Systematic Assessment of Nation-States' Motivations and Capabilities to Produce Biological Weapons

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Abstract

Remote detection of Biological Weapons (BW) proliferation is important, but challenging. We describe and use a joint socio-cultural influence and capability model to identify nation-states likely to have, or to develop BW. We utilize data about international hostilities and alliances, pharmaceutical capabilities, scientific and trade activities, and expert opinion. Our analysis suggests that Iran, Russia, Israel, China, Egypt, North Korea, India, Pakistan and Taiwan have both the motivation and capability to develop BW. The international community suspects Syria of having BW, but Syria has minimal apparent capability. Finally, Georgia, Sudan, Lebanon and Serbia have significant motivation and some capability.

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1 Introduction

Biological weapons (BW) are weapons of mass destruction capable of causing massive damage [21]. These weapons have a long history [18, 38, 28]. The development, production and stockpiling of BW is prohibited by the Bacteriological Weapons Convention (BWC). Unfortunately, many states are believed to maintain offensive BW programs despite their membership in the BWC. Many authors have criticized the BWC for lacking strong verification mechanisms and have suggested multiple verification protocols; e.g., [47, 27]. However, none of these protocols has been adopted.

In order to limit possible damage should a BW attack occur, some states maintain defensive BW programs. Such programs are explicitly permitted by the BWC, and work mainly on novel vaccines [9], early attack detection [43], treatment and protective equipment. These programs also investigate techniques for the early detection of BW attacks [30, 34] and the effectiveness of different response measures [8, 15]. Besides limiting the damage due to a possible BW attacks, defensive BW programs also reduce the attractiveness of biological attacks by opponents. Defensive BW programs, however, do not completely eliminate the risk of biological attacks or damage from them.

Assessing which states maintain offensive BW programs has the potential to reduce BW proliferation and usage. For example, international negotiations and pressure can help stop these BW programs. BW capabilities assessment is, however, very challenging. The dual-use nature of BW technology complicates distinguishing military-oriented and civilian-oriented programs. Moreover, the outlaw status of BW causes offensive BW programs to operate at high security levels. This secrecy limits the amount and quality of data available about current and past BW programs. This limited data hinders a thorough study of BW proliferation.

Despites the importance of BW capability assessment, the problem has attracted limited attention in the literature. Most previous work consists of case studies [46, 23, 14] on specific states or reports from insiders [2, 19]. A case study provides an in-depth and important examination of a given country's BW program. However, case studies are impractical to perform for all states in the world. It is important to first narrow down the list of states that require close monitoring. A small body of literature [21, 24, 31, 48, 11] addresses BW from a political science perspective. However, none of this work systematically examines all countries in order to determine which countries are likely to have offensive BW programs.

In this work, we approach the challenging problem of assessing which states have or are likely to have offensive BW programs. We present and utilize a joint socio-cultural influence and latent capability model that systematically addresses all nation-states in the world. We populate our model and present assessment results based on data that we collect exclusively from open-sources. We assess states' motivations to acquire BW by adapting the Friedkin model [17] from social influence theory. That model has been successfully adapted to predict many of the European Union decisions [25, 26]. In this work, we adapt the model to capture incentives and disincentives listed by Tucker [39], the founding director of the Chemical and Biological Weapons Program at the James Martin Center for Nonproliferation Studies of the Monetary Institute of International Studies.

We estimate states' latent BW capability by evaluating pharmaceutical capabilities, dual-use biological trade and BW research. Latent capability assessment measures whether a state has the industrial and scientific capability to establish an offensive BW program if the state chooses to do so. We utilize pharmaceutical capability information provided by the World Health Organization [45] and collect dual-use biological trade from the UN Comtrade database [40]. Pharmaceutical capability and dual-use biological trade measure whether a state has the industrial equipment to build a BW program. BW research trade measures whether a state has expertise related to BW agents. Our latent capability assessment has inevitably limitations because

of the secrecy surrounding BW programs. However, we believe that latent capabilities are more difficult to hide compared with actual offensive BW activities. Moreover, we believe that countries like North Korea that exhibit strong motivation for BW, but no apparent capabilities do require close monitoring.

In this work, we utilize exclusively open-source data. Such data is the only type of data available to us as academics. Moreover, when classified data is utilized in research, publishing results is difficult. We believe that exclusively relying on open-source data already exhibits interesting results. In cases where one has access to higher quality data from classified sources, the approaches described in the paper can be applied to the combination of open-source data and the available higher quality data. Our analysis suggests that Iran, Syria, Russia, Israel, China, Egypt and North Korea are suspected of pursuing activities prohibited by the BWC and have strong BW capabilities. Syria is suspected of offensive BW activities, but has minimal apparent capabilities. India, Pakistan and Taiwan are suspected in old sources, but not in current ones. Our analysis suggests that these states may have a motivation to develop BW and have strong capabilities, and should therefore be carefully monitored. Finally, Georgia, Sudan, Lebanon and Serbia have significant motivation to acquire BW and some basic BW capability. Georgia, Sudan, Lebanon and Serbia should also be monitored on a long-term.

We provide background on factors that motivate states to acquire BW in Section 2. We present our motivation assessment methodology in Section 3 and our latent capability assessment methodology in Section 4. We discuss our results in Section 5 and limitations in Section 6 before concluding.

2 Background

In this section, we first examine the incentives and disincentives a state to develop BW. We base most of our discussion on the work by Tucker [39]. Subsequently, we review technical requirements for a country to build BW capability.

2.1 Motivational Factors

Tucker [39] provides a list of plausible incentives and disincentives for BW proliferation. The first type of incentive listed by Tucker is in-kind deterrence to balance regional strategic power. If a country acquires a BW capability, its enemy states may seek similar capability in order to fill the resulting security imbalance. The second major incentive is deterrence of nuclear weapons use. Some states may seek BW with the goal of deterring nuclear attacks against them. This is particularly the case for states that lack the technical and financial infrastructure required to build nuclear weapons. Other incentives are tactical military use, pursuit of regional hegemony, sabotage and terrorism, and counterinsurgency and assassination.

The capability of BW to play a deterrent role may be unclear at first given that states usually keep their BW programs secret and almost never admit to having BW. Tucker explains that BW can play such role because a deterrent capability does not need to be formally declared in order to be effective. Countries can hint about their weapons, without formally admitting to having them. For example, Israel has never formally admitted to having nuclear weapons, but is able to use nuclear weapons as deterrent. Suspected BW proliferators can benefit from BW deterrence capability because of the difficulty to prove or disprove a country's ownership of BW. This difficulty is due to the lack of verification mechanisms of the BWC and Intelligence agencies' reluctance to release their classified information. In the context of deterrence, Koblentz notes that Bermudez Jr [6] and Baram [4] explain that the use of BW by North Korea and Iraq to deter American threats was unsuccessful. However, Iraqi and North Korean experiences do not imply that other countries will not seek BW for use as deterrent. The fact that BW have not deterred the United States

does not imply that these weapons will not deter less military powerful countries.

The primary disincentive listed by Tucker is the absence of a perceived security deficit. States that benefit from a credible security guarantee from a superpower, or that possess powerful conventional weapons or nuclear weapons may not perceive the need to acquire BW. Other disincentives are uncertain military utility and limited deterrence value. BW provide limited deterrence compared with nuclear weapons as BW have a slower and less destructive impact compared with nuclear weapons. Finally, the risk of provoking countermeasures, security problems associated with a BW capability, availability of defenses, and legal and moral constraints may all deter a state from acquiring BW. Besides Tucker, Koblentz [21] and Martin [24] also discuss incentives and disincentives for BW. Martin argues that BW are useful as strategic deterrent. Koblentz agrees with Tucker that BW may be u seful as in-kind deterrent, but disagrees with Martin that BW are useful as strategic deterrent. BW lack the ability to provide an "assured" strategic retaliation capability because of the uncertainty associated with the effectiveness of these weapons and the availability of defenses. Koblentz's argument is compatible with Tucker's argument. Tucker cites nuclear deterrence as an incentive, and the uncertain military value and the limited deterrent value as disincentives.

2.2 Latent Capabilities Assessment

Developing BW is not trivial, but feasible given the appropriate materials, expertise and equipment [21]. According to a report by the Office of Technology Assessment (OTA) [29], at least 100 states have the latent capability to develop BW. The majority of the expertise and equipment required is dual-use with civilian applications in the pharmaceutical and fermentation industries. According to the OTA report, Producing BW would be relatively easy and inexpensive for a state with a modestly sophisticated pharmaceutical or fermentation industry.

The OTA report also presents the steps that a state interested in developing a BW program is likely to take. Such state is likely to start with standard BW agents that have already been weaponized. These agents are available in many countries; e.g.; from infected animals or soil in endemic areas. Moreover, scientists throughout the world can obtain strains of biological pathogens from certain biological supply houses. While these stains are not virulent, they can still be useful to a BW program. After acquiring BW agents, a state can genetically modify them in order to increase their virulence. Genetic modification can use simple selection techniques. For example, cultivating agents in the presence of antibiotics can cause drug-resistant stains to emerge. The next step is agent development, which includes an assessment of the agent's stability, infectivity, course of infection and effective dosage. This step involves tests that can be carried out in a sealed aerosol chamber or a remote testing range.

3 Motivation Assessment

In this section, we explain our methodology for estimating states' motivation to acquire BW. We perform our estimation by adapting the Friedkin model [17] from the social influence theory. We present the data we utilize to set the model parameters in Section 3.1. We review the Friedkin model in Section 3.2 before explaining how we adapt the model in Section 3.3. In adapting the model, we first modify the model equation in Section 3.3 to capture incentives and disincentives for developing BW. Subsequently, we set the model parameters in Section 3.3.2.

Network	Size	Density	Time period	Clustering coefficient	Number of components
Hostilities network H	193	0.004	1992-2010	0.007	10 components and 135 isolates
Alliance network A	193	0.052	In force in 2000	0.465	7 components and 90 isolates

3.1 Data

The data sets employed address international hostilities and formal military alliances, the list of states suspected of working on offensive BW and states' trade-to-GDP ratio. Table 1 presents general characteristics of the hostilities and alliance networks.

3.1.1 Hostilities Network

We collect the list of international hostilities from the International Crisis Behavior Project (ICB) [10] and the Uppsala Conflict Data Program (UCDP) [13]. The ICB data covers military and non-military conflicts. We only keep data for the period 1992-2007 in order to exclude conflicts prior to the dissolution of the former Soviet Union in 1991. The UCDP data covers military conflicts that resulted in at least 25 deaths in a calendar year during the period 1993-2010.

We combine the ICB data and the UCDP data in order to construct the hostilities network $H = [h_{ij}]$. In constructing H, we distinguish between: 1) the presence of a military conflict, 2) the presence of a non-military conflict and 3) the absence of conflicts. More formally, h_{ij}=1 indicates a military conflict between states i and j, h_{ij}=0.5 indicates a non-military conflict between the two states and h_{ij}=0 indicates the absence of conflict between the two states.

3.1.2 Alliance Network

We utilize the alliance data from the Correlates of War project (COW) [12]. We only keep alliances that are still force in 2000, which is the most recent year in the dataset. Moreover, we only keep alliances that belong to the defense pact category. These alliances commit countries to intervene military on the side of any treaty partner that is attacked. We omit alliances that belong to the categories of neutrality, non-aggression treaty and entente agreement. Neutrality and non-aggression pacts specify that parties remain military neutral if any co-signatory is attacked, while ententes pledge consultation and/or cooperation in a crisis, including armed attack. Subsequently, we manually add the ROK-US mutual defense treaty between the United States and South Korea, and the Collective Security Treaty (Weinstein 2007), which are missing from the COW data set. Finally, we construct a binary alliance network $L = [l_{ij}]$, where $l_{ij} = 1$ indicates that states i and j are common members of at least one of the listed alliances and l_{ij}=0 indicates otherwise.

3.1.3 List of Suspected States

We collect the list of states suspected of maintaining offensive BW programs from three sources. Our sources consist of a report from the US Department of State [42], a report from the James Martin Center for Non Proliferation Studies [20], and work by Tucker [39]. Table 1 summarizes the nation-states that each source lists as suspected of working on offensive BW. The US Department of State report is an authoritative and recent source that is important to include. Unfortunately, the US Department of State report only addresses a partial list and might have incentive to omit some proliferators for diplomatic reasons. The

Table 1: List of nation-states suspected of maintaining an offensive BW program

The US Department of State [42]	**James Martin Center for Non-proliferation Studies [20]**	**Tucker [39]**
Iran, N. Korea, Russia, Syria	China, Egypt, N. Korea, Iran, Israel, Russia, Syria	Burma, China, Cuba, Egypt, India, Iran, Iraq, Israel, N. Korea, S. Korea, Laos, Libya, Pakistan, Russia, Taiwan

report by the James Martin Center for Non Proliferation Studies and the list in Tucker are based on a compilation of available open-source data. These two sources are not limited to a subset of states and are not subject to the same diplomatic pressure as the US Department of State report. However, these sources are error-prone since they only rely on open-source data. We explain in Section 3.3.2 how we merge and weigh these lists.

The US Department of State report examines the BWC compliance of China, Cuba, India, Iran, Iraq, Libya, North Korea, Pakistan and Russia, which are all state parties to the BWC. The report also examines BW-related activities of Syria and Egypt, which have signed, but not ratified the BWC. As a conclusion, the US Department of State report suspects Iran, North Korea, Russia and Syria of maintaining an offensive BW program. The James Martin Center for Nonproliferation Studies report suspects China, Egypt, North Korea, Iran, Israel, Russia and Syria. We consider that the James Martin Center for Non Proliferation Studies report suspects a state of maintaining an offensive BW program if the report declares that the state "likely maintains an offensive capability" as is the case with China and Iran, or that the state "possibly procudes BW agents" as is the case with North Korea and Israel, or that the state "likely performs some work beyond legitimate defense activities" as is the case with Russia. We consider that the report does not suspect a state of maintaining an offensive BW program if the report lists a state as only performing BW research or as having a former program. Finally, Tucker lists Egypt, Iraq, Iran, Israel, Lybia, Syria, Burma, China, North Korea, South Korea and Taiwan as states suspected of having ongoing BW programs. Tucker mentions that Russia and South Africa are other alleged BW proliferators, but that South Africa's program was reportedly dismantled. Tucker also mentions that Cuba, India, Laos, Pakistan and Vietnam appear on some lists of BW proliferators.

In collecting lists of suspected countries, we do not include sources such as [7] that list states that have some BW capability without mentioning whether these stats engage in activities prohibited by the BWC.

3.1.4 Trade-to-GDP Ratio

We use the trade-to-GDP ratio as a measure of a state's integration into the global economy [32]. A higher integration into the global economy suggests that the state places a high value on international relationships and is therefore less likely to break international law by pursuing prohibited weapons [33]. We use the international trade data (v3.0) from the Correlates of War project [5]. We only keep trade during 2009, which is the most recent year in the dataset. We compute the sum of the imports and exports of each country. Subsequently, we collect the Gross Domestic Product for 2009 from the World Bank [37]. Finally, we divide the total trade of each country by country's GDP in order to obtain the trade-to-GDP ratio.

3.2 Friedkin Model

The Friedkin model is a simple recursive model that describes the process of attitude change that result from the interaction with other actors and from actors' intrinsic conditions. The attitude we are interested in

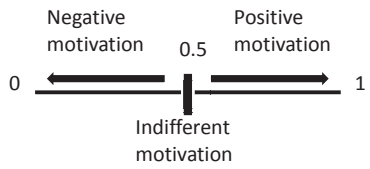

Figure 1: Scaling of motivation values. A larger motivation value represents a higher motivation. Motivation values larger than 0.5 represent positive motivation, motivation of 0.5 represents an indifferent motivation and motivation values smaller than 0.5 represent a negative motivation

studying in this work is the motivation to acquire BW. The Friedkin model stipulates that the motivations of actors at time t are a function of the influence network between actors, the motivations of all actors at time $t-1$ and the actors' initial motivations. More formally, in a group of N actors, the model is described by the following equation:

$$y_{(t)} = AWy_{(t-1)} + (I - A)y_{(1)}, t = 2, 3, .. \quad (1)$$

where $y_{(t)}$ is a Nx1 vector of the actors' motivations at time t. In this work, an actor's motivation follows the scaling depicted in Figure 1. $A = diag(a_{11}, .., a_{ii}, .., a_{NN}), 0 \leq a_i i \leq 1$ is a NxN diagonal matrix of actors' susceptibility to interpersonal influence. The matrix $W = [w_{ij}], (0 \leq w_{ij} \leq 1, \sum_{j=1}^{N} w_{ij} = 1)$ is a NxN matrix of interpersonal influence. More specifically, w_{ij} is the amount of influence that actor j has on actor i. The general formulation of the Friedkin model stipulates that $W = AC + I - A$ where $C = [c_i j]$ is a NxN matrix of relative interpersonal influence such that $(c_{ii} = 0, 0 \leq c_{ij} \leq 1, \sum_{j=1}^{N} c_{ij} = 1)$. Finally, $y_{(1)}$ is a Nx1 vector of the actors' initial motivations.

There are three main parts in the Friedkin equation. $Wy_{(t-1)}$ represents actors' extrinsic motivations at time $t-1$, that result from actors' interaction with each other. $y_{(1)}$ encodes actors' intrinsic motivations that result from actors' own characteristics. Finally, A encodes the proportional weight that each actor places on the extrinsic and intrinsic motivations.

3.3 Model Adaptation

In this section, we explain how we adapt the Friedkin equation model in order to model states' motivation to develop BW. Our model focuses on the top incentives and disincentives listed by Tucker [39] and partially captures some of the other factors. We need to modify the Friedkin equation model because this equation cannot readily account for both incentives and disincentives. We explain how we adapt that equation in Section 3.3.1 and explain how we set parameters in Section 3.3.2.

3.3.1 Model Equation Adaptation

Friedkin's equation captures extrinsic motivation i.e. inter-state influence through $Wy_{(t-1)}$. Unfortunately, that term cannot capture both incentives and disincentives, and the interaction between incentives and disincentives. We find a new term that captures in-kind deterrence, nuclear deterrence and the lack of perceived security threats. We then substitute $Wy_{(t-1)}$ in Equation 1 by the new term in order to find the adapted equation model. In order to simplify the discussion, we initially consider a single state that has a single enemy and derive a new term for the extrinsic motivation. Subsequently, we modify that expression into a vectorial expression that captures the extrinsic motivation of all states. Finally, we include that vectorial expression into Equation 1, obtaining the modified equation model.

Table 2: Qualitative description of the effect of a state's international environment on a state's extrinsic motivation to develop BW

Enemy has BW	**Enemy has nuclear weapons**	**State has nuclear reassurance**	**State's motivation for BW**
yes	yes	no	very high
yes	no	no	very high
no	yes	no	high
yes	yes	yes	moderate
yes	yes	yes	moderate
no	no	no	low
no	yes	yes	low
no	no	yes	low

We now consider the case of a single state with a single enemy. We derive an expression for the state's extrinsic motivation for BW as a function of: 1) whether the state's enemy has BW, 2) whether the state's enemy has nuclear weapons and 3) whether the state has nuclear reassurance. We consider that the state has nuclear reassurance if the state has nuclear weapons, or if the state has an ally that has nuclear weapons and that promises retaliation in case the state is attacked. We leave for future work capturing the fact that strong conventional weapons can also provide reassurance. Table 2 presents a qualitative description of the effect of different parameters on a state's extrinsic motivation. This qualitative description is based on motivational factors discussed in Section 2.1.

The motivation is high when the enemy has BW and/or nuclear weapons, and the state has no nuclear reassurance. The state perceives a great security deficit and has incentive to develop BW in order to fill that deficit . In the second case where the state has nuclear reassurance and the enemy has BW, The state has a moderate extrinsic motivation to develop BW. The state may desire BW in order to deter BW attacks using an option other than nuclear power, as is the case of Israel [39]. Alternatively, if the state has impeccable military power, the state may not perceive the need for BW, as is the case of the United States [21]. Finally, the extrinsic motivation is low in the case where the enemy has no BW and no nuclear weapons, and the case where both the state and the enemy have access to nuclear weapons, and the enemy has no BW. In the first case, the incentives for the state to develop BW are absent. In the second case, there is a balance between the two states.

In the previous paragraph, we considered that the state knew with certainty whether its enemy had BW. In reality, there is considerable uncertainty about other states' BW programs. We now assume that the enemy's likelihood of having BW is a continuous variable between 0 and 1 that has the scaling given in Figure 1. Figure 2 presents major trends in the state's extrinsic motivation for BW as a function of the enemy's likelihood of having BW. Figure 2 aims at quantitatively capturing incentives and disincentives discussed in Section 2.1.

From Figure 2, we see that the state's extrinsic motivation increases as the enemy's likelihood of having BW increases . From Figure 2, we also see that the motivation is higher when the state has no nuclear reassurance. Similarly, the motivation is higher when the state has a nuclear enemy. Finally, in the case where the state has a nuclear enemy and no nuclear reassurance, the extrinsic motivation is always high and less dependent on whether the enemy has BW. With the exception of this final case, the state's extrinsic motivation is always smaller than the enemy's likelihood of having BW. This difference implicitly captures disincentives such as BW uncertain military utility and the risk of provoking countermeasures.

We now derive a quantitative expression for the state's extrinsic motivation for BW as a function of

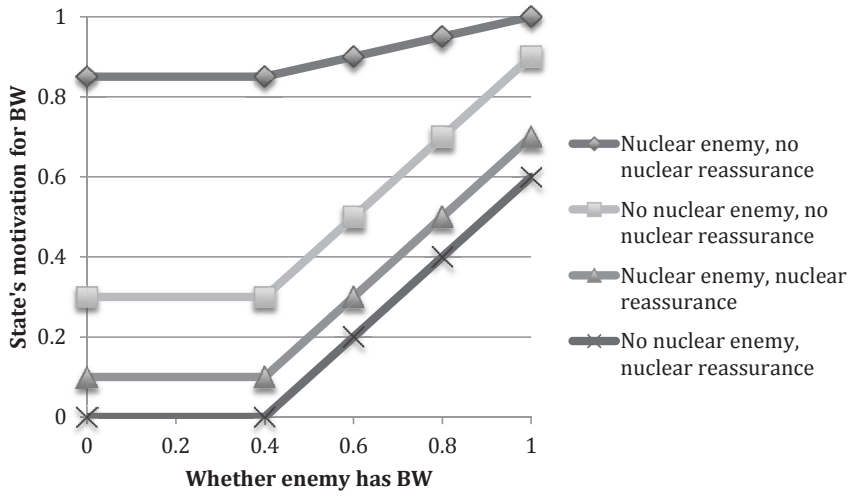

Figure 2: Major trends in a state's extrinsic motivation for BW.

whether the enemy has BW and nuclear weapons, and whether the state has nuclear reassurance. Let $M_{(t)}$ be the state's extrinsic motivation at time t such as $M_{(t)}$ has the scaling in Figure 1. Let $B_{(t-1)}$ be whether the state's enemy has BW at time $t-1$. As the knowledge of whether a state has BW is often uncertain, we consider that $B_{(t-1)}$ is a variable between 0 and 1 scaled according to Figure 1. Let c be whether the state's enemy has nuclear weapons and r whether the state nuclear reassurance. We consider that c and r are binary variables that do not vary over time because we assume that the set of nuclear states remains unchanged during our simulation. We can make this assumption because developing nuclear weapons requires much longer time than developing BW.

We find an expression of $M_{(t)}$ as a function of $B_{(t-1)}$, c and r through the use of regression. For the regression, we utilize the values of $M_{(t)}$ in Figure 2 when $B_{(t-1)}$ varies in $\{0.4, 0.6, 0.8, 1\}$, c varies in $\{0, 1\}$ and r varies in $\{0, 1\}$. In total, we utilize 16 different values. We run a regression on the terms $B_{(t-1)}$, c, r and the interaction terms $c.B_{(t-1)}$, $r.B_{(t-1)}$, $c.r$ and $c.r.B_{(t-1)}$, and obtain the expression:

$$M_{(t)} = -0.1 + B_{(t-1)} + 0.85c - 0.3r - 0.75cB_{(t-1)} - 0.75cr + 0.75crB_{(t-1)} \quad (2)$$

The regression R^2 is 1 and the p value is 4.5 10^{-120}. The above expression is linear in $B_{(t-1)}$ and can be rewritten as:

$$M_{(t)} = (1 - 0.75c + 0.75cr)B_{(t-1)} + (-0.1 + 0.85c - 0.3r - 0.75cr) \quad (3)$$

Equation 3 applies to only one state. We are interested in obtaining a vectorial expression that simultaneously captures the motivation of all states. We now consider that $M_{(t)}$, $B_{(t-1)}$, c and r are Nx1 vectors, where each value corresponds to one state. We obtain:

$$M_{(t)} = diag[1 - 0.75c + 0.75diag[c].r]B_{(t-1)} - 0.1 + 0.85c - 0.3r - 0.75diag[c].r \quad (4)$$

By replacing $Wy_{(t-1)}$ in Friedkin's equation by $M_{(t)}$, we obtain:

$$y_{(t)} = A(diag[1-0.75c+0.75diag[c].r]B_{(t-1)}-0.1+0.85c-0.3r-0.75diag[c].r)+(I-A)y_{(1)}, t = 2, 3, .. \quad (5)$$

Given that $B_{(t-1)}$ captures whether states' enemies have BW at time $t-1$, we can write $B_{(t-1)} = Wy_{(t-1)}$, where W is computed based on the hostility matrix as explained in Section 3.1.1. We therefore obtain our adapted equation model:

$$y_{(t)} = A(diag[1-0.75c+0.75diag[c].r]Wy_{(t-1)}-0.1+0.85c-0.3r-0.75diag[c].r)+(I-A)y_{(1)}, t = 2, 3, .. \quad (6)$$

Our adapted equation model is linear since c, r, W and A are constants. $y_{(t)}$ is the only variable that changes over time.

3.3.2 Parameters

In this section, we explain how we set the parameters of equation 6. We set $y_(1))$ by combining the lists of suspected states given in Section 3.1.3. We set A based on the trade-to-GDP ratio presented in Section 3.1.4. We set W based on A and the hostilities matrix presented in Section 3.1.1. Finally, we set c based on the hostilities matrix and the list of nuclear states, and r based on the alliance matrix c.f. Section 3.1.2 and the list of nuclear states. The nuclear states are the United States, Russia, France, the United Kingdom, China, India, Pakistan, North Korea and Israel [32].

In order to obtain $y_{(1)}$, we construct a binary vector corresponding to each of the lists given in Section 3.1.3. In that vector, a state has value 1 if the corresponding source suspects that state. We compute a weighted sum of the three vectors by giving weight 0.4 to the list by the US Department of State, weight 0.4 to the list by the James Martin for Non Proliferation Studies, and weight 0.2 to the list by Tucker. We give a smaller weight to Tucker's list because that list is older. The fact that the US Department of State report only addresses a partial list of countries may affect the results. However, we keep that report and weigh it highly because it is an authoritative source. After computing the weighted sum, we divide that sum by 2 and add 0.5 to the division result. As a consequence, states unsuspected of working on offensive BW have an initial motivation of 0.5, and suspected states have a initial motivation in the range]0.5,1].

A is a diagonal matrix with diagonal values between 0 and 1, which we set based on the trade-to-GDP ratio. We first scale the trade-to-GDP in order to be in the range [0,1]. The ratios in our data range between 0.003 and 17.693 with most values being smaller than 3.63. The only states having higher ratios are Nauru (9.094), Liberia (15.443) and Tuvalu (17.693). We divide all the ratios by 3.63 and manually set the ratios of Nauru, Liberia and Tuvalu to 1. Next, we compute 1 - the division results because the trade-to-GDP ratio and the susceptibility have an inverse relationship. Finally, we multiply the result by 2, and set the resulting vector as A's diagonal.

We have $W = AC + I - A$ where A is the susceptibility matrix discussed in the previous paragraph and C is obtained by modifying the hostility matrix. More specifically, we divide each row in the hostility matrix by the sum of that row in order to obtain the property $(0 \leq c_{ij} \leq 1, \sum_{j=1}^{N} c_{ij} = 1)$. As, the hostility matrix has a zero diagonal, the property $c_{ii} = 0$ directly follows.

c is a binary vector where a state has value 1 if the state has an enemy that has nuclear weapons. We consider that two states i and j are enemies if $h_{ij} = 0$. r is a binary vector where a state has value 1 if the state has nuclear weapons or has an ally that has nuclear weapons.

4 Latent Capabilities Assessment

In this section, we estimate states' latent capabilities to produce BW. We take a multi-dimensional approach that examines pharmaceutical capability, dual-use biological trade and BW research. Assessing pharmaceutical capability is important since a country with a moderately sophisticated pharmaceutical industry can

relatively easily produce BW [29]. Analyzing trade of dual-use biological equipment and commodities is relevant since these commodities and equipment can be used to produce BW. Finally, although advanced BW research may be unnecessary to produce crude BW, this research gives an insight into a country's know-how to develop advanced or novel BW. In the latent capability assessment part of this paper, we are mainly interested in whether a state has the necessary infrastructure to produce BW if the state wants to. In other words, this part of the paper does not attempt by itself to detect nation-states that currently maintain an offensive BW program. We narrow down the list of states that require close monitoring about BW activities by considering both the motivation and the latent capabilities.

4.1 Pharmaceutical Capability

We assign pharmaceutical capability scores based on capability information available in the World Medicines Situation report by the World Health Organization [45]. We assign a score of 4 to the 10 states with "sophisticated industry and significant research". These 10 states are responsible for the vast majority of medicine discovery. We assign a score of 3 to the 17 states with "innovative capability". These states have discovered and marketed at least one new molecular entity during the period 1961-1990. We assign a score of 2 to 13 states that have industries that make both ingredients and finished products. We assign a score of 1 to 84 states that manufacture finished products from imported ingredients. We assign score 0 to 42 states that have no pharmaceutical industry. Finally, we assign no score to the 23 states for which the report provides no information.

4.2 Number of BW Papers

We evaluate a country's BW research by counting the number of BW papers published by that country during the period 1980-2010. The number of BW papers provides an insight into a country's latent BW research capability. We consider a long time period in order to capture cases where a country performs open-domain research on a given BW agent, but performs military censorship on that research when deciding to weaponize that agent, as was the case of Russia in the 1970s and 1980s [29]. The number of BW paper is not intended to be a perfect measure of a country's BW research capability. A state developing a secret offensive BW program can prevent its researchers from publishing in the open domain. Moreover, two researchers with the same expertise can publish different amount of papers simply because these researchers publish in venues with different quality standards. Because of these limitations, we think that a large number of BW papers should be interpreted as strong BW research capability. However, a small number of these papers or their absence should not be mistaken as the lack of research capability. Factors such as state censorships should be taken into account.

We collect all papers from Web of Science [44] that have in their title, keywords or abstract the name of a weaponizable disease e.g. anthrax or a weaponizable agent e.g. Bacillus anthracis. We use the list of weaponizable diseases and agents published by the Center for Disease Control and Prevention (CDC) [16]. We utilize agents from categories A, B and C. In cases where the disease name is unspecific such as viral hemorrhagic fevers, we use that name as well as the specific agents listed as causing the disease. We use different variations in the naming of a disease or agent. For example, we also include the term "Y. pestis" when the CDC list contains "Yersinia pestis". We find different variations in the naming by searching online for each of these agents and writing down the different names that appear in the search results. We exclude from the collected papers policy and economy papers as well as news articles. The existence of these papers does not indicate that a state has technical BW expertise. We are left with about 90,000 papers, mainly biological and medical and also some engineering papers. We extract from the meta-data associated with

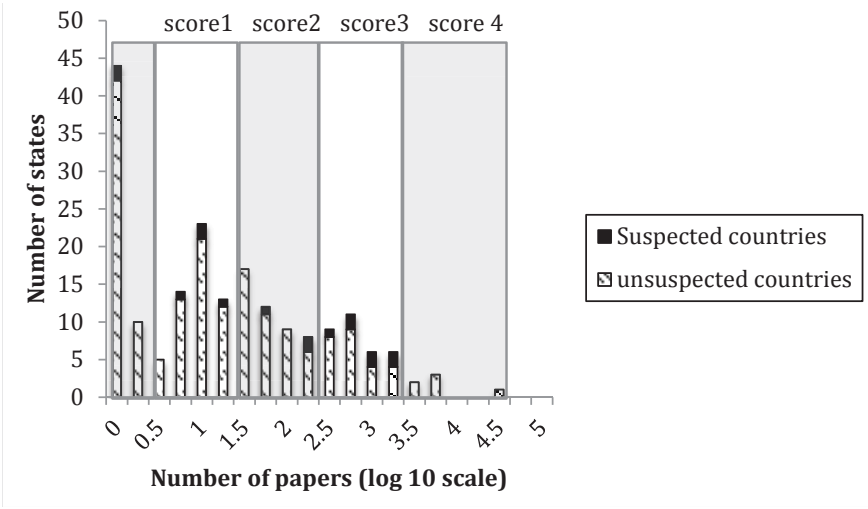

Figure 3: Research score assignment

the collected papers the states that wrote each paper. We consider that a certain state writes a paper when one of the paper's authors has an affiliation in that state.

We assign research capability scores to states based on the number of papers published by these states. The capability score assignment is presented in Figure 3. We assign a score of 0 to the 54 states with less than $10^{0.5}$=3 papers, a score of 1 to the 55 states with a number of papers between $10^{0.5}$=3 and $10^{1.5}$=31 papers, a score of 2 to the 46 states with a number of papers between $10^{1.5}$=31 and $10^{2.5}$=316 papers, a score of 3 to the 32 states with a number of papers between $10^{2.5}$=316 and $10^{3.5}$=3162 papers and a score of 4 to states with a number of papers higher than 3162 papers. The purpose of our score assignment is to differentiate between different orders of magnitude of the numbers of selected papers.

There are limitations with our collection methodology. By considering all papers about the weaponizable diseases and agents in our list, we also include papers relevant to public health safety, pandemic readiness efforts, disease diagnostics and surveillance. This is the case as most weaponizable diseases occur naturally. Although these papers are not directly relevant to building an offensive BW program, they exhibit some expertise handling and manipulating BW agents that is relevant to our latent capability assessment. Moreover, by only including papers about BW agents in the CDC list, we miss papers about BW agents that exclusively target animals and crops. Ban [3] provides an overview of agriculture biological warfare. We intend to include these papers in future work.

4.3 Dual-Use Biological Trade

We collect the trade of dual-use biological commodities during the period 1980-2010 from the UN Comtrade database [40]. The UN Comtrade database is a publicly available depository of international trade data. States inform the United Nations Statistics Division (UNSD) of their international trade at the end of each year and the UNSD makes the data available though the UN Comtrade database. Dual-use commodities are commodities with both civilian and military uses. Examples of these commodities are sterilization and biotechnology equipment as well as delivery equipment.

We collect the trade data by specifying the commodity codes of dual-use equipment. We obtain the list of these codes from a World Customs Organization report [1]. Unfortunately, dual-use biological commodities

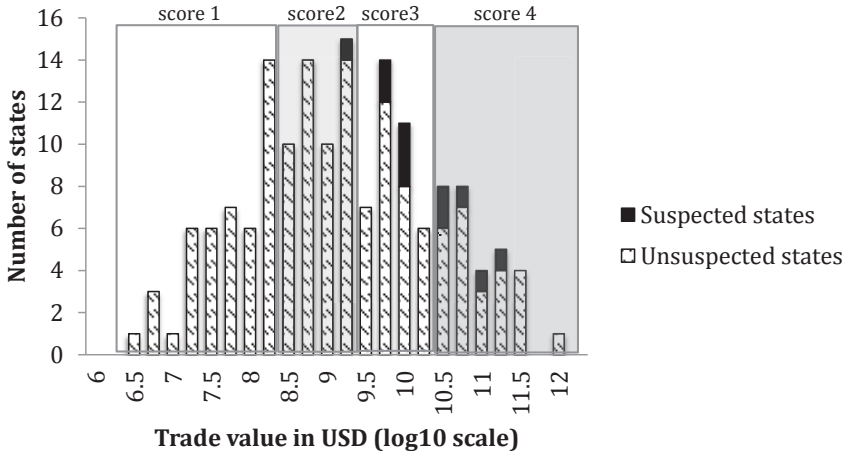

Figure 4: Trade score assignment

are typically included under large basket numbers. Due to this ambiguity, the collected trade data contains trade of dual-use commodities as well as other commodities with exclusively civilian applications. We adjust the collected trade data for inflation using the Producer Price Index (PPI) as deflator. Finally, we compute the total trade value of each state by computing the sum of the value of the state's imports and exports. Figure 4 depicts the capability score assignment based on the trade values. We assign a score of 1 to 44 states with trade value between 10^6 and $10^{8.5}$ USD, a score of 2 to the 49 states with trade value between $10^{8.5}$ and $10^{9.5}$ USD, a score of 3 to the 38 states with trade value between $10^{9.5}$ and $10^{10.5}$ USD and a score of 4 to the 30 states with trade value higher than $10^{10.5}$. We assign score 0 to 32 states that have a trade value equal to 0. These states probably simply did not report their trade data to the UNSD. We assign capability scores by distinguishing among different orders of magnitude of trade values. We also try to ensure that a similar number of states belong to each score category.

It is interesting to observe that all suspected states have high trade scores. We note, however, that a small trade score should not be interpreted as low capability. States may simply choose to misrepresent their trade data or to not report their trade data at all to the UN Comtrade. In this case, we will observe a low trade value.

5 Results

In this section, we discuss the results of our joint motivation and latent capability analysis. Table 4 presents the motivation values and capability scores of states that have a positive motivation (i.e. a motivation value ¿ 0.5) at equilibrium. We mainly focus on states with positive motivation because the motivation is the main driver for BW proliferation as a larger number of states have the basic latent capability to produce BW [29]. In order to gain more insight into the motivation dynamics of these states, Table 3 also includes the enemies of these states as well as whether these states have access to nuclear weapons directly or through an ally.

The initial motivation in Table 3 is the motivation obtained by weighing the list of suspected countries as explained in Section 3.3.2. The equilibrium motivation is the motivation obtained when running the adapted model until equilibrium. At equilibrium, the states' motivations remain unchanged across iterations. Table 3 reports equilibrium motivations obtained using our equation model given in Equation 6.

Table 3: Results of our joint motivation and latent capabilities assessment. The table only shows states with positive equilibrium motivation

State	Initial motivation	Equilibrium motivation	Research score	Trade score	Pharma score	Enemies	Nuclear reassurance
Iran	1	0.9667	3	3	1	United States, United Kingdom, France, Germany	None
Syria	0.9	0.9248	1	0	1	Israel	None
Russia	1	0.8587	3	4	3	Georgia	Has nuclear weapons
India	0.6	0.7495	3	4	3	Pakistan	Has nuclear weapons
Israel	0.8	0.7434	3	4	2	Lebanon	Has nuclear weapons
Pakistan	0.6	0.7373	2	3	1	India, United States, United Kingdom	Has nuclear weapons
N. Korea	1	0.7261	0	N/A	N/A	South Korea, United States	Has nuclear weapons
Taiwan	0.6	0.7155	3	N/A	3	China	None
Egypt	0.8	0.7105	2	3	2	Sudan	None
Iraq	0.6	0.6997	1	3	1	United States, United Kingdom, Kuwait, Saudi Arabia, Australia	None
Sudan	0.5	0.6777	1	2	N/A	United States, Chad, Egypt	None
Georgia	0.5	0.6755	2	2	1	Russia	None
Lebanon	0.5	0.6701	2	2	1	Israel	None
Afghanistan	0.5	0.6585	0	4	1	United States, United Kingdom	None
Serbia	0.5	0.6400	2	2	3	Bosnia and Herzegovina, Canada,Germany, Italy, Belgium, Spain, Netherlands, Portugal, Albania, Croatia, France, United Kingdom, United States	None
China	0.8	0.5625	3	4	3	Taiwan	Has nuclear weapons
Burma	0.6	0.5259	1	0	1	Thailand	None

5.1 Known Nuclear Powers: Russia, Israel, China, North Korea, India and Pakistan

The equilibrium motivations of Russia, Israel and China are lower than their initial motivation, but are still positive. All these states have nuclear weapons that provide them with reassurance. It is interesting to observe that Russia, Israel and China have impeccable capabilities. Finally, North Korea's equilibrium motivation is lower than the initial motivation, but is still positive. Given that North Korea has gained access to nuclear weapons, North Korea has less need for BW. North Korea exhibits non-existent capabilities. This is unsurprising given North Korea's extreme opacity. We think that North Korea should continue to be watched.

India and Pakistan are listed as suspected in the work by Tucker [39], but are not suspected in recent sources. The equilibrium motivations of India and Pakistan are higher than their initial motivations. This is surprising given that both India and Pakistan have nuclear weapons. Because of the rivalry between the two countries, even a small suspicion that the enemy has BW creates incentives for the other party to acquire such weapons. Both India and Pakistan have important capabilities and we think these two states should be watched.

5.2 Middle East

Iran Iran has strong equilibrium motivation because of Iran's hostile relationship with the United States, the United Kingdom and France, which are all nuclear powers. Iran has an active nuclear program, but has no nuclear weapons that can provide reassurance. Moreover, Iran probably hopes that BW among other weapons would deter a strike against its nuclear facilities. Iran has strong research and trade scores, which seem to be beyond the needs of its pharmaceutical industry. We think that Iran should continue to be watched.

Syria Syria has strong motivation because Syria is enemy of Israel, which is believed to have nuclear weapons and suspected of having BW. Syria, however, has little apparent capability [14]. Syria is suspected because Al Assad stated that "Syria was entitled to defend itself by acquiring, inter alia, its own biological deterrent" [41]. Syria, however, has few apparent capabilities. It may be that the United States has classified information about Syria's offensive BW capabilities. It may also be that Syria has no BW capability, but pretends having BW in order to deter attacks. Another possibility is that Syria acquired BW through its allies.

Lebanon Lebanon exhibits a positive equilibrium motivation because of the hostile relationship with Israel. Lebanon has latent capabilities that could be developed if Lebanon decides to pursue the BW route. Alternatively, Lebanon could obtain BW from its allies. Lebanon is likely to attract considerable international attention because the Syrian instability seems to spill over to Lebanon.

Egypt Egypt exhibits a relatively high equilibrium motivation and has reasonable capabilities. We think that our results concerning Egypt should be interpreted carefully since our data does not capture the situation after the revolution.

Iraq Iraq is believed to previously have a BW program that was dismantled. Iraq is mainly interesting from a historical perspective since it is difficult to imagine that Iraq will reacquire BW while foreign troupes are on Iraq's territory. In our analysis, the equilibrium motivation of Iraq is higher than Iraq's initial motivation

because Iraq has a hostile relationship with the United States and the United Kingdom, which are both nuclear powers. The capabilities analysis shows that Iraq has basic research and pharmaceutical capabilities, but a very strong trade score.

Turkey and Saudi Arabia Turkey and Saudi Arabia are two regional powers unsuspected of working on BW. Turkey is a NATO member and Saudi Arabia have strong ties with the United States.

5.3 Asia

In Asia, Taiwan may be interested in BW in order to balance China's nuclear and biological weapons. Although South Korea is suspected in some earlier reports [39], our analysis suggests that there is no need to watch BW related activities in South Korea as long as the military cooperation between the United States and South Korea is strong.

Taiwan Taiwan's equilibrium motivation is higher than its initial motivation because Taiwan has a hostile relationship with China and Taiwan does not have nuclear reassurance. We consider in our analysis that Taiwan has no nuclear reassurance from the United States because there is no formal defense pact between Taiwan and the United States. If our analysis were to take into account the fact that the United States would probably intervene if Taiwan is attacked, Taiwan's equilibrium motivation would probably be smaller than the one presented. However, the equilibrium motivation will not necessarily be negative. Taiwan has impeccable research and pharmaceutical capabilities. We think that Taiwan should be watched.

South Korea South Korea is suspected of having a BW capability in Tucker [39], but in our analysis South Korea has a negative equilibrium motivation due to its reassurance from the ROK-US mutual defense pact. As long as the military collaboration between South Korea and the United States is strong, there is probably no need to watch BW activities in South Korea.

Afghanistan Afghanistan also has positive equilibrium motivation for BW. Afghanistan has hostile relationship with the United States and the United Kingdom because of the American invasion of Afghanistan, and both the United States and the the United Kingdom have nuclear weapons. We note that because of the presence of international troops in Afghanistan, the Afghani government is unlikely to pursue BW.

Burma Burma's equilibrium motivation is smaller than its initial motivation. Burma does not have an enemy that has nuclear or biological weapons and therefore does not perceive a need for BW. Burma is currently under intense international scrutiny as it transitions into a democracy. Our analysis suggests that it is unlikely that Burma should be suspected of continuing any BW program.

Japan Japan has a negative equilibrium motivation and probably does need to be monitored concerning BW related activities. Japan has no enemies in our hostility data, and therefore, has no incentive to develop BW. As China reasserts itself as a regional power, tensions between Japan and China might arise. Even in this case, we think there is probably no need to watch Japan. The American defense pact provides reassurance to Japan, and Japan has strong norms against WMDs.

5.4 Europe

Georgia and Serbia are not suspected by any of our sources, but exhibit positive equilibrium motivation. Georgia has positive equilibrium motivation for BW because Georgia is enemy with Russia, and Russia has nuclear weapons and is suspected of having BW. Finally, Serbia is enemy with France, the United Kingdom and the United States, which all have nuclear weapons. Both Georgia and Serbia have basic capabilities that could be developed if these countries decide to pursue BW. We think that Georgia and Serbia should be watched for in the long-term.

5.5 Africa

Libya Libya is listed as suspected in Tucker [39], but have a negative equilibrium motivation. In our analysis, Libya's equilibrium motivation is negative because Libya does not have enemies that have nuclear or biological weapons in our data. We note that since our data does not capture the situation in Libya after the revolution, our results should be interpreted carefully. It is worth pointing out, however, that Libya agreed to dismantle its WMD program in 2003 and allowed inspections to ensure compliance [35]. Moreover, Libya's WMD program is considered a result of Muammar Qaddafi's ambitions and policies [35], and the Qaddafi regime has fallen.

Sudan Sudan is enemies with the United States and Egypt. The United States has nuclear weapons and Egypt is suspected of having BW. We note that in this work, we consider that Sudan is one country, and do not take into account the division of Sudan into Sudan and South Sudan. This is mainly due to the fact that we use historical data where South Sudan does not appear. We plan to take the division into consideration in future work. Due to Sudan's motivation and latent capabilities, we recommend that Sudan continue to be watched in the long term.

6 Limitations

We note that most of our sources and background papers are relatively dated. It is unclear whether the content of papers such as the report by the Office of Technology Assessment report [29] still applies today. However, we are unable to find more recent background work. This shortage of recent relevant work emphasizes the need for more work in the area.

In this work, we focus on state actors and do not include terrorist groups. Studying terrorist organizations is very different from studying state actors and is beyond the scope of this paper. Moreover, terrorist organizations have more difficulty than nation-states developing BW compared. Please refer to Koblentz [22] for discussion about biological terrorism, and to Tucker [38] and the START database [36] for open-access data sets about terrorist and criminal WMD activities. Our motivation assessment model focuses on the top incentives and disincentives discussed by Tucker [39], and addresses only partially some of the other factors. We would like to capture more incentives and disincentives in future work. We would also like to capture differences in how countries perceive these incentives and disincentives. For example, Koblentz [21] notes that BW are more attractive to dissatisfied states since dissatisfied states are less likely to respect international law. We could model the difference between satisfied and dissatisfied states by adding a disincentive term that is proportional to states' satisfaction score in equation 2. We leave working out the exact equation for future work.

We are unable to fully validate our computational model. In order to fully validate our model, we need reliable data about the timeline and circumstances of different states' BW programs. We would feed old data

into the model and see whether the model can accurately predict the next BW proliferators. Unfortunately, the required data is unavailable in open-source because of the secrecy surrounding most BW programs. We note that government agencies that have access to the data can perform such validation before using the model in their assessment. We also note that our computational model already has some validation since we base our assumptions on expert opinion.

7 Conclusion

In this paper, we present and utilize a joint motivation and capability assessment methodology to address BW proliferation. Our methodology is systematic as we examine all nation-states in the world. Addressing both the motivation and the capability sides for all nation-states provides a more accurate picture. We assess states' motivations based on a social influence model that incorporates international threats. We evaluate states' capabilities by examining these states' BW research, dual-use biological trade and pharmaceutical capabilities. Our results suggest that there are countries that need to be watched in addition to the countries already suspected by current sources. Within these countries, India, Pakistan and Taiwan should be high priorities for direct observations. These states have strong motivation for BW and important BW capabilities, but are currently not suspected of violating the BWC. Our results also indicate that Georgia, Sudan, Lebanon and Serbia should be watched for in the longer term. These four countries have motivation to develop BW and basic BW capabilities. These capabilities could be developed if these countries decide to pursue the BW route.

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