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Deterrence in Contests

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This paper explores the role of deterrence in contests. As a general rule, we show that for a deterrence strategy to be played by rational agents, it is necessary that the contest be destructive. We show for a very general class of functions that pure strategy deterrence equilibria where contestants deter one another do not exist. A corollary of this finding is that under fairly general conditions, agents should always be expected to engage in contests. Applied to international relations, our results imply that war is always a potential outcome despite deterrence attempts.

Introduction

Contests constitute an inefficient way to settle disputes. Two sources of inefficiencies may be identified. On the one hand, resources are diverted from productive activities to prepare for contests. On the other hand, if a contest actually occurs it may entail direct costs (e.g. asset destruction). Nevertheless, contests are widely observed. A large body of literature has addressed this conundrum.

Ideally, one would desire a settlement that simultaneously solves both inefficiencies. Were parties able to credibly commit not to devote effort in preparation of a contest, such a scenario would be achieved. This kind of commitment is, however, highly demanding (e.g. third party enforcement). One area where it is particularly compelling is the field of international relations (Fearon 1995; Powell 2006). Recognizing the difficulty of refraining from arming, scholars have therefore identified conditions preventing the outbreak of conflicts. The ancient maxim by the Roman strategist Vegetius quoted above singles out deterrence as a powerful strategy to avoid war.[1] Since international relations constitute a natural setting for applying theories of destructive contests, in the remainder of the paper we refer to war situations.

The canonical models on conflicts (Hirshleifer 1989; Skaperdas 1992) have assumed war to be a zero-sum game: the gain by one contestant from war as compared to peace, matches the loss of the other contestant. Most subsequent scientific research in the field has adopted this paradigm. A recurrent and robust finding in this class of games is that at equilibrium the contestants arm as if war is expected to occur with certainty.[2]

In this paper we show that relaxing the zero-sum game assumption, by modelling war as a destructive activity, changes these predictions dramatically. We extend the canonical general equilibrium conflict model of Skaperdas (1992) and show in this very general setting that even when war entails minor damages, an alternative motive for arming emerges: instead of preparing for war (hawk strategy), agents arm to *deter* potential aggressions (deterrence strategy). This, however, does not guarantee the emergence of peace at equilibrium, except for high destruction rates where agents forgo arms production. We show that for lower destruction rates, at equilibrium agents either randomize over their hawk and deterrence strategies, or solely play their hawk strategy. Hence if weapons are produced, a war may be initiated as a consequence of a rational choice.

The findings of our model are consistent with the empirical regularity that wars are never completely unavoidable. A critical implication of our analysis is that even when war entails relatively large destruction, peace never represents a certain outcome if arms have been produced. Notice, however, that there exists a whole range of possible armaments levels compatible with both agents preferring peace over war. In other words, while armed contestants may create a balance of power (Morgenthau 2006) that would prevent conflict, a power disequilibrium may also result in which war occurs.

Deterrence has a long history, as Vegetius' maxim testifies. Following the Second World War, the Cold War environment boosted research around this topic. Two broad schools developed around the concept of deterrence: structural deterrence theory and decision-theoretic deterrence theory. The former school posits that power parity across potential opponents combined with high direct costs of war increases the likelihood of deterrence (Waltz 1964; Brito and Intriligator 1984). The latter school adopts a game-theoretic approach and emphasizes the role of the threat's credibility in deterring one's opponent (Leventoglu and Slantchev 2007). Thomas Schelling (1960) elaborates thoroughly on the concept of deterrence in his famous book *The Strategy of Conflict*. According to him, a good strategist would prevent war through the 'skillful nonuse of military forces'. The core of his argument is that the success of deterrence rests on the credibility of the threat of retaliation. Although stressing the crucial role of the threat's credibility, Jervis (1976) warns about the risks associated with spiralling investments in arms. Indeed, arming to deter the opponent can lead to a vicious circle of increasing risk of a disastrous war (see also Glaser 1997).[3] A common feature of this early literature on deterrence is the exogeneity of the parties' power.

In recent years, other scholars have elaborated on the concept of deterrence (Garfinkel 1990; Grossman and Kim 1995; Neary 1996; Chassang and Padro-i-Miquel 2010; Jackson and Morelli 2009; Jacobsson 2009). The added value of some of these models has been to endogenize militarization. Indeed, if deterrence is an equilibrium, it results from a deliberate rational *choice* by agents. Exogenously assuming deterrent levels of arms for both opposing parties does not *necessarily* make deterrence an equilibrium, as either party might have an incentive to modify its armament level. On the one hand, increasing one's arms level might make the expected payoff of war larger than the returns of peace, while on the other hand, there might be a cost-saving reduction of weapons such that the opponent remains deterred.

In Garfinkel (1990) and Jackson and Morelli (2009), a deterrence equilibrium is obtained in a dynamic setting. An infinitely repeated game contributes to sustain cooperation by alleviating commitment problems. Using this Folk Theorem result, Garfinkel (1990) shows that if the discount factor is large enough, peace is sustained without any investment in arms. For lower values of the discount factor, positive amounts of weapons may be necessary to deter the outbreak of a war. Unlike Garfinkel (1990), Jackson and Morelli (2009) do not resort to the dynamic aspect of their setting to overcome commitment problems since they consider Markov perfect equilibria. In their model, purchased weapons become effective with a time lag. In other words, current investment in armaments by the potential opponent do not affect one's own current utility. Not arming, defined by the authors as the 'dove' armament levels, is a direct consequence of this feature. Indeed, under some conditions (e.g. low discount factor), it may be more profitable for contestants to devote all their resources to production. They show that if the costs of war are intermediate, at equilibrium the opposing parties will always mix three armaments levels labelled 'dove', 'hawk' and 'deterrent'. In linking the cost of war to the existence of 'deterrent' equilibria, their model and ours have a common ground. These two models, however, differ in many respects. First, the general equilibrium model that we propose generalizes their partial equilibrium approach. Second, in Jackson and Morelli

(2009) the direct cost of war is modelled as a fixed cost c, whereas we assume that a share of the contested production is destroyed in the fight. A third distinctive element of these two papers lies in the production technologies: whereas Jackson and Morelli (2009) impose linear production functions, we accommodate the more general case where production exhibits diminishing returns.

Grossman and Kim (1995) propose a static model of 'guns and butter' in which each party sequentially chooses its defence and offence levels of armaments, before deciding whether or not to go to war. Deterrence results from producing sufficient defensive weapons in the first stage of the game such that investing in offensive weapons is not worthwhile for the opponent. We do not distinguish between types of armaments. Instead, in our model deterrence results entirely from the direct cost that war would inflict on society.

The closest papers to our contribution are Neary (1996) and Jacobsson (2009). Both authors propose a static two-stage model in which two agents simultaneously choose their armament levels in the first stage, before simultaneously deciding whether or not to go to war in the second. In particular, Jacobsson (2009) shows that the game admits no pure strategy equilibrium even for minor destruction rates. On the other hand, when war entails substantial destruction, a peaceful weaponless equilibrium emerges. With respect to these contributions, we adopt a more general class of production and fighting functions. The only requirement regarding the production function in our model is concavity, while the fighting technology that we consider is much broader than the Tullock contest success functions (Tullock 1980) assumed in the above-mentioned papers. Jacobsson (2009) sets up a partial equilibrium model, whereas we adopt a general equilibrium approach. The distinction between the two types of model lies in the fact that the value of the prize in a general equilibrium approach is endogenously determined by the agents' arming decisions.[4] We relax the symmetry assumption and generalize Jacobsson's (2009) findings.

While international relations provide a natural framework to develop our argument, the analysis extends to other fields featuring contests (e.g. electoral campaigning, legal litigations). For instance, if going to court decreases the joint expected value of winning a trial, the litigants may attempt to collect sufficient evidence during the pretrial negotiations to deter their opponent from taking the case to court. This may yield substantially different outcomes as compared to the existing literature (see Farmer and Pecorino 1999, 2002; Hirshleifer and Osborne 2001; Robson and Skaperdas 2008; Choné and Linnemer 2010).

The rest of the paper is organized as follows. In Sections I and II we sequentially present the model and a general analysis of the agents' optimal behaviour. In Section III we derive the game's equilibria under the assumption of non-destructive conflict, while in Section IV we restrict the problem to destructive conflicts. Section V concludes by discussing the implications of our results for the conflict theory literature.

I. The Setting

Two risk-neutral agents, labelled 1 and 2, allocate their resource endowment $R^i > 0$ ($i = 1, 2$) in guns G^i and butter $X^i = R^i - G^i$. The agents' specific production technology $C^i(R^i - G^i)$ transforms butter into consumables. In the remainder of the paper we write $C^i(R^i - G^i)$ more concisely as $C^i(G^i)$. Guns create no wealth. Their role is to either improve the likelihood of appropriating the aggregate production in case of a dispute, or deter the enemy from launching an attack. We designate the former weapons by the term 'hawk' armaments, while the latter are called 'deterrent' weapons. More specifically, agent 1's probability of winning a potential war and hence of capturing the entire production of both agents is denoted by $p(G^1, G^2)$. Agents 1 and 2 interact in a two-stage game. They allocate their resources between guns and butter in the first stage of the game. In the second stage, the agents observe the output as well as the quantity of weapons produced, and decide whether or not to wage a war.

If either agent decides to attack the other, the outcome is conflict and the ensuing payoffs are given by

$$U^{1w}(G^1, G^2) = \delta p(G^1, G^2)(C^1(G^1) + C^2(G^2)), \tag{1}$$

$$U^{2w}(G^1, G^2) = \delta(1 - p(G^1, G^2))(C^1(G^1) + C^2(G^2)), \tag{2}$$

where $\delta \in [0, 1]$ is a parameter that captures the destructiveness of war, and the superscript w stands for war.

If neither agent chooses to attack the other, the resulting utilities are given by

$$U^{ip}(G^i) = C^i(G^i), \quad i = 1, 2,$$

where the superscript p denotes peace.

We impose the following standard assumption on the production technology.

Assumption 1.

$$C^i(0) = 0, \quad \frac{\partial C^i}{\partial X^i} = C^i_1 > 0, \quad \frac{\partial^2 C^i}{\partial X^i \partial X^i} = C^i_{11} \leq 0.$$

Regarding the conflict technology, we restrict the analysis to the following class of functions:

$$p(G^1, G^2) = \frac{F(G^1)}{F(G^1) + F(G^2)} \quad \text{if } G^1 + G^2 > 0, \tag{3}$$

$$p(G^1, G^2) = p(G^2, G^1) = 0 \quad \text{if } G^1 + G^2 = 0. \tag{4}$$

This last condition precludes the occurrence of conflicts in the total absence of weapons.

Moreover, we impose the following assumption on the power function $F(\cdot)$.

Assumption 2.

$$F(0) = 0, \quad F_1(G) > 0, \quad \frac{F_{11}(G)}{F_1(G)} \leq 2\frac{F_1(G)}{F(G)}.$$

Assumption 2 accommodates both convex and concave power functions. In the convex case, however, it restricts the degree of convexity for large values of $F(\cdot)$. In other words, a powerful agent should not experience too high marginal increases in power. Assumption 2 is used in the first subsection of the Appendix to show quasi-concavity of the agents' war utilities as given by equations (1) and (2). Before proceeding with the problem's analysis, we ought to underline a critical implication of the above assumptions.

We look for the subgame perfect Nash equilibria of this game, solving by backwards induction.

II. Analysis

In the second stage, agent 1 prefers war over peace if the following condition is satisfied:[5]

$$\delta p(G^1, G^2)(C^1(G^1) + C^2(G^2)) \geq C^1(G^1).$$

On the other hand, peace is preferred if this weak inequality is inverted.

The optimal guns level for a hawk is obtained by solving the following maximization problem:

$$\max_{G^1} \delta p(G^1, G^2)(C^1(G^1) + C^2(G^2)) \quad \text{s.t. } 0 \leq G^1 \leq R^1.$$

Using concise notation, the first-order condition for agent 1 is given by

$$(5) \qquad U_1^{1w} = p_1(C^1 + C^2) - pC_1^1 \geq 0.$$

This expression implicitly defines the hawk's best response. In the first subsection of the Appendix we address the conditions that allow us to derive the hawk best response for agent 1.

Interior solution:

$$G^{1w}(G^2) = G^{1w}$$
$$\text{if } p_1(G^{1w}, G^2)\left[C^1(G^{1w}) + C^2(G^2)\right] - p(G^{1w}, G^2)C_1^1(G^{1w}) = 0.$$

Corner solutions:

$$G^{1w}(G^2) = \begin{cases} 0 & \text{if } p_1(0, G^2)\left[C^1(0) + C^2(G^2)\right] - p(0, G^2)C_1^1(0) < 0, \\ R^1 & \text{if } p_1(R^1, G^2)\left[C^1(R^1) + C^2(G^2)\right] - p(R^1, G^2)C_1^1(R^1) \geq 0. \end{cases}$$

Alternatively, agent 1 can deter his potential opponent. His maximization problem is then as follows:

$$\max_{G^1} C^1(G^1) \quad \text{s.t.} \begin{cases} C^2(G^2) > \delta(1 - p(G^1, G^2))(C^1(G^1) + C^2(G^2)), \\ 0 \leq G^1 \leq R^1. \end{cases}$$

The deterrent armament levels are therefore the minimal amounts of guns that make the opponent *strictly* better off under peace.[6] Agent 1's optimal deterrent amount of guns (signified by a superscript *d*) is therefore as follows.

Interior solution:

$$G^{1d}(G^2) = G^{1d}$$
$$\text{if } C^2(G^2) = \delta(1 - p(G^{1d} - \varepsilon, G^2))(C^1(G^{1d} - \varepsilon) + C^2(G^2)),$$

with ε infinitesimally small.

Corner solution:[7]

$$G^{1d}(G^2) = 0 \quad \text{if } C^2(G^2) > \delta(1 - p(0, G^2))(C^1(0) + C^2(G^2)).$$

It is important to underline that in the present setting, these two armament levels are the only ones conceivable.[8] Agent 1 therefore chooses the utility maximizing armaments level—hawk or deterrent—for any guns level G^2 of agent 2. Formally,

$$(6) \qquad G^1(G^2) = \begin{cases} G^{1w}(G^2) & \text{if } U^{1w}(G^{1w}, G^2) \geq U^{1p}(G^{1d}, G^2), \\ G^{1d}(G^2) & \text{otherwise.} \end{cases}$$

In the next two sections we derive the equilibrium results for non-destructive and destructive conflicts, respectively.

III. Non-destructive War ($\delta = 1$)

In this section we consider war as a zero-sum activity. Under this assumption, the only cost of conflict to society is represented by the inefficient allocation of resources to non-productive activities. Indeed, the socially optimal resource allocation requires that $G^1 = G^2 = 0$. In this setting, we show that the following proposition holds.

Proposition 1. If conflict is not destructive, the hawk armament levels always dominate the deterrent armament levels.

Proof. See the Appendix. □

Notice first that if agent 1 prefers war, by the definition of the deterrence strategy, agent 1's optimal deterrence guns level is lower than his optimal hawk guns level, while the inverse is true for agent 2. The gains to agent 1 of reducing his guns investment to the deterrence level do not offset the foregone expected rewards of war. For agent 2, on the other hand, the burden of the deterring guns investment is too large as compared to the expected war payoffs.

Since—in the absence of destruction—only the optimal weapons levels are always equal to the hawk armament levels, the next result follows.

Proposition 2. If conflict is not destructive, there exists a unique equilibrium armaments level.

Proof. See the Appendix. □

War is the unique equilibrium of this game, except in the particular case where agents are indifferent between peace and war at optimality.[9] As a consequence of Proposition 1, we thus obtain in Proposition 2 a standard result in the conflict literature: at equilibrium the agents invest inefficiently high amounts of resources in conflict activities. Indeed, by the very definition of a zero-sum game, if agent 1 prefers peace, agent 2 necessarily prefers war (and vice versa). To help the reader to better grasp the functioning of the model, we have plotted in Figure 1 a simulation of the reaction functions of the two agents in the present context of non-destructive conflicts. On the x-axis is represented agent 2's armament level, while on the y-axis one reads the guns of agent 1. The actions space is divided into two areas separated by the dashed line representing all the pairs of guns (G^1, G^2) such that *both* agents are exactly indifferent between peace and war.[10] The dark shaded area represents all the weapons combinations making agent 2 strictly better off under war than under peace, while in the other area it is agent 1 who has a preference for the conflict outcome. Since we have shown that the deterrent armament levels are always dominated by the hawk armament levels, it follows that only the 'hawk' reaction functions are relevant, and hence depicted in Figure 1. This implies that in the area where an agent would prefer peace, his best response nevertheless consists in selecting hawk armament levels, in expectation of his foe anyway declaring war. Notice that since the probability function is not defined in (0,0), the reaction functions actually cross only once. In Figure 1, the equilibrium is unique and the outcome of the game is war with certainty since agent 1's dominant strategy consists in attacking his foe. For symmetric agents the dashed line crosses the intersection of the two reaction functions, and at equilibrium *both* agents are completely indifferent between peace and war.

The next section explores the consequences of war being a negative sum game.

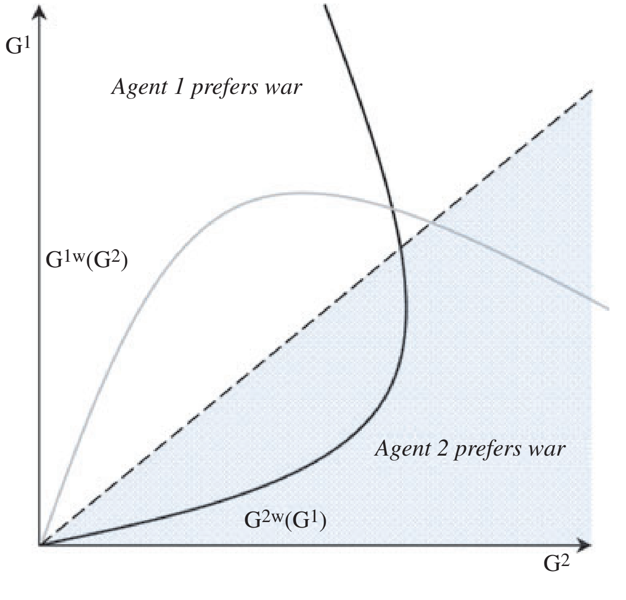

FIGURE 1. Conflict equilibrium.

IV. Destructive War ($\delta < 1$)

Assuming that war is destructive perhaps constitutes a more realistic hypothesis. A first central consequence is described in the next proposition.

Proposition 3. There always exists a destruction rate $(1-\delta)$ making the deterrent armaments the optimal weapons for some guns levels of the opponent.

Proof. See the Appendix. □

It is important to stress that destruction adds one different motive for arming. In the model presented in the previous section, agents were producing guns either in the expectation of attacking their opponent, or to defend themselves from a forthcoming aggression. In the present model, agents may instead decide to arm to make war unattractive for their opponent. If war is not destructive, agent 1's optimal guns level deterring agent 2 always makes agent 1 willing to attack agent 2. As soon as some production gets destroyed during war, however, both agents strictly prefer preserving peace for some levels of guns. As a consequence, agent 1's deterrent guns level does not necessarily make him willing to attack agent 2. The claim in Proposition 3 follows.

This potentially affects the equilibrium outcome and the very existence of an equilibrium. In the subsection entitled 'Existence of an equilibrium ($\delta < 1$)' in the Appendix, we show that an equilibrium still exists.

In the remainder of this section we address the conditions under which the different equilibria may arise. In particular, we want to isolate the conditions under which war and deterrence equilibria emerge. We define as a deterrent equilibrium an equilibrium where both contestants arm to deter their opponent with a positive probability, and where, therefore, peace occurs with strictly positive probability. A first qualification that generalizes Jacobsson's (2009) finding is provided in the next proposition.

Proposition 4. A pure strategy deterrence equilibrium with positive guns never exists.

Proof. See the Appendix. □

In Proposition 1 we show that the deterrent best response is always dominated by the hawk best response when δ=1. War destruction creates scope for deterrent armaments to dominate hawk armaments for some guns levels as shown in Proposition 3. And yet, a pure strategy deterrence equilibrium never emerges if agents invest positive amount of their resources in the production of guns. The intuition underpinning this result goes as follows. Take any initial combination of guns (G^{1o}, G^{2o}). For this distribution of power, at least one agent strictly prefers peace (U^{ip}) to war (U^{iw}) since war is a negative-sum game. Assume that this is agent 1. The optimal level of guns to deter agent 1 is necessarily lower than G^{2o}. Indeed, agent 2 can cut his expenditure in guns and still deter agent 1. The reduction in G^2 increases agent 1's war payoff, until war becomes as attractive as peace to the latter. When agent 1 is made indifferent between war and peace, it must then be the case that agent 2 strictly prefers peace to war for this new distribution of power, since conflict is destructive. This process eventually reduces the guns to a level where at least one agent finds it profitable to follow his hawk best-reply function.

This whole process can be visualized in Figure 2. This graph represents the same game depicted on Figure 1, with the difference that war is assumed to be destructive (δ<1). The destructiveness of conflict allows for the emergence of an additional zone to the ones identified in Figure 1. In the area between the two new curves $G^{2d}(G^1)$ and $G^{1d}(G^2)$, both agents prefer peace to war. The lower locus captures all the combinations of guns making agent 2 indifferent between peace and war, while leaving agent 1 strictly better off under peace. This defines the deterrent armament levels of agent 1. Indeed, since war is destructive, where both agents were previously indifferent between peace and war, it is necessarily the case that they now strictly favour peace. As a consequence, in that area, an agent's best response cannot be described by the hawk armament levels. Indeed, on the one hand one's opponent would not declare war in that zone, hence there is no need to arm in anticipation of being attacked. On the other hand, the arming agent is not willing to initiate hostilities in that area, thus it is futile to waste resources in anticipation of a conflict. One can see in Figure 2 that for low levels of G^2, agent 1 will find it optimal to *not deter* agent 2, and, instead, to revert to the hawk armament levels since with few weapons agent 1 can have a significant strategic advantage over his foe.

A particular case emerges where at equilibrium agents completely forgo guns production. Indeed, if war is sufficiently destructive, the above-described undercutting process never pushes any agent to switch to his war strategy.[11] A pure strategy 'deterrence' equilibrium would then emerge. Although we present this case for completeness, such an equilibrium does not seem to add any major insight to the current discussion on deterrence. Therefore in the rest of the paper non-militarized equilibria will be disregarded.

A corollary follows from Proposition 4.

Corollary 1. If aggregate spending in guns is positive, war always occurs with positive probability.

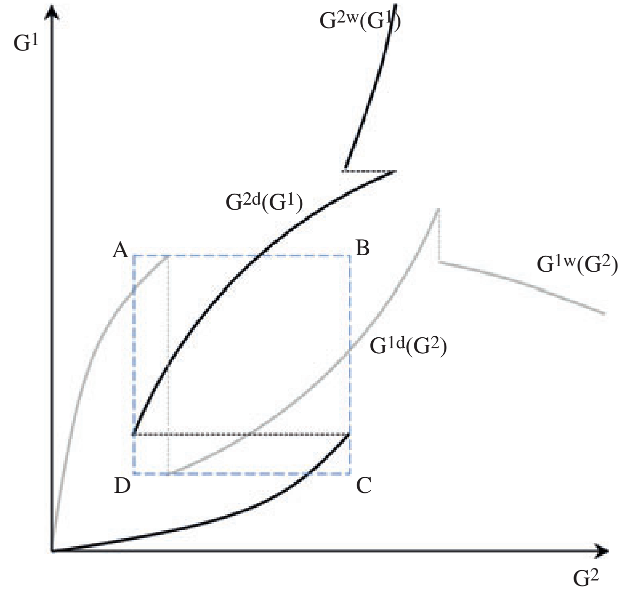

FIGURE 2. Mixed strategy equilibrium.

Indeed, this game always has an equilibrium, and we show that deterrence is never played by agents as pure strategies at equilibrium, if aggregate military spending is positive. This, in turn, rules out the only possibility to have peace with certainty, if guns have been produced.

A qualification of the equilibrium's nature can prove interesting. It can be shown that for any relative endowments in resources, there exists a destruction rate $(1-\underline{\delta})$ below which a pure strategy war equilibrium results (see the subsection 'Pure strategy war equilibria ($\delta < 1$)' in the Appendix). For these low destruction rates, the hawk armaments remain optimal for some militarization levels despite destruction. As a consequence, a war equilibrium arises.

When fighting is sufficiently destructive, the 'pure' war equilibrium collapses since at least one agent finds it optimal to deter his foe. In fact, any destruction rate above $(1-\underline{\delta})$ leads to a mixed strategy equilibrium, in which agents play with positive probability their hawk and deterrence pure strategies. This type of equilibrium can be visualized in Figure 2, where the four points A, B, C, D represent the game's potential outcomes. A scenario in which both agents choose their deterrence guns level in the first stage occurs with a positive probability. When this materializes (point D in the figure), both agents own sufficient guns to deter one another, while none finds it optimal to initiate a war. An armed peace equilibrium results. Similarly, peace would result if both agents chose their hawk armament levels, as point B lies in the area in which both agents prefer peace. The two remaining outcomes represent situations in which either agent 1 (point A) or agent 2 (point C) declares war. Notice, however, that while *ex post* peace can be the equilibrium outcome of the game, *ex ante* the probability of war breaking out is always strictly positive.

Interestingly, peace can be a potential outcome of this game even in the presence of arbitrarily small destruction rates $(1-\underline{\delta})$. The next proposition highlights this result.

Proposition 5. For any production and fighting technologies, there exists a relative resource endowment such that even when fighting provokes minor damages, peace occurs with strictly positive probability.

Proof. See the Appendix. □

Whenever a balance between the agents' relative production and relative power results at equilibrium, if conflict is not destructive, both agents are indifferent between war and peace. Under such a scenario both contestants arm in expectation of war. As soon as fighting entails some direct utility loss, however, a mixed strategy equilibrium ensues in which the agents mix their hawk and deterrence armament levels.

V. Concluding Remarks

In this paper, we explore the role of deterrence in contests. Using a general equilibrium model of 'guns and butter', we show that when war entails damages, an alternative motive for arming emerges: instead of preparing for war, agents arm to *deter* potential aggressions. If the losses associated with war are sufficiently large, only mixed strategy equilibria survive. Agents then purchase deterrent armaments with some probability and hawk armaments with the complementary probability. On the one hand, this implies that destruction creates scope for peace to emerge at equilibrium. On the other hand, a critical implication of our analysis is that even for extremely destructive war technologies, peace is never a certain outcome if weapons have been produced.

The assumption supporting the mixed strategy equilibrium, namely that war is destructive, is almost redundant. In addition to the loss of assets, war also entails other direct costs (e.g. casualties, diseases, decline in productivity, uncertainty). The literature on conflicts is well aware of these costs (Garfinkel and Skaperdas 2007; Blattman and Miguel 2010). And yet, some relevant contributions to conflict theory, although assuming that war is destructive, fail to consider the deterrence strategy.

Alternative consequences of war may create a sufficient gap between the aggregate production under peace and war for deterrence to occur ($\delta<1$). If, for instance, the trade volume between the two potential foes is negatively affected by war, as argued in the literature (Polachek 1997; Dorussen 1999), then both agents might refrain from attacking their commercial partner while maintaining the optimal armament level to deter one another. Complementarities in production (Rider 1999) lead to the same conclusions. Finally, assuming risk-averse agents creates the necessary disparity in returns to obtain deterrence, as they prefer the certain equivalent under peace to the risky bet of war.

APPENDIX

Quasi-concavity of U^{1w}

Regarding quasi-concavity, we closely follow the steps of Skaperdas (1992), and Skaperdas and Syropoulos (1997); we use Lemmas 1 and 2 to establish Lemma 3, which guarantees quasi-concavity of U^{1w}.

Lemma 1. Under Assumption 2, $p_{11}p \le 2(p_1)^2$ and $-p_{22}(1-p) \le 2(p_2)^2$.

We will make extensive use of p as given by (3), and to economize notation we do not write the arguments of function $F(\cdot)$, but rather adopt the notation $F(G^1) = F$ and $F(G^2) = H$. Differentiating (3) yields

$$p_1 = \frac{F'H}{(F+H)^2} = \frac{F'}{F}p(1-p) \tag{A1}$$

and

$$\begin{aligned} p_{11} &= \frac{(F''p(1-p) + p_1F'(1-2p))F - (F')^2p(1-p)}{F^2} \\ &= \frac{FF''p(1-p)}{F^2} - \frac{2p^2(1-p)(F')^2}{F^2}. \end{aligned}$$

Thus $p_{11}p \le 2(p_1)^2$ can be written as

$$FF'' \le 2(F')^2.$$

This last inequality is necessarily true by Assumption 2. The second claim of the lemma can be proved similarly.

Lemma 2. $U^{1w}_{11} < 0$ if $U^{1w}_1 \le 0$.

If $U_1^{1w} < 0$, then $p_1(C^{1w} + C^2)/p < C_1^{1w}$. Replacing this term in U_{11}^{1w}, we obtain

$$U_{11}^{1w} = p_{11}(C^{1w} + C^2) - 2p_1 C_1^{1w} + pC_{11}^{1w}.$$

This eventually gives

$$U_{11}^{1w} < \frac{C^{1w} + C^2}{p}\left[p_{11}p - 2(p_1)^2\right] + pC_{11}^{1w}.$$

Because of the production function's concavity, a sufficient condition for establishing the result is therefore that $p_{11}p \leq 2(p_1)^2$, which is shown in Lemma 1.

Lemma 3. $U_{11}^{1w} \leq 0$ for all G^1.

Denote by $\overline{G^1}$ the smallest value of G^1 such that $U_1^{1w}(G^1) < 0$. By Lemma 2 we can directly deduce that $U_1^{1w}(G^1) < 0$ for all $G^1 \geq \overline{G^1}$. To establish the present lemma's result, we thus need that $U_1^{1w}(G^1) \geq 0$ for all $G^1 < \overline{G^1}$, which is necessarily true since if there exists some $G^{1\prime} < \overline{G^1}$ such that $U_1^{1w}(G^{1\prime}) < 0$, then $\overline{G^1}$ is not the smallest value of G^1 such that $U_1^{1w}(G^1) < 0$.

Proof of Proposition 1
Assume that agent 1 wants to deter agent 2. Then, since $\delta = 1$,

$$p(G^{1w}, G^2)(C^1(G^{1w}) + C^2(G^2)) < C^1(G^{1d}).$$

The deterrent levels of guns for agent 1 must satisfy

$$(1 - p(G^{1d} - \varepsilon, G^2))(C^1(G^{1d} - \varepsilon) + C^2(G^2)) = C^2(G^2),$$

which can be rewritten as

$$p(G^{1d} - \varepsilon, G^2)(C^1(G^{1d} - \varepsilon) + C^2(G^2)) = C^1(G^{1d} - \varepsilon).$$

And since G^{1w} is the argmax of U^{1w}, it is necessary that the following inequality holds:

$$p(G^{1w}, G^2)(C^1(G^{1w}) + C^2(G^2)) \geq p(G^{1d} - \varepsilon, G^2)(C^1(G^{1d} - \varepsilon) + C^2(G^2)).$$

Combining these results yields

$$C^1(G^{1d}) > C^1(G^{1d} - \varepsilon),$$

which cannot be true since $C(\cdot)$ is decreasing in G.

Proof of Proposition 2
First we prove existence.

Lemma 4. Under Assumptions 1 and 2, a pure strategy equilibrium always exists.

For the existence part of Proposition 2, we need that the strategy set of each agent is compact and convex, and that each agent's utility function is continuous in all the agents' strategies, and quasi-concave in his own strategy.

From agent 1's viewpoint (analogous reasoning may be carried through for agent 2), the compactness and convexity of the strategy set is a direct consequence of $G^1 \in [0, R^1]$, while the continuity of U^{1w} follows from the continuity of p and C^1.

The above results together with Lemma 3 complete the proof of Lemma 4.

Now we prove uniqueness.

Lemma 5. Provided that an equilibrium exists, it is unique if $U^{1w}(G^{1*}, G^{2*}) \neq C(G^{1*})$.

We first prove that if an interior equilibrium exists, it is the unique equilibrium if $U^{1w}(G^{1*}, G^{2*}) \neq C(G^{1*})$. We then show that when $U^{1w}(G^{1*}, G^{2*}) \neq C(G^{1*})$, if no such interior equilibrium exists, the unique equilibrium (G^{1*}, G^{2*}) is such that *either*$G^{1*} = R^1$*or*$G^{2*} = R^2$.

To show the uniqueness of an interior equilibrium, it is sufficient to prove that the composite function $\Gamma^1(G^1) = G^1(G^2) \circ G^2(G^1)$ is continuous, singled-valued, and such that whenever it admits a fixed point, $(\partial G^{1w}/\partial G^2)(\partial G^{2w}/\partial G^1) < 1$. Continuity and single-valuedness of $G^i(G^j)$ follow from the continuity of U^{1w} in G^1 and G^2, and from the quasi-concavity of U^{1w} in G^1.

Lemma 6. $U_1^{1w} = 0$ implies $\partial G^{1w}/\partial G^2 = 0$, and $U_2^{2w} = 0$ implies $\partial G^{2w}/\partial G^1 = 0$.

By using the implicit functions theorem on $G^1(G^2)$ and on $G^2(G^1)$, we obtain

$$\text{(A2)} \qquad \frac{\partial G^{1w}}{\partial G^2} = -\frac{U_{12}^{1w}}{U_{11}^{1w}}, \quad \frac{\partial G^{2w}}{\partial G^1} = -\frac{U_{12}^{2w}}{U_{22}^{2w}}.$$

We construct the reasoning for U_{12}^{1w} alone since the proof follows the same lines for U_{12}^{2w}. By using U_1^{1w} as given by equation (5), we obtain

$$\text{(A3)} \qquad U_{12}^{1w} = p_{12}(C^{1w} + C^2) - p_1 C_2^2 - p_2 C_1^{1w}.$$

Given, however, that we assume that we are at equilibrium, and superscripting the equilibrium variables by a star, by equation (5) and analogous reasoning for agent 2 we must have

$$\text{(A4)} \qquad C_1^{1w*} = \frac{p_1^{w*}(C^{1w*} + C^{2w*})}{p^{w*}}, \quad C_2^{2w*} = -\frac{p_2^{w*}(C^{1w*} + C^{2w*})}{1 - p^{w*}}.$$

Replacing these two optimality conditions in (3) yields

$$U_{12}^{1w} = p_{12}^{w*}(C^{1w*} + C^{2w*}) + \frac{p_1^{w*} p_2^{w*}(C^{1w*} + C^{2w*})}{1 - p^{w*}} - \frac{p_1^{w*} p_2^{w*}(C^{1w*} + C^{2w*})}{p^{w*}},$$

which, rearranged, gives

$$U_{12}^{1w} = \frac{C^{1w*} + C^{2w*}}{p^{w*}(1 - p^{w*})}[p^{w*}(1 - p^{w*})p_{12}^{w*} + p_1^{w*} p_2^{w*}(2p^{w*} - 1)].$$

The term in square brackets, however, can be shown to be zero. Indeed, setting the term equal to zero and rearranging it, we obtain

(A5) $$-\frac{p^{w*}p^w_{12}}{p^{w*}_1 p^{w*}_2} = \frac{2p^{w*}-1}{1-p^{w*}}.$$

It can be shown that

$$\frac{p_{12}}{p_2} = \frac{(1-2p)F_1}{F}.$$

Replacing p_{12}/p_2 and p_1 as given by (A1) in the left-hand side of (A5) establishes the result.

Assume that an interior equilibrium (G^{1*}, G^{2*}) exists. For this equilibrium to be unique, the function $\Gamma(\cdot)$ should admit no fixed point in either 0 or R^1, unless $G^{1*}=0$ or $G^{1*}=R^1$. Notice that under Assumption 2, $G^{1w}(G^2)>0$ for all G^2. This dismisses $G^{1*}=0$ from being an equilibrium.

To complete the proof, we show that for any $G^1 > G^{1*}$, $\partial\Gamma(G^1)/\partial G^1 < 0$. By equations (A2) we know that

$$\text{sgn}\left(\frac{\partial\Gamma(G^1)}{\partial G^1}\right) = \text{sgn}\left(\left(-\frac{U^{1w}_{12}}{U^{1w}_{11}}\right)\times\left(-\frac{U^{2w}_{12}}{U^{2w}_{22}}\right)\right) = \text{sgn}\left(U^{1w}_{12}U^{2w}_{12}\right).$$

By using the first-order conditions for agent 2 (i.e. the analogue of condition (5)), we can obtain

$$U^{2w}_{12} = -p_{12}(C^{1w}+C^2) + p_1 C^2_2 + p_2 C^{1w}_1 = -U^{1w}_{12}.$$

Since $G^1 > G^{1*}$ by Lemma 2, we have $U^{1w}_1 < 0$. Moreover, since agent 2 is assumed to be at optimality, $U^{2w}_2 = 0$. Substituting for both C^{1w}_1 and C^{2w}_1 from equations (A4), we deduce that $U^{2w}_{12} < 0$. It follows directly that $\partial\Gamma(G^1)/\partial G^1 < 0$ for all $G^1 > G^{1*}$.

If, instead, an interior equilibrium does not exist, then the only possible equilibrium is one in which an agent invests all his resources in guns. This follows directly from the existence proof and the fact that at equilibrium agents always produce guns.

Lemma 7. If $U^{1w}(G^{1*}, G^{2*}) = C(G^{1*})$, then the number of equilibria is infinite.

If agent 1 is indifferent between peace and war, so is agent 2. Lemma 7 thus follows immediately from the definition of a Nash equilibrium since any mix between war and peace for agent 1 is a best response to any mix between war and peace for agent 2, and vice versa. The probability space being continuous, the number of equilibria is infinite.

Proof of Proposition 3

By the definition of the deterrence armaments levels,

$$\delta(1-p(G^{1d}-\varepsilon, G^2))(C^1(G^{1d}-\varepsilon)+C^2(G^2)) = C^2(G^2).$$

Notice that $\lim_{\delta\to 0} G^{1d} = 0$, which implies $\lim_{\delta\to 0} U^{1p} = C^1(0)$. On the other hand, $\lim_{\delta\to 0} U^{1w} = 0$.

Existence of an equilibrium ($\delta < 1$)

We construct this proof for agent 1 alone since it extends straightforwardly to agent 2.

To establish the equilibrium existence, we apply Kakutani's fixed point theorem to the correspondence $\Gamma^1 = G^1(G^2)\circ G^2(G^1)$.

Notice first that the strategy set $G^1 \in [0, R^1]$ is non-empty, compact and convex.

To prove the continuity of Γ^1, it is sufficient to show that $G^1(G^2)$ is continuous on the interval $[0, R^2]$. From (6) we know that $G^1(G^2)$ is equal to either $G^{1w}(G^2)$ or $G^{1d}(G^2)$.

Regarding $G^{1w}(G^2)$, it is non-empty for all $G^2 \in [0, R^2]$. Moreover, $G^{1w}(G^2)$ is continuous on $[0, R^2]$ if $U^{1w}(G^1, G^2)$ is continuous in (G^1, G^2) and quasi-concave in G^{1w}. The continuity and quasi-concavity proofs can be found in in the first and third subsections of this Appendix.

Regarding the deterrent best response $G^{1d}(G^2)$, it is also non-empty for all $G^2 \in [0, R^2]$. To prove continuity of $G^{1d}(G^2)$, we apply the implicit functions theorem on the implicit function $\varphi(G^{1d}, G^2)$.

This theorem states that if

- $\varphi(G^{1d}, G^2) = 0$,
- $\varphi(G^{1d}, G^2)$ is continuous,
- $\partial\varphi(G^{1d}, G^2)/\partial G^{1d} \neq 0$ at $G^{1d} = \widehat{G}^1$,
- $\varphi(G^{1d}, G^2)$ has continuous first partial derivative with respect to G^{1d} in a neighbourhood $\widehat{G}^1$, then $G^{1d}(G^2)$ is continuous in G^2.

Denote

$$\varphi(G^{1d}, G^2) = C^2(G^2) - \delta(1 - p(G^{1d}, G^2))[C^1(G^{1p}) + C^2(G^2)] = 0.$$

Notice that $\varphi(G^{1d}, G^2)$ is continuous as each of its components is continuous. Moreover,

$$\frac{\partial\varphi(G^{1d}, G^2)}{\partial G^{1d}} = \delta(p_1(G^{1d}, G^2)[C^1(G^{1d}) + C^2(G^2)] - (1 - p(G^{1d}, G^2))C_1^1(G^{1d})) > 0$$

since $p_1 > 0$ and $C_1^1 < 0$.

Continuity of $\partial\varphi(G^{1d}, G^2)/\partial G^{1d}$ follows from the continuity of all the elements. $G^1(G^2)$ is continuous in G^2 because both $G^{1w}(G^2)$ and $G^{1d}(G^2)$ are continuous in $G^2 \in [0, R^2]$, and because $G^1(G^2) = \lambda G^{1d}(G^2) + (1-\lambda)G^{1w}(G^2)$ for all G^2 such that $U^{1d}(G^{1d}(G^2), G^2) = U^{1w}(G^{1w}(G^2), G^2)$, for all $\lambda \in [0,1]$.

To complete the proof, the convex-valuedness of Γ^1 still needs to be established. Since both $G^1(G^2)$ and $G^2(G^1)$ have been shown to be convex-valued, Γ^1 is necessarily convex-valued.

Proof of Proposition 4

Suppose that an equilibrium with both agents playing their mutually deterrent armament levels (G^{1d*}, G^{2d*}) exists, and $G^{1d*} + G^{2d*} > 0$. By the definition of such armaments, it is necessary that

$$C^1(G^{1d*}) > \delta p(G^{1w}(G^{2d*}), G^{2d*})(C^1(G^{1w}(G^{2d*})) + C^2(G^{2d*})).$$

Therefore there always exists an ε such that the following is true:

$$C^1(G^{1d*}) > \delta p(G^{1w}(G^{2d*} - \varepsilon), G^{2d*}\varepsilon)(C^1(G^{1w}(G^{2d*} - \varepsilon)) + C^2(G^{2d*} - \varepsilon)).$$

Moreover, by the definition of a deterrent equilibrium, G^{2d*} is such that the following equation must hold:

$$C^1(G^{1d*}) = \delta p(G^{1d*}, G^{2d*} - \varepsilon)(C^1(G^{1d*}) + C^2(G^{2d*} - \varepsilon)).$$

Combining those two expressions, we obtain

$$\begin{aligned} &p(G^{1d*}, G^{2d*} - \varepsilon)(C^1(G^{1d*}) + C^2(G^{2d*} - \varepsilon)) \\ &> p(G^{1w}(G^{2d*} - \varepsilon), G^{2d*} - \varepsilon)(C^1(G^{1w}(G^{2d*} - \varepsilon)) + C^2(G^{2d*} - \varepsilon)), \end{aligned}$$

which contradicts $G^{1w}(G^2)$ being the argmax of U^{1w}.

Pure strategy war equilibria ($\delta < 1$)
We show that a pure strategy war equilibrium exists if and only if $1 > \delta \geq \underline{\delta}$.

We first prove the if part.

Take δ^1 such that

$$C^1(G^{1d}(G^{2w*})) = \delta^1 p(G^{1w*}, G^{2w*})(C^1(G^{1w*}) + C^2(G^{2w*})).$$

Such a δ^1 exists and is unique. Indeed, when $\delta = 0$,

$$C^1(G^{1d}(G^{2w*})) > \delta p(G^{1w*}, G^{2w*})(C^1(G^{1w*}) + C^2(G^{2w*})).$$

Moreover, by Proposition 1, if δ=1, then $U^{1w*} \geq U^{1d}$. Since $C^1(\cdot)$ is continuous, δ^1 exists.

To show uniqueness of δ_1, it is sufficient to prove the monotonicity of $\partial(U^{1d} - U^{1w*})/\partial\delta$. Notice that G^{1d} is implicitly defined as follows:

$$C^2(G^2) = \delta(1 - p(G^{1d} - \varepsilon, G^2))(C^1(G^{1d} - \varepsilon) + C^2(G^2)).$$

We thus obtain that $\partial G^{1d}/\partial\delta > 0$, which implies that $\partial C^1(G^{1d})/\partial\delta < 0$. Moreover, using (equation 1) we deduce that $\partial U^{1w}/\partial\delta > 0$, thus implying that $\partial(U^{1d} - U^{1w*})/\partial\delta < 0$ for all δ.

If

$$C^2(G^{2d}(G^{1w*})) \leq \delta^1(1 - p(G^{1w*}, G^{2w*}))(C^1(G^{1w*}) + C^2(G^{2w*})),$$

then $\underline{\delta} = \delta^1$.

Otherwise, following the above reasoning, there exists a unique $\delta^2 = \underline{\delta}$ with $\delta^2 > \delta^1$ and such that

$$C^2(G^{2d}(G^{1w*})) = \delta^2(1 - p(G^{1w*}, G^{2w*}))(C^1(G^{1w*}) + C^2(G^{2w*})).$$

We can therefore conclude that there exists a unique $\underline{\delta} = \max\{\delta^1, \delta^2\}$.

The only if part is straightforward. War being an equilibrium implies

$$C^1(G^{1d}(G^{2w*})) \leq \delta p(G^{1w*}, G^{2w*})(C^1(G^{1w*}) + C^2(G^{2w*})), \tag{A6}$$

$$C^2(G^{2d}(G^{1w*})) \leq \delta(1 - p(G^{1w*}, G^{2w*}))(C^1(G^{1w*}) + C^2(G^{2w*})). \tag{A7}$$

Reduce the value of δ until either expression (A6), or expression (A7) (or both) holds with equality, and denote this δ as δ'. Any $\delta < \delta'$ makes the pure strategy war equilibrium collapse. Setting $\underline{\delta} = \delta'$ completes the proof.

Proof of Proposition 5
Fix the total resource endowment $R = R^1 + R^2$. Suppose first that for δ=1 there exists a relative endowment for which agent 1 is indifferent between war and peace at equilibrium. Formally: m100

$$C^1(G^{1w*}(G^{2w*})) = \delta p(G^{1w*}, G^{2w*})(C^1(G^{1w*}) + C^2(G^{2w*})).$$

This implies that agent 2 is also indifferent:

$$C^2(G^{1w*}(G^{2w*})) = \delta(1 - p(G^{1w*}, G^{2w*}))(C^1(G^{1w*}) + C^2(G^{2w*})).$$

For any δ<1, the unique war equilibrium (see Proposition 2) collapses. Since we showed in the earlier subsection entitled 'Existence of an equilibrium (δ<1)' that an equilibrium always exists, it follows that peace occurs with positive probability.

Suppose, on the contrary, that for δ=1 agent 2 prefers war to peace at equilibrium for any relative endowment. Then agent 1 necessarily prefers peace to war. Consider the limiting case for which $R^1 \to 0$. This implies that $G^{1w} \to 0$ and hence $p(G^{1w}, G^{2w}) \to 0$ and $C^1(G^{1w}) \to 0$. The utility of agent 1 at equilibrium is thus given by

$$\lim_{R^1 \to 0} U^{1w} = \lim_{R^1 \to 0} [\delta p(G^{1w*}, G^{2w*})(C^1(G^{1w*}) + C^2(G^{2w*}))] = 0.$$

On the other hand, the utility of agent 2 is given by

$$\begin{aligned}\lim_{R^1 \to 0} U^{2w} &= \lim_{R^1 \to 0} [\delta(1 - p(G^{1w*}, G^{2w*}))(C^1(G^{1w*}) + C^2(G^{2w*}))] \\ &= \delta C^2(G^{2w*}).\end{aligned}$$

Thus, at the limit, agent 2 is indifferent between war and peace at equilibrium for δ=1. It follows that for any δ<1, agent 2 strictly prefers peace to war. To complete the proof, observe that since at the limit both agents prefer peace to war, the unique war equilibrium collapses.

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NOTES

1. Alternative solutions include (exogenous) commitment to transfer resources (Fearon 1995; Powell 2006), (exogenous) commitment not to attack each other (Beviá and Corchon 2010), reducing information asymmetries (Powell 1999; Fortna 2008), and bargaining (Powell 1996; Esteban and Sákovics 2008).
2. This argument holds unless the contestants' fighting technology is extremely poor and/or the cost of fighting is disproportionately elevated, in which case no contestant finds it optimal to deviate from the weaponless—peaceful—equilibrium (Meirowitz and Sartori 2008).
3. The interested reader can refer to the first chapters of Zagare and Kilgour (2000) for a more complete review of works on deterrence.
4. For a detailed comparison between general and partial equilibrium conflict models, see Neary (1997).
5. All results in the paper are derived solely for agent 1 for notational convenience.
6. Indeed, making the opponent exactly indifferent between peace and war implies that the opponent would play the war action with a positive probability in the game's subsequent stage.
7. Notice that $G^{1d} < R^1$ since $C^2(G^2) > \delta p(R^1, G^2)(0 + C^2(G^2))$ for all G^2.

8. The literature on conflicts has recently pointed at the 'dove' armaments, where the dove completely abstains from arming in the expectation of not always being attacked (Meirowitz and Sartori 2008; Jackson and Morelli 2009). This action is always dominated in our setting. Indeed, either the opponent is expected to arm, and therefore the best response cannot be to remain weaponless since this would yield a payoff of zero because of Assumption 2, or the opponent is expected to be weaponless, and purchasing an ε amount of weapons implies that the armed contestant grabs all the production of the two agents with unit probability.
9. Analytically, this indifference occurs when $p(G^{1*}, G^{2*})(C^1(G^{1*}) + C^2(G^{2*})) = C^1(G^{1*})$. In that case, there exists an infinity of equilibria since in the game's second stage any combination of war and peace yields the same payoff. For instance, this configuration arises for symmetric agents, as in Jacobsson (2009).
10. In the simulation we consider the following specific functional forms: $p(G^1, G^2) = G^1/(G^1 + G^2)$, and $C(G^1) = R^1 - G^1$. Accordingly, the relationship between G^1 and G^2 satisfying the indifference condition is such that $G^1 = G^2(R^1/R^2)$.
11. This is the case if

$$\delta < \min\left\{\frac{C^1(0)}{C^1(0) + C^2(0)}, \frac{C^2(0)}{C^1(0) + C^2(0)}\right\}.$$

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