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Health-promoting alliances

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Abstract

This paper explores how nations can save on prophylactic costs by allying to forestall the spread of a pathogen. Our study represents an alternative to noncooperative approaches, where the relative wealth of a nation is more important than its strategic location. The distribution of cost savings among participants is shown to depend on the configuration of nations and the pathway of the pathogens. In some cases, a country's position and size matter, while in other cases, they do not affect its relative share. Alternative ethical considerations may additionally alter the distribution of cooperative benefits. The analysis demonstrates why a country such as the US may be motivated to underwrite the Centers for Disease Control (CDC).

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> Global public health on an ongoing basis would, if it truly existed, constitute disease prophylaxis for every locality, from rich nation to poor. (Garrett, 2000, p. 557)

1. Introduction

Globalization is a mixed blessing from the perspective of public health. Disease surveillance systems (e.g., the World Health Organization's (WHO) rumor website) and the diffusion of modern technologies and ideas worldwide improve diagnostic procedures

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and clinical practices. Yet also, neoliberal aspects of globalization in the form of free-market reforms and fiscal budget balancing strain local public health services, especially in the developing world (Rodrik, 1997; McMichael and Beaglehole, 2000). There has also been an increased incidence of diseases such as AIDS, malaria, Ebola, and plague. As these diseases recognize no political borders, local epidemics rapidly escalate to regional concerns and global integration magnifies the potential for dispersion through air travel and commerce. Indeed, the reappearance of tuberculosis in more virulent and antibiotic-resistant strains underscores the fragility and interconnectedness of the state of global public health. The potential consequences are transparent when one remembers that the single greatest killer of the twentieth century was the smallpox virus, which, prior to its eradication in 1977, claimed more lives than the combined wars from this violent century (Garrett, 2000, p. 111).

The demands on public health systems worldwide, and particularly those in less-developed countries that are flashpoints for epidemics, raise the question of burden sharing in a microbial-unified world. Transnational activities to promote public health involve a host of public goods whose benefits are wholly or partially nonrival and nonexcludable. Examples include the eradication of diseases, the discovery of cures, the monitoring of contagion, and the creation of prophylactic barriers. The nonexcludability of benefits can lead to free riding and burden-sharing problems where either the rich or those with the greatest preference for the public good assume the greatest burdens. Indeed, there is a normative debate in public health circles about the obligations of wealthy nations to contribute more than poor ones to control and monitor the spread of disease (Yach and Bettcher, 1998). These arguments are akin to the Olson and Zeckhauser (1966) positive version of the free-rider problem for military alliances—the exploitation hypothesis—that asserts that as deterrence provides the greatest benefit for wealthy nations, burdens will be shouldered by the richest allies (Sandler and Hartley, 2001).

This paper investigates how nations can gain by forming coalitions to curb the spread of a disease or some other threat under alternative scenarios defined by the spatial configuration of nations and the pathways of the pathogens. Just as countries in a pending land war can ally so as to save costs from sequestering borders needing protection (Arce M. and Sandler, 2001a), nations facing the spread of diseases can ally to limit cost by reducing the borders or entry points requiring guarding. The same arrangements that facilitate cooperative gains from prophylactic efforts also apply to surveillance activities. The cooperative game approach that we use provides an alternative insight on burden sharing that is based on a country's spatial location and the epidemiology of a disease, rather than exploitation based on relative wealth. For example, because tuberculosis can be effectively treated with inexpensive and readily available antibiotics, and Ebola can be stopped with sufficient infection barriers in hospitals (e.g., gloves, masks, and syringes), it is in the interests of nations, which are not directly vulnerable, to bolster efforts abroad to reduce the risks and costs of contagion. Furthermore, the spread of many diseases such as AIDS and multi-drug-resistant tuberculosis has less to do with free riding on the part of poor nations than their lack of capacity to address the problem nationally (Jamison et al., 1998). The approach used here recognizes the role of a weakest-link nation in the chain of a disease's transmission and derives burden-sharing solutions that increase overall capacity through cooperation.

A further purpose is to demonstrate that alternative ethical or normative considerations can alter the distribution of benefits achieved through cooperation under some scenarios, but not others. When a country is either in a protected position (e.g., buffered by other countries), or in a more vulnerable exterior position, its relative share of the cooperative gains may differ under alternative division rules. In some scenarios, the country's position solely determines its relative gain, while in other scenarios, its position and the pathway of the pathogens influence its relative share. The analysis indicates why the US is motivated to underwrite the Centers for Disease Control (CDC) even though the country is not in the direct pathway of some diseases.

A third purpose of this paper is to establish that the analysis and conclusions are directly applicable to other public good concerns with a spatial aspect, such as thwarting transnational terrorists, inhibiting the diffusion of revolutions, and promoting the interdiction of narcotics.

2. Preliminaries and the baseline case

Side payments are a normal part of global public health financing; the WHO and World Bank are financed primarily through side payments (contributions) made by member nations. About 10% of total development assistance is spent on health activities (Walt, 1998, p. 434), the vast majority of which are side payments in the form of bilateral aid between nations. This is because a great deal of aid that goes towards addressing the transmission and surveillance of disease is to raise *capacity*. As globalization has raised the awareness of protecting a country's entry points from communicable disease and bioterrorism, the issue is no longer exclusively one of aid, but self-protection.

In the analysis of this paper, the capacity issue is represented by the *degree of vulnerability*, as measured by the spatial location and cost of protecting entry points. If, for example, one nation cannot contain a health risk due to insufficient funds or technological expertise, others will become exposed. In such cases, increasing the overall level of provision involves raising the capacity where it is currently lowest through side payments. Capacity-building efforts are presently going on in hot zone regions of multiple drug-resistant tuberculosis (MDR-TB), such as the former Soviet Union, Southeast Asia, and southern Africa. Other nations are willing to share the cost of treatment in hot zones as a means for inhibiting the spread of MDR-TB elsewhere. The 10/90 Disequilibrium—the fact that less than 10% of research funding on health is focused on 90% of the world's health problems (most funding goes to health concerns in developed countries)—is an indication of the need for side payments to bolster research on diseases of interest to developing countries (particularly if they pose a future threat to the developed world).

The current reality of the organization of international health policy is one of coalition building, partnerships, and networks to organize and fund efforts aimed at the public aspects of disease transmission and health security in an integrated, globalized world. Further, our spatial analyses indicate cases in which effective health policy requires the transfer of funds from an indirectly exposed to a directly exposed country, irrespective of relative wealth. From this perspective, a cooperative game-theoretic approach where health alliances are examined in terms of coalition and contribution pairs sheds new insights into how trans-boundary health interventions can be efficiently organized and financed. More formally,

Definition. Given a set of players, ***N***, a *coalition* is a (nonempty) subset of N. In other words, a coalition is an element of the power set $2^N \backslash \{\emptyset\}$, which is the set of all possible nonempty of subsets of N. The members of a coalition are denoted by a set of elements within braces, for example, {1,3} is the coalition consisting of players 1 and 3. This paper is confined to the three-country case, where N={1,2,3} is the grand coalition.

The net benefits of alliance $\{S\}$ with $\#S$ members are given by the *characteristic function*, $v(\{S\})$, which, for convenience, is denoted by $v(S)$ for any coalition S. The value $v(S) \in \Re$ gives the overall gains for forming the coalition S, which are measured in terms of *cost savings*, and allows for side payments to be made across members of the coalition (cost savings are transferable). By convention, $v(\emptyset)=0$.

Of course, not all coalitions are equally desirable, nor are all coalition members equally treated. The characteristic function itself determines the minimal amount that a particular coalition must receive as a whole in order to form an alternative alliance. Whether or not the coalition itself is likely, however, depends upon the distribution of $v(S)$ to the individual members of S. The minimum rationality conditions defined for payoffs accruing to the members of a coalition are defined as follows:

Definition. An *imputation* for coalition S is a payoff vector $(u_1,u_2,\ldots,u_s)$, satisfying individual rationality:

$$v(i) \leq u_i \text{ for all } i \text{ in } S, \tag{1}$$

and group rationality for the grand coalition:

$$v(N) = \sum_{i=1}^{N} u_i. \tag{2}$$

In Eq. (2), N is the number of members in N. Individual rationality is necessary to secure the commitment of any particular agent to a health alliance, since it must be in the agent's interest to do so. Group rationality ensures that the grand coalition exhausts the distribution of cost savings (Pareto efficiency).

There are multiple competing solutions for games in characteristic function form. The most prevalent are the core, Shapley value, and nucleolus. As shown below, each is, in part, designed to implement a particular ethical norm. By considering each solution, we address the issue of distributing the cost savings of a health alliance among members from an ethical perspective. In contrast, it is serendipitous if the Nash outcome of a non-cooperative game coincides with a norm.

Definition. The *core* of a characteristic function game satisfies the following set of $2^N - 1$ inequalities:

$$v(S) \leq \sum_{i \in S} u_i \text{ for all } S \text{ subsets of } N. \tag{3}$$

The core is the set of allocations that no coalition can improve upon (block). By substituting either i or N in the characteristic function of Eq. (3), the reader can see that all allocations in the core are both individually rational and Pareto efficient, respectively. In addition, Eq. (3) requires that each coalition receives at least as much as it would, acting apart from all other coalitions, $v(S)$. The core may not exist. A nonempty core typically does not yield a single-valued solution, but rather a geometric area of unblocked imputations.

An alternative to the core is the Shapley value, whose underlying ethic is that each agent should receive the average *marginal* contribution that it brings to all possible coalitions.

Definition. The *Shapley value* for player i is the payoff $\phi_i(v)$ given by:

$$\phi_i(v) = \sum_{S:i \in S} \frac{(\#S-1)! \cdot (N-\#S)!}{N!} \cdot [v(S) - v(S - \{i\})]. \tag{4}$$

The term $\#S$ denotes the number of members of coalition S. The term in brackets on the right-hand side of Eq. (4) gives member i's marginal contribution to coalition S: it measures the difference between the characteristic function values when $\{i\}$ is a member of S and when $\{i\}$ is subtracted from S. This difference is taken over all possible ways that coalitions can form: $(\#S-1)! \cdot (N-\#S)!/N!$. Unlike the core, the Shapley value always exists, and it is single-valued (rather than a set-valued geometric area).

The *nucleolus* is based on the idea of minimizing the objections that a coalition might make against a given imputation, $\boldsymbol{u}=(u_1,\ldots,u_s)$ (Schmeidler, 1969). In particular, the *excess of a coalition* is defined to be:

$$e(S \mid \boldsymbol{u}) = v(S) - \sum_{i \in S} u_i. \tag{5}$$

If positive, the excess measures how much less a coalition is receiving under $\boldsymbol{u}$ than what it can do on its own. A coalition would surely object to any positive excess.

Definition. The *nucleolus*, $N(v)$, is the set of imputations that minimize the maximum excess across all coalitions.

Like the Shapley value, the nucleolus is a single-valued solution that always exists, but unlike the Shapley value, the nucleolus is always an element of the core (if the core exists). For the three-player case, Moulin (1988, pp. 136–137) provides a complete characterization of closed-form formulae to calculate the nucleolus. These are given in Appendix A.

In what follows, we wish to express the benefits of forming a health alliance in terms of the *cost savings* accruing to members of a coalition. It is natural, therefore, to require that there are no cost savings under autarky. This implies a normalization of the original characteristic function, $v'(i)=a \cdot v(i)+b_i$, such that $v'(i)=0$ for all i. This normalization corresponds to a positive affine transformation of the payoffs for the individual players. For larger coalitions, we require that $v'(S) = a \cdot v(S) + \sum_{i \in S} b_i$ to ensure strategic equivalence between $v(\cdot)$ and $v'(\cdot)$. Such a normalization is known as S-equivalence (Owen, 1995, p. 216).

2.1. Ethical norms

These solution concepts also correspond to competing *ethical norms* for the allocation of cost savings. As the number of players becomes large, the core shrinks to the set of perfectly competitive outcomes (Debreu and Scarf, 1973), a result that is the fundamental link between cooperative and noncooperative approaches to competition (Edgeworth's conjecture). This makes the core attractive for those who advocate market-based solutions. For a health alliance, the core has the added desirable property that no subcollection of participating countries would choose to withdraw for the purpose of improving its welfare. Since the Shapley value and the nucleolus lie within the core for our analysis, the ethical choice involves a core allocation. Any discussion of burden sharing will be *inversely* related to the *cost savings* identified by these allocations.

The *centroid* is the center of gravity or mass of the vertices of the core. As such, the centroid represents a norm of *equal treatment*, subject to the coalitional rationality constraint in Eq. (3). The sharing of cost savings is based on average contributions to those coalitions who can block any imputation outside the core.[1]

The Shapley value lies within the core when a game satisfies the definition of *convexity*: $v(S \cup T)+v(S \cap T) \geq v(S)+v(T)$ for all coalitions S and T. The Shapley value corresponds to an ethic of receiving the *arithmetic average* of one's *marginal contribution* where all possible coalitions are regarded as equally likely.[2]

The nucleolus represents an alternative center of mass of the core—its *lexicographic center*. The norm is to begin by minimizing the excess of all coalitions. Once a coalition is found whose excess cannot be further minimized, the procedure is then restricted to the "subgame" of remaining coalitions whose excess can be further minimized, and this process is iterated. Axiomatically, this process implies a value judgment where the ethic is to lower the highest suffering (as measured by the excess) as much as possible. From a health perspective, this seems to be a reasonable ethic to consider. Africa is receiving the

[1] The centroid has a number of drawbacks. A prominent one is if the core is empty, the centroid is undefined. In addition, an earlier study of military alliances indicates that infinitesimal changes to the characteristic function may result in finite changes in the centroid, thus giving rise to a discontinuity (Arce M. and Sandler, 2001a).

[2] Shapley (1953) shows that his value solution concept is the unique function that jointly satisfies the axioms of (i) Pareto efficiency, (ii) equal treatment of strategic equals, and (iii) decomposability. The second axiom means that marginal contribution, rather than identity, matters. For decomposability, if there is a set of "subgames" defined by characteristic functions ω and ω' such that $v(S)=\omega(S)+\omega'(S)$ for every S, then $\phi_i(v)=\phi_i(\omega)+\phi_i(\omega')$ for every i. The decomposability axiom is controversial, because it implies that the game as a whole (v) is strictly the sum of its parts ($\omega+\omega'$). As the incentives for joining coalition S in game ω may be substantially different from those for joining S in ω', there may be no reason to expect one's marginal contribution to be equal to that of joining S in both games together.

bulk of attention in the AIDS donor community because of the immense impact of the pandemic there relative to the rest of the world. If an alternative ethic is advocated, such as lowering the excess in as many locations as possible, then the nucleolus is not the proper solution, because it does not satisfy this ethic (Maschler et al., 1992, p. 92).

2.2. Baseline case

We begin with a baseline case that illustrates the analysis. This case concerns prophylactic efforts by countries to keep a disease from entering its territory. The configuration of countries for the baseline case, also known as case 1, is depicted in

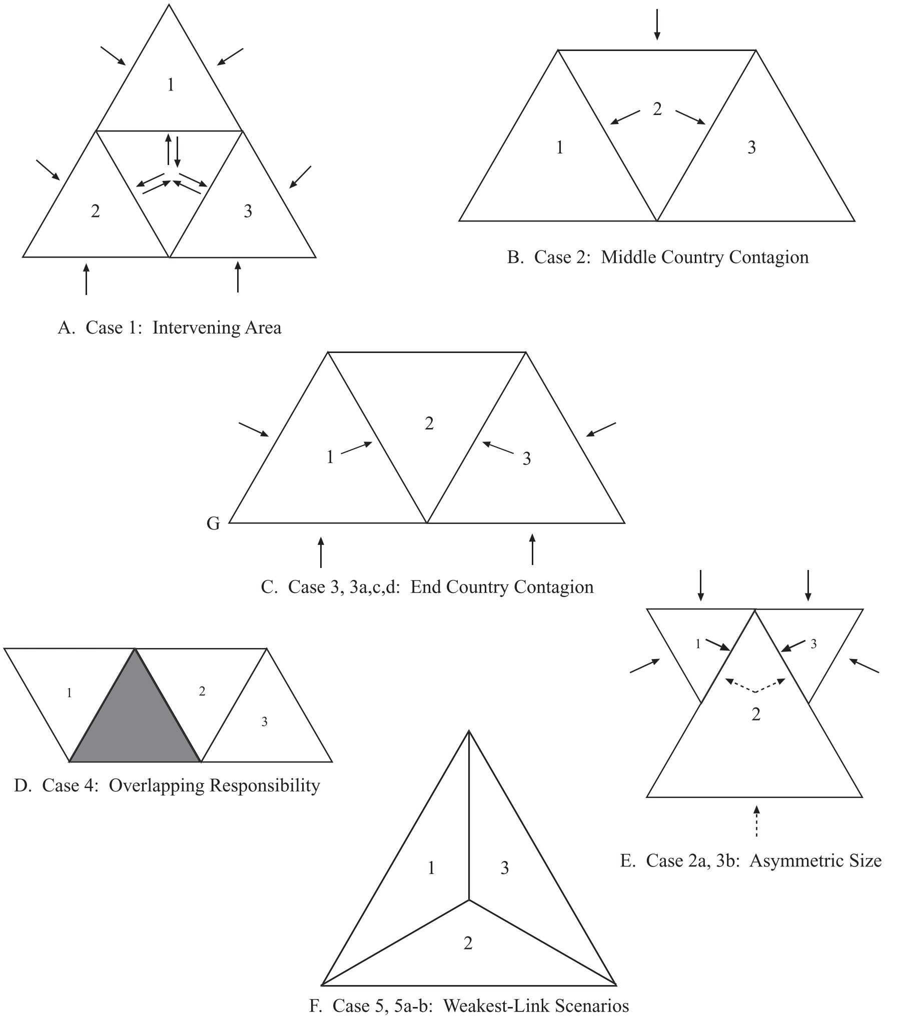

Fig. 1. Alternative configurations of nations and pathogen pathways.

Fig. 1 in panel A, where the pathogens can come from outside or from an intervening area mutually shared by the three countries. The contagion is universal in the sense that all borders are at risk. Moreover, the intervening area represents a region of overlapping responsibilities such as a body of water, a commons, or a disputed territory. To simplify the analysis without losing content, we initially choose symmetrically shaped countries that are equilateral triangles[3] with 1-in. length sides. For some pathogens (e.g., animal diseases, pests), land perimeter may indeed represent what needs patrolling, while for other diseases or scenarios, only entry points (e.g., border crossings, ports, and airports) require guarding. Thus, the reader must think about the triangle's perimeters displayed in the diagram as the length of the vulnerable points of entry and not necessarily the country's perimeter. In the baseline case, all countries can be infected from the outside or through an intervening area. Every inch of border costs 1 to protect from the pathogen.

Without a coalition to reduce the cost of guarding entry points, each country incurs a cost of 4 from defending its two exterior sides (at a cost of 1 apiece) and also its two borders in the intervening area with the other two countries (at a cost of 1 per border). If, however, any two countries were to ally and share responsibilities, each two-country coalition would have to protect just five borders—i.e., the four exterior sides and the sole border in the intervening area with the remaining country. A grand coalition of the three countries would have to protect just the six exterior borders. Obviously, the same model would apply if the coalitions are formed to save cost on surveillance by sequestering interior entry points. This situation is analogous to the European Union's (EU) policy of monitoring exterior, rather than interior, borders for migration and customs regarding EU citizens.

To be in the core, the imputation $\boldsymbol{u}$ for the three-nation alliance must satisfy:

$$\begin{aligned}
&v(i) = -4 \le u_i, \qquad i = 1,2,3,\\
&v(1,2) = -5 \le u_1 + u_2\\
&v(2,3) = -5 \le u_2 + u_3\\
&v(1,3) = -5 \le u_1 + u_3\\
&v(1,2,3) = -6 = u_1 + u_2 + u_3.
\end{aligned} \tag{6}$$

To simplify the analysis, we find a normalization $v'(i) = v(i) + 4$, $i = 1,2,3$ (where $v'(S) = v(S) + \sum_{i \in S} b_i; b_i = 4$) so that the transformed characteristic function values are non-

[3] The actual shape of the countries makes no difference in these *symmetric* models, so that rectangles, pentagons, or some other figure can be substituted for triangles without altering the *relative payoff shares*. We use triangles since their minimal number of sides limits computations, while allowing for a large variety of alternative geographical configurations.

negative and the maximal gain to the grand coalition is 6. The latter gain results from the three interior perimeters, which require no guarding in any directions. Based on the *S*-equivalence normalization, the core must satisfy:

$$\begin{aligned}
&v'(i) = 0 \leq u_i, \quad i = 1,2,3,\\
&v'(1,2) = 3 \leq u_1 + u_2\\
&v'(2,3) = 3 \leq u_2 + u_3\\
&v'(1,3) = 3 \leq u_1 + u_3\\
&v'(1,2,3) = 6 = u_1 + u_2 + u_3.
\end{aligned} \tag{7}$$

The core of the baseline prophylactic game is found graphically in Fig. 2 using a *simplex* in the form of an equilateral triangle whose three vertices correspond to a single nation obtaining the entire gain of 6 from the maximal cost sharing of the grand coalition. Each of the sides of the simplex holds the payoff to one member at zero (i.e., $u_i = 0$), while the other two members divide the gain of 6 (i.e., $u_j + u_k = 6$). For example, the base of the simplex corresponds to $u_3 = 0$, or equivalently to $u_1 + u_2 = 6$. The perpendicular distance of a point in the triangle from any side indicates the payoff to the ally whose payoff is zero along that side of the simplex; for instance, the midpoint of the perpendicular, dropped from the (0, 0, 6) vertex, to the triangle's base denotes a u_3 value of 3. Every *interior* point of the simplex has a nonzero payoff for all three coalition participants, but not every point is in the core. To be in the core, three inequalities must be satisfied, $u_1 + u_2 \geq 3$, $u_2 + u_3 \geq 3$, and $u_1 + u_3 \geq 3$, which define the inscribed triangle in Fig. 2 with vertices (0, 3, 3), (3, 3, 0), and (3, 0, 3) as the core. The centroid is (2, 2, 2), indicating an equal division among coalition members, which is an intuitively reasonable outcome given that all coalition members have identical and symmetric locations vis-à-vis the threat and their counterparts.

Applying the formula in Eq. (4), we derive the Shapley value, denoted by (ϕ_1, ϕ_2, ϕ_3), where a member's payoff is the average marginal contribution that it provides to all possible coalitions. For nation 1, we have

$$\begin{aligned}
\phi_1 = {}& (2/6)[v'(1) - v'(\emptyset)] + (1/6)[v'(1,2) - v'(2)] + (1/6)[v'(1,3) - v'(3)]\\
&+ (2/6)[v'(N) - v'(2,3)].
\end{aligned}$$

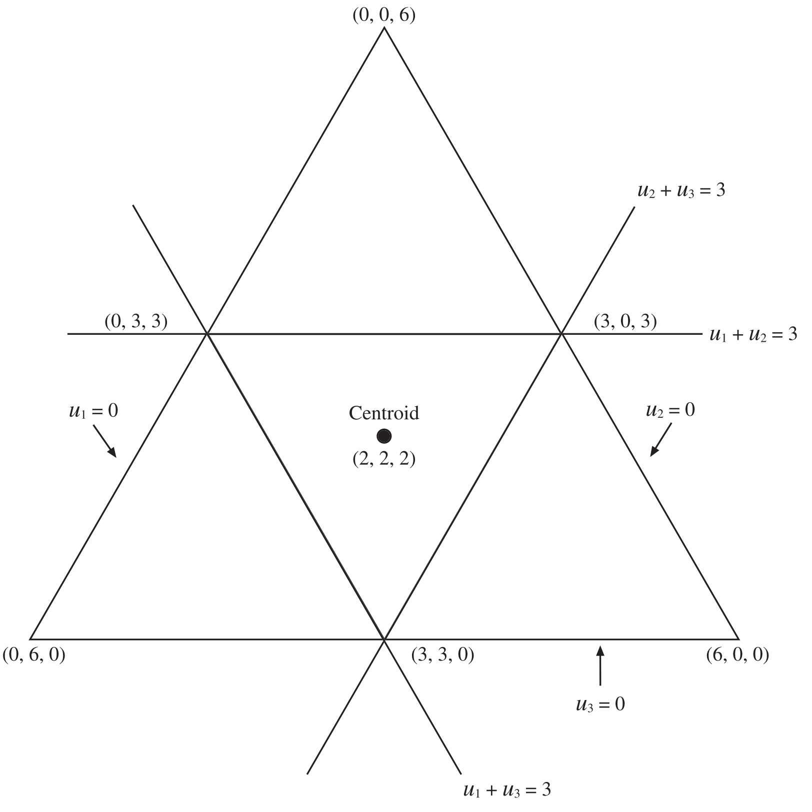

Fig. 2. Simplex for baseline case.

By substituting from Eq. (7), we get $\phi_1 = 2$; this is the expected marginal impact that any coalition derives from ally 1’s presence. It is obvious that $\phi_2 = \phi_3 = 2$ owing to symmetry, so that the Shapley value equals the centroid.

For the nucleolus, this game satisfies *class* 5 as defined in Appendix A. Applying the formula yields the nucleolus as (2, 2, 2). Thus, the nucleolus coincides with the Shapley value and the centroid, so that ethical norms do not make a difference in this case for an ally’s share. Sufficient symmetry exists to rule out any potential disagreement between the *positive* interpretation of the solution concepts—indicating what cost sharing outcomes occur—and a *normative* interpretation of what they should be like.

3. Contagion: further cases

We next investigate alternative pathways of the contagion. Given the earlier derivations, we are equipped to examine numerous cases efficaciously. Case 2 is depicted in panel B in Fig. 1, where the pathogen must enter middle country 2 prior to infecting the end countries, which are not in the front line of defense against the disease. Apt examples include AIDS's origin in Africa with a subsequent spread east and north to Asia and Europe, and west to the Americas. By going it alone, each country must protect a single border at a cost of 1. Any coalition involving country 2 requires that just 2's top border be cordoned off at a cost of 1. In contrast, a coalition of country 1 and 3 requires that their respective borders with country 2 be protected at a cost of 2.

By applying the transformation $v'(i) = v(i) + 1$ for all i (and extending this to $v'(S)$ for S-equivalence), we derive the normalized characteristic function with nonnegative cost savings:

$$
\begin{aligned}
&v'(i) = 0 \leq u_i, \quad i = 1,2,3,\\
&v'(1,2) = 1 \leq u_1 + u_2\\
&v'(2,3) = 1 \leq u_2 + u_3\\
&v'(1,3) = 0 \leq u_1 + u_3\\
&v'(1,2,3) = 2 = u_1 + u_2 + u_3.
\end{aligned}
\tag{8}
$$

When these equations are applied to the simplex with a maximal gain of 2, the core is the rhombus with vertices (0, 1, 1), (0, 2, 0), (1, 1, 0), and (1, 0, 1) formed by $u_1 + u_2 = 1$, $u_2 + u_3 = 1$, $u_1 = 0$, and $u_3 = 0$.[4] The centroid of the rhombus core is (0.5, 1, 0.5), where each of the end nations receive a quarter of the total gain, with half going to the only nation directly in the pathway of the disease. At first, this may appear surprising, but, in fact, the vulnerable middle country is pivotal for the existence of any benefits from allying—thus, its greater influence and resulting reward. This is clearly indicated by the zero cost savings for the end-country coalition in Eq. (8). Furthermore, alternative ethical rules do not upset this distribution of benefits among coalition members as the Shapley value, nucleolus, and centroid coincide. Thus, disproportionate burden sharing stems from spatial rather than wealth considerations in our cooperative-game representation. The cooperative solution can therefore be used as a focal point for any subsequent non-cooperative bargaining among the countries (Harsanyi, 1961), thereby suggesting that an African coalition with, say, the United States and the European Union (EU) places the bargaining strength squarely in the hands of the African country, so that more burdens are placed on the United States and the EU.

The importance of position rather than size can be illustrated by allowing the middle country to be twice the dimension of country 1 and 3, so its borders are 2 in. apiece. This is represented by case 2a in panel E of Fig. 1, where the pathway of the pathogens

4 From this point onward, we suppress all calculations.

corresponds to the dashed arrows. The overall gain to the grand coalition is still 2 from the savings of not having to patrol the borders with country 1 and 3. The system of equations identifying the core is again Eq. (8), so that all solutions remain unchanged. Things would change, however, if country 2 must also protect against an external threat on its eastern and western boundaries, where it borders no other country. In such a scenario, more of the cooperative gains would go to the end countries.

Case 3, illustrated in panel C of Fig. 1, is the inverse of case 2. Now, the end countries are in the direct pathway of the disease, while the middle country can only be infected by the pathogen passing through an end country. In the absence of any coalitions, country 1 (3) must spend 2 to protect two 1-in. entry points. *Initially*, we assume that neither country protects itself from country 2, the potential source of a secondary infection, thereby relying on the middle country to secure itself against the disease from either end country. Country 2 has two interior entry points to protect for a cost of 2. Either coalition containing the middle country ({1,2} or {2,3}) incurs a cost of 3, while {1,3} incurs a cost of 4. A two-country coalition involving country 2 saves 1 in cost from not having to guard country 2’s border with its ally. Using the transformation, $v'(i)=v(i)+2$, $i=1,2,3$, we again obtain the equation system in Eq. (8), so that all three solutions equal (0.5, 1, 0.5), as in case 2.

It is surprising that the solutions to cases 2 and 3 are identical even though the pathways of the diseases are completely different. For these two cases, the spatial position vis-à-vis others and not the pathways influences the distribution of the gains. As such, country 2 is again pivotal in determining whether any cost savings result from allying. Case 2 can provide a justification for a second-line-of-defense country supplying health-care assistance to the front-line countries. An organization like the CDC not only provides assistance, but also allows the United States to set the agenda regarding which communicable diseases to track and fight. In case 3, it is the vulnerable exterior countries that are disadvantaged in the bargaining. This scenario may correspond to why assistance is not coming from the rich countries to fight (orphan) tropical diseases; rich countries are only indirectly at risk.

If, in case 3, the exterior countries *also protect* their interior borders with country 2, so that arrows (not shown) are added to panel C pointing to countries 1 and 3, then the grand coalition creates a total net gain of 4 in cost savings from two sequestered interior borders that no longer require guarding in *two directions*. Given that the going-it-alone costs of the exterior countries are 3, while it is just 2 for the middle ally, we need two normalizing transformations: $v'(i)=v(i)+3$ for $i=1,3$, and $v'(2)=v(2)+2$ (in deriving $v'(S)$, $b_1=b_3=3$ and and $b_2=2$ for S-equivalence). The coalition {1,3} can save 2: when the four exterior borders are protected, there is no need to protect the two interior borders with country 2. In fact, each of the two-country coalitions saves 2 in cost. The core is the inscribed triangle with vertices (0, 2, 2), (2, 0, 2), and (2, 2, 0) and a centroid at (4/3, 4/3, 4/3). Moreover, the centroid, the Shapley value, and the nucleolus remain equal to one another. In this scenario, the three countries are in equivalent positions despite a different stand-alone cost for country 2. Thus, guarding interior borders makes a difference.

The above series of examples illustrate how ethical norms of distribution, as embodied by alternative solution concepts, can agree even though the spatial distribution of an alliance and/or the source of contagion is varied. A key insight provided by these examples is that a country is *pivotal* for an alliance if its *spatial position* determines the cost savings, irrespective of whether that country is a direct or indirect source of the pathogen. When a country is pivotal, it receives a larger share of the cost savings. It remains to be seen as to whether sufficient asymmetry will cause the solution concepts to differ, and if asymmetry will break the tendency for spatially pivotal countries to recoup cost savings.

3.1. Asymmetries

We begin by allowing for different border lengths of an exterior country—say country 1—in case 3a. We again assume that countries 1 and 3 do not guard their interior border. In panel C of Fig. 1, we suppose that the vertex at G is pushed in, so that country 1's two exterior borders are each three-quarters the size of its interior border, or three-quarters of an inch in length. This scenario may arise if country 1 is geographically smaller, or possesses fewer entry points. Any factor that reduces the resources required to guard the border is also consistent with these smaller boundaries to protect.

As in case 3, countries 2 and 3 must spend 2 apiece in securing their borders, but country 1 must now only spend 1.5 to be safe. Coalition {1,2} incurs a protection cost of 2.5, while coalitions {2,3} and {1,3} incur a prophylactic expenditure of 3 and 3.5, respectively. The grand coalition spends 3.5 to be safe. Two normalizations are required to satisfy zero-cost savings under autarky: $v'(i) = v(i) + 2$ for $i = 2$, 3, and $v'(1) = v(1) + 1.5$. Based on the transformed system of equations, the core is a rhombus in the simplex with vertices at (0, 1, 1), (0, 2, 0), (1, 1, 0), and (1, 0, 1), and a centroid at (0.5, 1, 0.5). Shortening the exterior borders of an outer country makes no difference in the solution, because the countries' relevant contributions to the cost savings depend on the interior borders.[5] Furthermore, the Shapley value and the nucleolus equal the centroid as before. More asymmetry is required for the alternative ethics to matter.

Asymmetry does not necessarily influence the solution if the middle country becomes large relative to the end countries. Consider case 3b in panel E of Fig. 1, where country 2 is an equilateral triangle with 2-in. sides, like case 2a, but the pathways of the pathogens are indicated by just the six solid arrows. The total gain for the grand coalition is 2 and, moreover, the normalized characteristic function is Eq. (8), so that all three solutions are again (0.5, 1, 0.5). Country 2 accrues the lion's share of the costs savings because it is spatially pivotal for any alliance.

The next example of asymmetry involves the amount that the middle country must spend to protect its border with country 3. Once again, the exterior countries do not protect their interior border with country 2. For case 3c, panel C in Fig. 1 applies for which country 2 must spend 2 to guard its eastern border and 1 to protect its western border. This scenario may arise if country 2's eastern border is more porous than its western border, so that more guarding is required.

Countries 1 and 3 must still spend 2 on their individual protection, while country 2 now spends 3. Alliances {1,2} and {1,3} incur 4 each in protection expense, while {2,3} incurs only 3 in protection expense. Cost savings for this latter coalition are greater because the

[5] If the two exterior countries also protect their interior border with country 2, then all three solutions equal (4/3, 4/3, 4/3), which is identical to the corresponding case 3.

costly border to protect becomes sequestered, thanks to country 3. The grand coalition must spend 4 on protection. By normalizing the resulting cost equations,[6] the maximal gain to the grand coalition is 3 and the resulting core is a pentagon with vertices at (0, 1, 2), (0, 3, 0), (2, 1, 0), (2, 0, 1), and (1, 0, 2). The centroid requires an even division with each nation receiving 1 in payoffs. Country 2 draws even with its exterior neighbors, as it has less to offer country 1, while country 3 has more to offer country 2.

One should suspect that in a marginal sense, country 2 still has much to provide as a pivotal coalition member—e.g., an alliance between just the end countries still achieves nothing—and should gain relatively handsomely from 2's participation. The Shapley value bears out this suspicion and equals (0.5, 1.5, 1) with the extra saving being shared between countries 2 and 3, whose positions are responsible for the savings. The nucleolus equals the Shapley value for this scenario. In many ways, the three solutions for case 3c are surprising because the real culprit, country 3, maintains its same payoff no matter what the underlying ethic is. There is now sufficient asymmetry for the underlying ethic to have some impact on the relative division among the three countries.

A different scenario—case 3d—is where the difference in cost arises from a more virulent strain of the pathogen coming from country 3, so that more effort (costing 2) is required at country 2's eastern border. We again assume that country 3 does not protect its western border. Given the virulence of the pathogen coming indirectly from country 3, country 1 now spends 2 to protect its western border, while country 2 expends just 1 to cover its side of this border. Country 1's stand-alone cost is 4; country 2's stand-alone cost is 3; and country 3's stand-alone cost is 2. The grand coalition saves 5. The centroid of the core[7] and the nucleolus equal (2, 2, 1), while the Shapley value equals (11/6, 11/6, 8/6). Although the Shapley value gives a little more to country 3 owing to its greater marginal contribution, the relative positions of the countries in the alternative allocations are the same.

3.2. An intervening area of overlapping responsibilities

We conclude this section on contagion with a new kind of asymmetry—an intervening area of shared responsibilities between two countries. This case is displayed in panel D of Fig. 1 and is called case 4. The pathogens can come from any of the six external borders and the two interior boundaries of the shaded intervening area. In comparison to the baseline case, potential coalition members are not symmetrically located with respect to the intervening area. Countries 1 and 2 share responsibilities for guarding the shaded area, in which country 1 protects this area's eastern and bottom boundaries and country 2 protects this area's western and bottom boundaries. In the absence of any coalition, countries 1 and 2 must each guard four sides, while country 3 guards three sides. Any two-country coalition involving country 2 has a prophylactic expense of 5. The most disadvantaged coalition involves countries 1 and 3 with a prophylactic cost of 7.

[6] The required normalizations are $v'(i) = v(i) + 2$, $i = 1, 3$, and $v'(2) = v(2) + 3$.

[7] The required normalizations are: $v'(1) = v(1) + 4$; $v'(2) = v(2) + 3$; and $v'(3) = v(3) + 2$. The core is a trapezoid with vertices (0, 3, 2), (2, 3, 0), (3, 2, 0), and (3, 0, 2).

The simplex now displays alternative imputations for sharing the grand coalition's gain of 5. With the appropriate normalization,[8] the core corresponds to a rhomboid, bounded by $u_1+u_2=3$, $u_1=0$, $u_3=0$, and $u_2+u_3=3$. The corresponding centroid is (3/2, 5/2, 1), where country 2 continues to acquire half of the total gain as was true for cases 2 and 3. Unlike these earlier cases, country 1 acquires a greater share relative to country 3, since the former's position vis-à-vis the intervening area grants it a more pivotal role in generating cooperative gains. The asymmetry of this scenario does not differentiate the payoffs for the Shapley value and the nucleolus, both of which coincide with the centroid.

4. Weakest-link scenarios

Hirshleifer (1983) presented a classic example of a weakest-link public good where several individuals live on a circular island in the middle of a river.[9] For those times when the river rises, each must erect a levee to stay dry, for which the lowest height of the levee determines the flood protection afforded by the entire levee. For the purposes of this paper, the weakest-link analogy applies if the pathogen's crossing of any border poses an immediate risk to all of the other countries, as in the circular island example. A weakest-link vulnerability is depicted in panel F of Fig. 1, where each nation borders the other two. For case 5, the pathogens can come through the three external borders or, if a breach occurs elsewhere, via one of its inner borders by passing through a less vigilant or unlucky neighbor. This simplified representation is descriptive of any cluster of nations (or states within a nation) with multiple contiguous inner borders. If each nation is to be sufficiently secured at a minimal cost, a coalition is inevitable so that attention can be directed just at the outer perimeter.

In this symmetric representation, each nation consists of an isosceles triangle with an outer border of 1 in. and equal inner borders of $\sqrt{3}/3$ in. each.[10] In the absence of a grand coalition, each nation will have to protect its outer border and its two inner borders at a cost of $1+(2\sqrt{3}/3)$. Each of the two-country coalitions must spend $2+(2\sqrt{3}/3)$ on prophylactic measures, while the grand coalition must spend just 3.

The normalization, $v'(i)=v(i)+1+(2\sqrt{3}/3)$ transforms the characteristic function values so that stand-alone cost savings are zero. The maximal savings to the grand coalition is $2\sqrt{3}$, which arises from the three inner sides of length $\sqrt{3}/3$ that do not have to be guarded in two directions. The set of equations defining the core is:

$$\begin{aligned} &v'(i)=0\leq u_i, \qquad i=1,2,3,\\ &v'(j,k)=2\sqrt{3}/3\leq u_j+u_k, \qquad j,k=1,2,3,\ k\neq j, \\ &v'(1,2,3)=2\sqrt{3}=u_1+u_2+u_3. \end{aligned} \tag{9}$$

[8] This normalization consists of $v'(i)=v(i)+4$, $i=1$, 2, and $v'(3)=v(3)+3$.

[9] On the game-theoretic aspects of weakest-link public goods and the related case of weaker-link public goods, see Arce M. and Sandler (2001b).

[10] The size of the inner sides is found through the use of Pythagorean theorem and the theorem of the medians of a triangle. The latter indicates that the medians trisect one another (Coxeter and Greitzer, 1967).

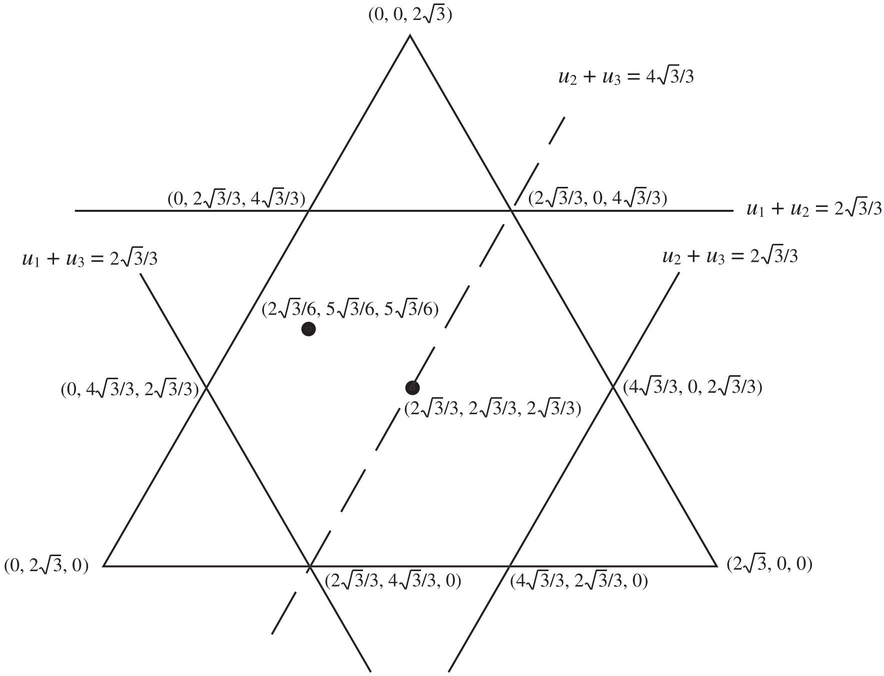

Fig. 3. Simplex representation for the core for two alternative weakest-link cases.

In Fig. 3, we display the simplex representation for the core, associated with this system of equations. The reader needs to ignore the dashed lines, but not the point on this line. The core consists of the area defined by the six-sided figure demarcated by the solid line restrictions corresponding to Eq. (9). As displayed, the centroid is the center of mass of this core, for which each nation receives an equal payoff of one third of the grand coalition's savings of $2\sqrt{3}$. Given the scenarios' symmetry, it is not surprising that our three solutions coincide. We end up with a classic weakest-link outcome of matching behavior (Hirshleifer, 1983; Cornes and Sandler, 1996).

Two asymmetric weakest-link scenarios are investigated for the configuration of nations in panel F of Fig. 1. In case 5a, the pathogens can only come through country 2's outer boundary, so that its prophylactic efforts cost 1. Nations 1 and 3 can only be infected once the pathogen passes through nation 2. Each second-line-of-defense country must spend $2\sqrt{3}/3$ protecting its inner borders, because the pathogen can either pass directly or indirectly, via its other neighbor, from country 2. Coalitions {1,2} and {2,3} spend 1 in protection, while {1,3} expends $2\sqrt{3}/3$ in protection. Straightforward computations give a triangular core with vertices $(0, 2\sqrt{3}/3, 2\sqrt{3}/3)$, $(2\sqrt{3}/3, 0, 2\sqrt{3}/3)$ and $(2\sqrt{3}/3, 2\sqrt{3}/3, 0)$ within the simplex, and a centroid at $(4\sqrt{3}/9, 4\sqrt{3}/9, 4\sqrt{3}/9)$.[11] The three solutions coincide, indicating that despite the asymmetric pathway, the symmetry of the solution is preserved.

[11] The normalizations are: $v'(i) = v(i) + (2\sqrt{3}/3)$, $i = 1, 3$, and $v'(2) = v(2) + 1$. The grand coalition saves $4\sqrt{3}/3$ in costs, while each of the two-country coalitions saves $2\sqrt{3}/3$.

Even though nation 2 is the source of the contagion, this burden sharing reflects the weakest-link property that capacity building at the low-end (nation 2) must occur for cost savings to be achieved. Nation 2 draws even with its neighbors owing to its pivotal spatial position in creating the cost savings. This case differs from case 2, where again only one country was in the pathogen's direct path, thereby highlighting that *spatial position vis-à-vis the other countries matters*.

Our remaining example of weakest link introduces sufficient asymmetry to make two of the three solutions differ from one another. In case 5b, only countries 2 and 3 are in direct pathway of the pathogen (in panel F). One can imagine country 1 to be the United States, which can import a disease that first got started elsewhere. Examples include the flu and AIDS, as well as diseases eradicated in the United States but not elsewhere.

Stand-alone cost is $1+(2\sqrt{3}/3)$ for front-line countries 2 and 3, and $2\sqrt{3}/3$ for country 1. Two-country coalitions involving country 1 must spend $1+(2\sqrt{3}/3)$ in prophylactic cost, while the coalition {2,3} and the grand coalition must only pay 2 in such cost. In Fig. 3, the core is the trapezoid formed by $u_1+u_2=2\sqrt{3}/3, u_1=0, u_1+u_3=2\sqrt{3}/3,$ and $u_2+u_3=4\sqrt{3}/3$. The centroid is $(2\sqrt{3}/6, 5\sqrt{3}/6, 5\sqrt{3}/6)$, where symmetry is lost and the front-line countries gain at the expense of country 1. This follows because the front-line countries are more responsible for cost savings. In other words, cost savings only occur if country 1 invests in the capacities of countries 2 and 3. The Shapley value can be shown to equal $(4\sqrt{3}/9, 7\sqrt{3}/9, 7\sqrt{3}/9)$, which assigns more of the gain to country 1 owing to its marginal influence. Nevertheless, this solution also recognizes that country 1 is not pivotal; it derives costs savings only through partnering with the directly vulnerable countries.[12] Once again, spatial issues matter for the weakest link as well; the nucleolus equals the centroid, but not the Shapley value.

Numerical differences aside, all three solutions ethics are in agreement that country 1's share diminishes as compared to the other two weakest-link scenarios, even though country 1 is *never* the source of the threat. As in case 2, this finding supports the United States' role in underwriting the CDC and being a major supporter of other international efforts to stem the spread of diseases that may eventually pose a problem at home. Relative position, and not its relative wealth, places the United States at a disadvantage.

5. Other applications

Although we couched the analysis in terms of securing borders from pathogens, there are many alternative applications, including efforts to protect against transnational terrorism. When taking such actions, a country must guard all entry points, which requires a centralized effort—e.g., global, not just federal, standards of airport monitoring. Without protection of an equivalent magnitude everywhere, the country is only as secure from the

[12] To date, nonmatching, asymmetric outcomes for weakest-link noncooperative representations have arisen owing to wealth differences and/or price differences where one nation contributes to another's territory (Vicary and Sandler, 2002).

terrorist threat as the level of security afforded by its or some other country's weakest-link port of entry. If neighbors confront spillover terrorism from other regions (e.g., the Middle East), as is the case for the EU,[13] then the manner in which defensive burdens are shared among targeted nations depends on their position vis-à-vis one another and the directional threat from the terrorists. Countries with more liberal immigration policies become the pathway. Thus, the analysis of this paper can shed light on bargaining advantages from cooperative efforts to keep out the terrorists. If the pathway is through, say, France owing to its liberal asylum policies, then France will be at a *bargaining advantage* in allied efforts to stem the spread of European terrorism.[14] For years, the United States has secured its own borders only to have its citizens and property attacked abroad, where it has little influence on efforts to thwart terrorism.[15] A cooperative alliance to secure the borders of the targeted countries against a terrorist threat not only saves on prophylactic expenditures, but may also limit losses from nations working at cross purposes in a Prisoners' Dilemma type security escalation (Sandler and Lapan, 1988). The current war against terrorism is, in part, an effort to root out the terrorists at their source before they disperse worldwide, as in case 2.

The methodology of this paper lends itself to the study of actions to limit the spread of revolutions, a concern throughout northern Africa where revolutionary ideology and forces can emanate from Algeria, Iraq, Egypt, Saudi Arabia, and elsewhere (US Department of State, 2002). Another apt application involves narcotic interdiction where neighboring countries, or those connected through airports or commerce, seek to secure their territory from drug trafficking.

Cooperative efforts in regards to monitoring and surveillance activities can also be studied with the models presented earlier. Technology is providing advanced methods for monitoring larger areas from fewer vantage points so that significant cost savings can be achieved through country collectives. In the case of monitoring, overlapping areas of responsibilities (e.g., the oceans) figure prominently. Atmospheric observatories on Mauna Loa on the island of Hawaii illustrate the quintessential collective effort where a single set of stations can ascertain atmospheric concentrations of carbon dioxide and other pollutants globally.

6. Concluding remarks

Globalization has caused a heightened awareness of the occurrence and transmission of disease and other threats throughout the world. Yet the benefits of alliances to promote

[13] Spillover terrorism from the Middle East has been tracked yearly by the *Patterns of Global Terrorism*, an annual report put out by the US Department of State for the US Congress. For example, Middle East spillover terrorism into other regions consisted of 43 attacks in 1989 and 45 attacks in 1988, with the largest share in Europe (US Department of State, 1990, pp. 5, 8–9).

[14] France's liberal asylum policy is the tradition of "France, Terre d'Asile." Wilkinson (1991, p. 293), a renowned terrorist expert, blames this policy on allowing terrorists to use France as an entry point into the EU.

[15] Of course, the four hijackings on 11 September 2001 is a notable exception to the security of US soil. Nevertheless, very few attacks occur on US soil (US Department of State, 2002).

global public health are too often lost in rhetoric framed in terms of obligations based upon a country's relative wealth, or responsibility as the source of contagion. Using cooperative game theory, we have shown that the spatial location of a country can be an important alternative consideration for assessing the potential benefits of health- or safety-promoting alliances.

For example, in panel B of our analysis, country 2 is the middle country and the source of contagion, while in panel C, country 2 is no longer a direct source of outbreak. Yet, in these divergent cases, country 2 is pivotal for the success of any alliance that produces prophylactic cost savings through the substitutability of efforts at outbreak sources rather than protecting one's own entry points. Given its greater marginal contribution to a cost-saving alliance, a country's burden decreases when it is most at risk owing to location. This suggests that African nations ought to be significant *net* recipients of health-related aid when front-line diseases such as AIDS place them between regions, not directly exposed. Alternatively, when the centrally based country is only indirectly exposed (as in panel C), its burden may correspondingly drop because its spatial location implies that its marginal importance to sequestering borders remains high. This is in agreement with the orphaning of efforts to control many tropical diseases; developed nations are not directly exposed, hence, alternative institutions are needed to overcome market failure. The novel insight is that *relative position* and *pathway exposure* can reverse burden-sharing arguments, based solely on the source of an epidemic or a country's relative wealth.

This tendency carries over when asymmetries are introduced, either through the number of entry points and shared regions of responsibility (e.g., the atmosphere or oceans), or the direction of the pathogens. Asymmetries can cause solution concepts to differ in their prescriptions for burden sharing. When these concepts disagree, they are usually in consensus in ordering the countries' relative burdens, thereby providing rough guidelines for creating effective institutional responses.

Finally, we have identified why a country like the United States underwrites an institution such as the CDC, whose monitoring and crisis-response functions extend far beyond US borders. This follows because the United States recognizes that savings result by pushing prophylactic or monitoring efforts beyond US entry points to the front line of the contagion itself. Sending a CDC team to the source of an Ebola or plague outbreak is a substantially more cost-effective prophylactic than ensuring that a breach does not occur at any US entry point. Such principles also apply to a host of containment problems including transnational terrorism.

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Appendix A

Moulin (1988, pp. 136–137) fully characterizes the nucleolus γ=(γ_1,γ_2,γ_3) under the following conditions:

Games must be superadditive—for any partition $\{S_1,\ldots,S_K\}$ of N, $\sum_{i=1}^{K} v(S_i) \le v(N)$ holds.

Zero independence: without loss of generality we can assume $v(i)=v(j)=v(k)=0$.

Up to a permutation: $0 \le v(j,k) \le v(i,k) \le v(i,j) \le v(N)$.

Class 1: $v(i,j) \le (1/3)[v(N)]$
$\gamma_i=\gamma_j=\gamma_k$=(1/3)[$v(N)$]

Class 2: $(2/3)[v(i,k)]+(1/3)[v(i,j)] \le (1/3)[v(N)] \le v(i,j)$
$\gamma_i=\gamma_j=(1/4)[v(N)+v(i,j)]$; $\gamma_k=(1/2)[v(N)-v(i,j)]$

Class 3: $(2/3)[v(j,k)]+(1/3)[v(i,j)] \le (1/3)[v(N)] \le (2/3)[v(i,k)]+(1/3)[v(i,j)]$
$\gamma_i=(1/2)[v(i,j)+v(i,k)]$; $\gamma_j=(1/2)[v(N)-v(i,k)]$; $\gamma_3=(1/2)[v(N)-v(i,j)]$

Class 4: $(2/3)[v(i,k)+v(j,k)]-(1/3)[v(i,j)] \le (1/3)[v(N)] \le (2/3)[v(j,k)]+(1/3)[v(i,j)]$
$\gamma_i=(1/4)[v(N)+v(i,j)]+(1/2)[v(i,k)-v(j,k)]$;
$\gamma_j=(1/4)[v(N)+v(i,j)]+(1/2)[v(j,k)-v(i,k)]$;
$\gamma_k=(1/2)[v(N)-v(i,j)]$

Class 5: $(1/3)[v(N)] \le (2/3)[v(i,k)+v(j,k)]-(1/3)[v(i,j)]$
$\gamma_i=(1/3)[v(N)+v(i,j)+v(i,k)-2v(j,k)]$;
$\gamma_j=(1/3)[v(N)+v(i,j)+v(j,k)-2v(i,k)]$;
$\gamma_k=(1/3)[v(N)+v(i,k)+v(j,k)-2v(i,j)]$

For nucleoli calculations according to the above formulae see Table 1.

Table 1
Nucleoli calculations according to the above formulae

Case	*Player i,j,k designation*	Class
1	$i=2$, $j=1$, $k=3$	5
2	$i=2$, $j=1$, $k=3$	3
2a	$i=2$, $j=1$, $k=3$	3
3	$i=2$, $j=1$, $k=3$	3
3a	$i=2$, $j=1$, $k=3$	3
3b	$i=2$, $j=1$, $k=3$	3
3c	$i=2$, $j=3$, $k=1$	3
3d	$i=2$, $j=1$, $k=3$	5
4	$i=2$, $j=1$, $k=3$	3
5	$i=1$, $j=2$, $k=3$	3
5a	$i=1$, $j=2$, $k=3$	5
5b	$i=3$, $j=2$, $k=1$	4

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