motivated to join the treaty.

Aakvik and Tjøtta (2011) applies a difference-in-difference approach to investigate the effectiveness of the Helsinki and Oslo Protocols on reducing sulfur emissions in Europe. Their panel consists of 30 European countries during 1960–2002. Notably, sample countries include signatories and nonsignatories. In their study, neither protocol had a significant impact in reducing sulfur below the Nash equilibrium level. A similar conclusion is found by Finus and Tjøtta (2003) for the Oslo Protocol using a calibration method. The lack of cooperative gains is also shown for the Gothenburg Protocol by Vollenweider (2013) based on a difference-in-difference approach. There are many other articles on the effectiveness of LRTAP protocols, most of which uncover little or no cooperative gains, consistent with Barrett (1994a) and Carraro and Siniscalco (1993).

11. *Concluding Remarks*

We briefly return to the seven recurrent themes of the survey. First, our three specific GPG case studies – climate change, biodiversity, and global health – and our myriad examples – e.g. UN peacekeeping, ozone-shield depletion, universal regulatory practices, and averting global financial crises – are consistent with the proper allocation of GPGs having huge gains for global welfare. Those gains are not only for the current generation, but may also be for future generations as the avoidance of climate change and antibiotic-resistant diseases aptly illustrate.

Second, diverse collective action concerns, tied to GPG provision, are captured by the array of aggregator technologies and the configurations of publicness properties, associated with GPGs that range from curing infectious diseases to protecting against internet viruses. GPGs constitute a rich set of goods that require alternative policy approaches tailored to their special properties. Third, GPGs are linked to strategic behavior that involves noncooperative and cooperative game theory. With respect to GPG provision, not only do countries take strategic moves with respect to their counterparts' actions, but also noncoalition countries respond strategically to a coalition's GPG actions. In the latter case, those induced actions can partly undo the cooperative gains of the coalition, thereby mitigating the effectiveness of treaties and multilateral organizations. Fourth, to properly confront GPG provision, the world community must design novel institutional arrangements that account for strategic behavior so that allocative efficiency goals are pursued. Fifth, appropriately tailored institutional arrangements – e.g., clubs, international treaties, or multilateral organizations – must account for GPGs' properties and contextual considerations. For climate change, those considerations have proven particularly difficult as illustrated by the contrast drawn with successfully addressing ozone-shield depletion. Sixth, GPGs are associated with the appearance of new actors (e.g., private-public partnerships) that provide new sources of funding and, at times, essential leadership for some GPGs. These new agents are especially important in dealing with issues of global health. Seventh, lessons learned from the study of GPGs inform best practices for other transnational public goods, below the global level. In fact, the linkage of some regional collectives may provide a way forward to supplying select GPGs, particularly when there are nuanced differences at the regional levels (e.g., differing strains of malaria). As regional integration assumes an increasing importance, driven by the rising importance of Brazil, China, and India, the interface between RPGs (e.g., regional infrastructure) and GPGs (e.g., global trade flows) take on an enhanced importance.

Many fruitful future directions exist for the analysis of GPGs. There is a need for more empirical studies of GPGs, such as those on actions to control ozone-depleting substances following the Montreal Protocol (see, e.g., Congleton 1992 and Murdoch and Sandler 1997). New studies must possess an identification strategy to account for the strategic endogeneity of one country's actions with respect to those of other countries, so that the reversed causality between a country's GPG provision and the collective GPG provision of other countries is properly taken into account with instruments. The latter spillovers generally adversely affect a country's own GPG provision. Better principles for designing global institutions are required – e.g., achieving the right mix of country-specific and GPG complementary joint products – to circumvent free-riding incentives. For sub-Saharan countries, Amin (2016) shows how the furtherance of eco-tourism – a country-specific biodiversity-based joint product – and GPG-earmarked foreign assistance promoted the preservation of biodiversity. Further such empirical studies can validate whether institutional engineering has the sought-after influence. Those design principles can also rely on instituting aggregator technologies that bolster GPG provision or the application of income redistribution to augment provision in such non-neutrality situations. To date, the engineering of global institutions to provide GPGs is in its infancy. Another research direction is to ascertain an improved understanding of the interrelationship among GPG problems. To date, GPGs' provisions are examined in isolation. Consider ozone-shield depletion and climate change. The primary substitute for chlorofluorocarbons – an ozone-shield depleter – was hydrofluorocarbons, which is a greenhouse gas. Years later, those hydrofluorocarbons require phasing out to better address climate change. Global conflicts in some countries can have global health consequences, as stymied efforts to eradicate polio from three countries illustrate so well. Future GPG research must become more proactive in identifying and addressing the drivers of new GPGs and GPBs. As globalization accelerates, the interest in GPGs is likely to grow greatly. The development of novel technologies can have unintended worldwide consequences as the creation and use of nuclear power and chlorofluorocarbons demonstrate. As technological advances accelerate, the creation of novel GPGs and GPBs are apt to grow. Some of those goods and bads may come from efforts to exploit outer space, which may result in not only scientific breakthroughs but also unwanted externalities with global consequences.

We conclude on a more speculative note by indicating some GPGs and GPBs that are anticipated to exercise a growing influence. With the increased use of orbital slots above the earth and between the earth and the moon, satellites present an externality problem in terms of signal interference and collision. Thus, there is a growing need for global collective action to depose of orbital garbage. How those efforts will be coordinated is an open GPG question. Currently, reentry burnup has been the solution, which has its own externalities as large nuclear-fueled satellites do not disintegrate completely upon reentry. Another garbage issue of growing importance is the accumulation of plastics in the ocean, which threatens sea life, shorelines, and shipping. Cyberspace poses a number of global benefits and threats. On the benefit side, the internet can disseminate discoveries and best practices. The latter may involve surgeons-in-training in developing countries viewing state-of-the-art surgical procedures on the internet performed in the world's premier hospitals. Cyber threats will surely entail ever more difficult viruses and ransomware to detect and eliminate. Recent elections (e.g., the 2016 US presidential election or the Brexit vote) show how the internet can be exploited to sway outcomes and to spread misinformation. Countries must take a more coordinated approach to curtail such threats to democracy; but countries want to act independently. Cyberspace can also present a GPB in terms of enhance terrorism as terrorist groups use the internet to coordinate widely dispersed followers, post propaganda videos, recruit members, heighten anxiety, and supply operational guidelines. Another GPG of increasing importance involves addressing failed states, unable to control their own territories – e.g., Afghanistan, Syria, and Yemen. Such states have come to host transnational terrorist groups and to be embroiled in conflicts that result in violence and refugee spillovers.

With the continued problem to control climate change, countries may resort to geoengineering or the large-scale deliberate manipulation of the earth's environment to offset some of the manifestations of climate change (Barrett 2008 and National Research Council 2015a, 2015b). Geoengineering may assume two basic alternative forms: carbon dioxide reduction (CDR) and albedo modification (AM). CDR counters the atmospheric accumulation of greenhouse gases by augmenting the storage capacity of oceans, soils, and forests (e.g., reforestation). The myriad CDR methods are currently rather expensive and present similar collective action issues to other efforts to limit greenhouse gases and climate change. One particularly costly CDR method is direct air capture and sequestration that literally scrubs carbon dioxide from the atmosphere to be then stored.[62] AM methods affect the percentage of incoming solar energy that is reflected back into outer space (National Research Council 2015b). Enhanced reflectivity occurs by enhancing the albedo of land areas, the oceans, the lower atmosphere, and clouds. One rather inexpensive AM technique involves injecting sulfur particles into the stratosphere through the use of guns, planes, or balloons to cool the planet by reflecting more sunlight back to space. That and other AM methods present a collective action concern since a single capable country can take action on its own, given the best-shot nature of many AM methods (Sandler 2018). Such cooling may be opposed by some countries (e.g., those that gain from a warmer and wetter climate), resulting in a collective action dilemma similar to confronting a rogue country. Matters are made worse owing to addiction because once such AM

[62] Sandler (2018) presents a survey on geoengineering along with an extensive list of references.

actions are employed, stopping them can result in catastrophic consequences as temperatures quickly warm.

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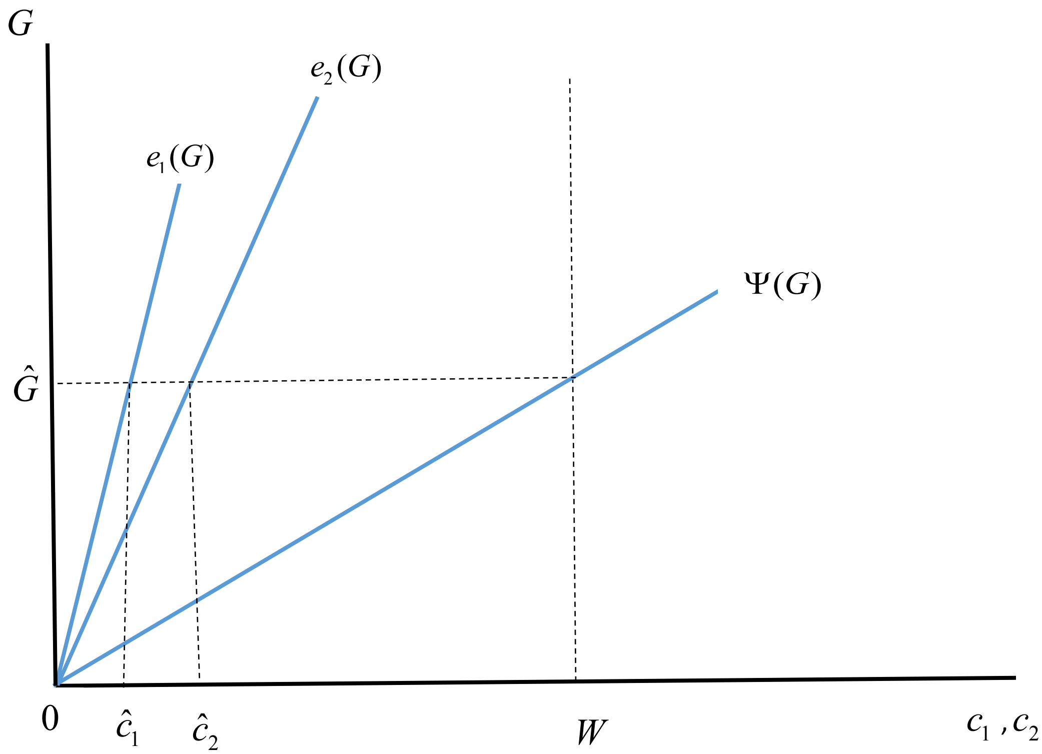

Figure 1. Two-country Nash Equilbrium GPG Supply

TABLE 1
GLOBAL PUBLIC GOODS: AGGREGATE TECHNOLOGIES AND THREE PUBLIC GOOD TYPES

Aggregation Technology	Pure Public Good	Impure Public Good	Club
Summation: Overall level of GPG equals the sum of the countries' contributions.	Limiting greenhouse gas emissions or preserving biodiversity	Curbing organized crime in a globalized world or deploying peacekeeping assets	INTELSAT communication network
Weighted sum: Overall level of public good equals a weighted sum of the countries' contributions.	Controlling the spread of an infectious outbreak (e.g., Ebola)	Reducing acid rain or ambient pollutants	System of canals and waterways
Weakest link: Smallest contribution of the world's countries determines the GPG's aggregate level.	Maintaining the functionality or integrity of a global network	Surveillance of financial crises or a disease outbreak	Air-traffic control system
Weaker link: Smallest contribution of the world's countries has the greatest influence on the GPG's aggregate level, followed by the second smallest contribution, and so on.	Inhibiting the spread of financial instability or maintaining sterilization	Inhibiting pest or crop disease diffusion	Global Internet network
Threshold: Benefits from the GPG only arise once its cumulative contributed quantity surpasses a threshold amount.	Establishing an early-warning system for disasters, including tsunamis	Suppressing large-scale forest fires or curbing flooding	Crisis-management teams or counterterrorism force
Best shot: Largest contribution by a country determines the good's aggregate level.	Eliminating a rogue country or diverting a comet	Developing financial or agricultural best practices	Providing satellite launch facility
Better shot: Largest contribution by a country has the greatest influence on the good's aggregate level, followed by the second largest contribution, and so on.	Uncovering best practices, including treatment regimes for diseases	Limiting the diffusion of transnational terrorist campaigns or drug trafficking	Biohazard facility

TABLE 2

AGGREGATOR TECHNOLOGIES: PROGNOSIS AND RECOMMENDATIONS FOR GPGS

Aggregator	Prognosis	Recommendations
Summation	• Free-riding tendency stems from the perfect substitutability of contributions. • Prisoners' Dilemma (PD) game structure applies. • General tendency is for underprovision.	• Grants and loans are needed to support provision. • Multilateral institutions need support supply. • Repeated interaction may ameliorate PD concerns.
Weighted sum	• Less of a tendency for underprovision since one country's provision is not a perfect substitute for that of another country. • Countries with larger impacts are incentivized to act.	• Institute monitoring to gather information on countries' supply influence. • Spatial considerations may be essential.
Weakest link	• Efficient if countries possess same tastes and GDP. • More equal income distribution promotes provision. • Matching contributions are desired. • There is a need to shore up weakest links, which poses free-riding concerns.	• Capacity building is essential when countries differ. • Global institutions, dominant country, partnerships, and others can assist weakest-links countries.
Weaker link	• Efficient if countries are sufficiently similar. • Matching and non-matching behavioral outcomes are relevant. • There is a reduced need to shore up weakest links.	• Some capacity building is required. • Global institutions, dominant country, and partnerships, and others can help to some extent.
Threshold	• Threshold creates incentives to contribute. • Reaching the threshold presents a coordination problem but there are still free-riding incentives. • Leadership promotes coordination.	• Multilateral institutions can induce countries to be threshold contributors, thereby offering coordination. • Dominant country or institution can provide leaders.
Best shot	• Global income inequality promotes provision. • Multiple best shooters results in a coordination problem. • Poor regions may not possess a best shooter.	• Rich or dominant country fosters provision. • Multilateral organizations and others can pool actions. • Regions must coordinate their provision activity.
Better shot	• Multiple countries can contribute. • Contributions do not have to be coordinated or concentrated. • Provisions beneath the largest may be desirable.	• Reduced need for rich country leadership. • The pooling of contributions is less of a necessity. • Less provision supply by outsiders may be required unless rich countries are uninterested.

TABLE 3
SELECT INSTITUTIONAL CATEGORIES IN THE GLOBAL HEALTH SECTOR

Categories	Purposes
Multilaterals WHO, World Bank, UNDP, UNEP, United Nations	Pooling of funds for best-shot and better-shot health GPGs, and bolstering of capacity for weakest-link and weaker-link health GPGs. Participate in partnerships and facilitate networks. Oversee fund disbursement and accounting, thereby limiting asymmetric information. Channel funds to regional entities.
Public-private partnerships Onchocerciasis Control Partnership, GAVI, Global Fund, Global Polio Eradication Initiative, Stop TB Partnership	Link together diverse participants that may include donor countries, recipient countries, NGOs, corporations, and multilateral organizations. These partnerships utilize their components' unique expertise and/or funds to target tropical diseases and other plagues in developing countries. Can tackle a host of aggregator technologies by offering capacity or pooling resources.
Networks Global Environment Facility (GEF) Consultative Group for International Agricultural Research (CGIAR)	Join interests and similar projects in diverse regions throughout the planet. GEF is supported by the World Bank and donor countries, while CGIAR is funded by donor governments and NGOs. CGIAR forms a partnership of funders and international agricultural research centers. Networks can address best-shot and weakest-link health-based GPGs. Serves to attract new sources of funds to circumvent neutrality concerns.
Charitable Foundations Wellcome Trust, Gates Foundation, Open Society Foundations, Rockefeller Foundation	Attract and offer new sources of funding for foundation-favored GPGs involving health and other concerns (e.g., education, gender equality, and democracy). Some foundations leverage funds for orphan drugs and addressing plagues. Focus on curbing diseases where there are little commercial interests. Offer leadership, capacity for weakest-link health GPGs, and pooled resources for best-shot health GPGs.
Nongovernmental Organizations (NGOs) Médecins Sans Frontières (MSF), Red Cross, Save the Children	Champion specific health GPGs and complementary activities (e.g., enhancing nourishment). Some NGOs (not listed) provide funding for supporting some health-related partnerships.
Nation-Based Institutions Centers for Disease Control (CDC), National Institutes of Health (NIH), Pasteur Institute	Isolate new diseases and develop treatment regimes and vaccines. There is a focus on best-shot GPGs concerning new pathogens that may pose a risk on the world. These institutions also address weakest-link GPGs that include outbreak surveillance.