Agents and Conflict: Adaptation and the Dynamics of War

Civil wars pose one of the most challenging threats to peace in the post-WWII era. The successful resolution of ongoing civil wars is particularly difficult. Parties opposing peace successfully subverted negotiated agreements in contexts as diverse as Rwanda, Northern Ireland, and Bosnia. Despite growing attention to civil wars in the empirical literature, little formal-theoretic work addresses the dynamics of civil wars. Empirical work demonstrates that the resolution of civil wars is both complex and uncertain: civil war combatants are heterogeneous in their traits, incompletely informed, and thus, boundedly rational, capable of learning from history and adapting their behavior—all hallmarks of a complex adaptive system. I employ an agent-based model, therefore, to capture these characteristics and address the conditions affecting the dynamics and evolution of civil wars. In particular, I focus on the evolutionary context of civil wars including learning and adaption and find that civil wars with adaptive combatants exhibit vastly different behavior than those without adaptive agents.

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1. INTRODUCTION

Civil wars pose one of the most challenging threats to international peace. Empirical work shows that the average duration of ongoing civil wars in 1999 was 16 years [1], suggesting that civil wars become endemic in many places. The failure to resolve civil wars can have extremely devastating consequences on populations and countries. Angola's reversion to civil war in 1992, for example, resulted in the deaths of ~300,000 people. Following the 1993 Arusha Accords in Rwanda, moreover, a Hutu faction subverted the Arusha peace agreement, triggering a genocide in which 500,000–800,000 Rwandans died.

Scholars have offered various explanations for the difficulty of resolving civil wars including: the lack of a credible commitment to abide by a peace agreement, the presence of natural resources that motivate and finance rebellion, the involvement of third-party interstate actors, and the "indivisibility" of the issues in dispute.[1] Increasingly, much of the current literature examines civil war resolution using

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[1] *In this article I do not attempt to review the literature comprehensively. More extensive literature reviews on this general topic can be found elsewhere* [2, 3].

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game-theoretic or statistical models (or both). With few exceptions, these approaches (sometimes explicitly, sometimes implicitly) analyze civil wars as contests between only two unitary actors, which possess unchanging characteristics and exceptional information processing abilities. Arguably, "the statistical literature often relies on unrealistically static or simplified assumptions—for example, that the interests and identities of the parties to the war are fixed. Yet the case study literature points to the evolution of identities, institutions, and political economies during war ..." [3, p 252–253]. Case studies also show that there are often multiple combatants with the set of actors changing over time. In Chechnya during the late 1990s and early 2000s, for example, the rebels evolved from one fairly coherent faction to three loosely connected factions. While highlighting many complexities of civil war resolution overlooked by statistical and formal work, unfortunately, case studies tend to be unsystematic and, as the term implies, focus on a single case.

In this article, I address the evolution and dynamics of actors in civil wars with an emphasis on fluctuations in the set and characteristics of actors over time. I use an agent-based computational model that incorporates many aspects of civil war peace processes and that traces the dynamics and evolution of civil wars within a multi-agent context.[2] In particular, the model includes multiple civil war combatants who are heterogeneous in traits such as resource endowments and propensities for aggressively pursuing violence. Furthermore, agents are not completely informed and have varying capacities to learn from history. As agents learn, their beliefs about the likely terms of an agreement affect decisions to continue war or pursue peace. Learning, in turn, facilitates adaptation.

The model developed in this article focuses primarily on a comparison of adaptive and nonadaptive agents. Adaptation—as I use the term in this article—refers to periodic changes in the number and characteristics of participating combatants. In some civil wars, the set and characteristics of the combatants are relatively constant displaying little or no adaptive characteristics. Some groups have numerous institutional barriers—rules from governing bodies or procedures of operation within combat units—that impede the efficient execution of group strategies. In Chechnya, for instance, the Russian military could not adapt to Chechnya's urban combat strategy [7]. In other cases, agents might have the ability to adapt, but too little time. Some civil wars begin with coups followed by unexpected, and heavy, violence. In these cases, it is possible that groups are caught off guard and cannot adapt to the quick changes. In other civil wars, combatants appear to be considerably more adaptive. In the current Iraq war, for example, various insurgent factions have likely been successful due to their ability to adapt to coalition strategies by decentralizing their operations. In Chechnya during the 1994–1996 war, otherwise unfriendly clans adapted by centralizing their capability structures. Adaptation might also occur when new social movements form and begin violence or when a third-party intervenes to provide support for an existing party. Although some works include groups' abilities to adapt discussing, for example, government responses to insurgency in Africa [8], little work focuses exclusively and systematically on adaptation from a theoretical perspective.

In this article, I find that adaptive combatants produce civil war dynamics that differ greatly from those produced by nonadaptive combatants. When groups are adaptive, the intensity of violence is frequently severe, manifesting itself through sudden outbursts of violence, similar to punctuated equilibrium dynamics.[3] Violence occurs, but periods of relative agreement are also highly likely. When combatants are not adaptive, fewer outbursts of violence occur and the outbursts are less severe, but certain groups tend to dominate interactions, making unilateral victory a frequent outcome. From the model, I make two claims and briefly explore their plausibility using empirical data on civil wars between 1945 and 1999 as well as data on the Rwanda and Iraq civil wars.

2. AN AGENT-BASED MODEL

The model consists of agents representing warring factions in a civil war peace process. I begin by outlining the basic model wherein, similar to game-theoretic models of bargaining during wartime [10–12], agents interact in battles and negotiations. In the simplest version of the model, agents make decisions under conditions of complete information, given resources and offers regarding the distributional terms of an agreement. I then incorporate uncertainty into the model by allowing agents to have beliefs about the changing distribution of resources (given the outcomes of battles), and I explore how decision-making changes in this context. Finally, I discuss the inclusion of parameters to explore more systematically in the analysis of the model: agent aggressiveness and a selection mechanism that allows for the possibility of adaptation. Because civil wars are often long and difficult to resolve, I vary whether (and how much) adaptation is possible to understand whether it compounds problems of uncertainty. The model allows the set and characteristics of actors to evolve over time, thereby changing the landscape of war. I track levels of violence, as

[2] *Agent-based models of intrastate violence are not unprecedented and examine topics such as ethnic conflict and genocide* [4] *and insurgency* [5, 6].

[3] *The concept of punctuated equilibrium dynamics carries a specific meaning in the context of evolutionary dynamics* [9]. *I use the term more generally in this article to refer to sudden increases in violence amidst longer periods of relative calm.*

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TABLE 1

Summary of Notation

Symbol	Name
π	Resources
ρ	Resource ratio
σ	Proposed agreement
ω	Investment amount
γ	Probability of battle victory
δ	Difference in resources invested
$\dot{\rho}$	Beliefs about resource ratio
α	Battle gains
β	Battles losses
ϕ	Weight for new information
θ	Aggressiveness

well as the likelihood that certain agents dominate the control of resources. See Table 1 for a summary of the notation used in the model.

2.1. The Basic Model

A set of heterogeneous agents, i, represents parties engaged in a civil war and, subsequently, the peace process. Each i is endowed with resources, π_i (drawn uniformly in $[0, 100]$), that include not only material capabilities, but also less formal factors, such as support conferred by group social structures. Since the aggregation of agent resources can represent terms of an agreement Π, let $\Pi = \sum_i \pi_i$. Resources can fluctuate over time, therefore, let $\pi_{i,t}$ indicate agent i's resources at time t. Despite fluctuations of individual resources, I assume that the overall terms of the agreement are fixed, and thus $\sum_i \pi_{i,t} = \Pi$ for any t. Let

$$\rho_{i,t} = \frac{\pi_{i,t}}{\Pi} \tag{1}$$

be agent i's share of the resources at time t, and if $\pi_{i,t} = \Pi$, then i is completely dominant, controlling everything such as the state's means of coercion, institutions, and economic arrangements. Finally, agent utility is strictly increasing in π_i.

Because peace processes consist of multiple phases [13], agents interact in a fixed sequence of events such that they (1) attempt to negotiate an agreement and (2) engage in violence. These events occur in discrete time ($t : t = 1, 2, \ldots, n$), where t_1 = negotiation, t_2 = battle, t_3 = negotiation....

2.1.1. Negotiations

Each run begins with negotiations that allow agents to avert war by settling beforehand. In each round of negotiations, an agent proposes a distribution of agreement terms. The agent is chosen by a "weighted random" mechanism whereby agents with greater resources are chosen proportionally more often to make offers, because they are better able to seek revision (or maintenance) of the status quo.[4]

The proposer offers a possible agreement σ^{Π} to all agents, where σ_i represents the share offered to agent i. An agent accepts or rejects the offer by investing resources, ω_i, in battle. (Hereafter, I also refer to the investment of resources in battle, ω_i, as "violence.") Agents invest

$$\omega_i = \rho_i - \sigma_i. \tag{2}$$

by comparing the amount of the agreement they are offered, σ_i, to their share of the distribution of resources, ρ_i [Eq. (1)]. The agent proposing the possible agreement never proposes an unacceptable offer to itself and, for now, assume that investment only occurs when $\rho_i > \sigma_i$. Thus, "negative investment" is not a possibility, although I relax this assumption below.

Typically, combatants in a civil war fight over issues or try to meet specific objectives. Some degree of political representation or territorial autonomy often satisfies the participating groups. Under complete information, because agents know how much of the distribution of resources they control, ρ_i determines the minimal offer an agent is willing to accept in order to avoid battle. If an agent controls a certain proportion of the resources, then it will not accept an offer that is less than what it currently controls. This arrangement captures the notion that group demands are a function of what a group is *able* to demand. For example, a group that controls only 1% of the resources is not likely to succeed in demanding 50% from a proposed agreement. Yet if that same group somehow captures 95% of the resources, then it can at least expect 95% from a proposed agreement.

2.1.2. Battles

If any i invests resources in battle, then dyadic battles occur between agents. Thus, even if an agent does not invest resources in battle, it might still end up fighting other agents. Empirically, this is similar to an offensive attack on a group in which a group must attempt to defend itself (even if it is not prepared to do so). If resources are invested into battle in a given time period, then on average, all agents fight at least one battle. The outcome of battle is determined probabilistically as a function of agent investment, where the more an agent invests in battle, the more likely it is to win. Therefore, let the probability that agent i wins the battle against agent j at time t be

$$\gamma_i = \frac{\omega_{i,t}}{\omega_{i,t} + \omega_{j,t}}. \tag{3}$$

Over the course of the war, resources increase or decrease following individual battles based on whether an agent

[4] *In a given run, it is highly unlikely that the weakest agent will propose settlement terms, but it remains a possibility. Allowing the possibility that weak agents can propose possible terms of a settlement is justifiable empirically because weak groups may want to avoid further war that is likely to result in their complete defeat. Because weak agents have the desire, and actually propose settlements, this does not imply that they have the ability to make them stick. Whether or not agents agree with the weak-actor's proposal is an individual choice.*

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wins or loses. Resources change according to the following rule:

$$\pi_{i,t+1} = \pi_{i,t} + |\omega_{i,t} - \omega_{j,t}| \quad \text{if } i \text{ wins}$$
$$= \pi_{i,t} - |\omega_{i,t} - \omega_{j,t}| \quad \text{if } j \text{ wins.} \tag{4}$$

This rule allows agents to increase or decrease in resources proportional to their relative investments and based on the outcome of battle.[5] The amount that resources increase or decrease is based on the absolute value of the difference in the amounts of resources invested in battle $\omega_{i,j}$. Because many battles are fought in a given war (over time and on multiple fronts) this rule captures gains or losses of smaller scale. In other words, changes in resource levels are based only on investment and not on the entire set of resources controlled by the actor.[6]

The distance between levels of investment is important because it captures the idea that the outcomes of battles are based on initial inputs. As a hypothetical example, if agent 1 invests 9 units of resources in a battle whereas agent 2 invests 1 unit of resources in battle, then the increase (decrease) of resources from victory (defeat) for that particular battle is 8 units. On the other hand, if agent 1 invests 6 units of resources and agent 2 invests 4 units, then the winner only increases by 2 units of resources. The two different cases illustrate the idea that the greater the differential, the more ability there is to inflict damage (for the actor that invests more). Moreover, it is also more difficult to absorb damage (for the actor that invests less). In the latter case, agent 2's level of investment is closer to parity (4 units to 6 units rather than 1 unit to 9 units) and, thus, it can absorb more damages even though it might still lose.

Now, assume the simplest case in which agents have complete information about the entire distribution of resources, ρ. In this case, any agent proposing distributional terms of an agreement will offer each agent its precise share of the distribution of resources. For each agent, $\rho_i - \sigma_i = 0$, and no battle occurs. Thus, based on the simplest version of this model, incomplete information is a necessary condition for war to occur. It is also possible that agents have other ambitions in addition to obtaining shares of an agreement that match their share of the resource distribution. I now explore the effects of decision-making under incomplete information.

2.2. Introducing Uncertainty

Empirically, combatants possess incomplete information about resource levels, and reducing uncertainty is not an easy task. Indeed, Clausewitz argued, "a great part of the information obtained in war is contradictory, a still greater part is false, and by far the greatest part is subject to considerable uncertainty" [14]. Thus, I proceed by modeling agent behavior under conditions of uncertainty.

Assume that the agent proposing distributional terms of an agreement does not know the true distribution of resources, ρ. Each agent knows its own level of resources, but does not know the levels for other agents, and therefore does not know relative shares of the overall distribution. In this case, the proposer offers a possible agreement σ^{Π}, based on its beliefs about the distribution of resources. In other words, the proposer offers a share of the overall agreement, σ_i to each agent with the shares summing to Π. If the proposing agent believes, for example, that it has 75% of the distribution, and all others have 25% collectively, then the proposer offers 75% of the distribution to itself ($\sigma_i = 75\%$) and divides up the remaining 25% among the others according to its beliefs.

Agents form and update their beliefs based on the mean of the Beta distribution in a way similar to [15]:

$$\dot{\rho}_i = \frac{\alpha_{i,t}}{\alpha_{i,t} + \beta_{i,t}}. \tag{5}$$

In this distribution, α can be conceived of as the amount of resources an agent controls and β the amount of resources an opponent controls. α and β are initially assigned by recovering resource values for each parameter such that beliefs match the true distribution ($\dot{\rho}_i = \rho$) for all agents. Then beliefs are perturbed from the true ratio by drawing new values of α and β that fall within a maximum range of up to 25% (of total resources) in either direction.[7] For example, ex ante, two groups involved in a war might actually have 50% of the overall resources ($\pi_i = 50$ and $\pi_j = 50$). But one of the agents might believe that it has 75% of the distribution. In this case, the agent might be assigned initial values of $\alpha_i = 75$ and $\beta_i = 25$, and therefore, $\dot{\rho}_i = \frac{75}{(75+25)} = 0.75$.

Once agents begin interacting with each other, they use new information about gains or losses of resources and accordingly either increase or decrease their beliefs about the true distribution of resources, ρ_i. The logic is similar to Bayesian updating: agents have prior beliefs about the distribution of resources, but given *new* information, they update to form posteriors. In other words, if an agent gains resources, then it adds the gains to α_i and recalculates its beliefs. If the agent loses resources, it adds the losses to β_i and recalculates. In the first case, beliefs increase whereas in the second case they decrease.

It is possible for beliefs to converge or diverge from the true distribution. Assume that each agent has a

[5] *If both agents invest the same amount, the outcome is the same for both. One possibility would be to add a cost parameter. The frequency with which two agents both invest the exact same amount, however, is extremely low and therefore I chose not to add another parameter.*

[6] *If the model captured the war as a one-shot lottery or even limited to two or three interactions, then this rule would be less useful as the loser's entire set of resources is not at stake.*

[7] *Although the default range for drawing new values for beliefs is 25% of total resources in either direction (from α and β), I vary this range in sensitivity analysis.*

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belief weight $\phi_i \in U[0,2]$ (heterogeneous across agents) that allows agents to weight new information differently (higher or lower depending on whether $\phi_i < 1$ or $\phi_i > 1$). The higher the weight the more an agent believes it gains (or loses) from battle. More precisely, agents weight their beliefs as a function of the difference in resources gained or lost. Let $\delta_i = |\omega_{i,t} - \omega_{j,t}|$ and accordingly agents update their beliefs to

$$\dot{\rho}_i = \frac{\alpha_{i,t} + (\phi_i \cdot \delta)}{\alpha_{i,t} + (\phi_i \cdot \delta) + \beta_{i,t}} \quad \text{if } i \text{ wins} \tag{6}$$

$$= \frac{\alpha_{i,t}}{\alpha_{i,t} + \beta_{i,t} + (\phi_i \cdot \delta)} \quad \text{if } j \text{ wins.} \tag{7}$$

Because new information is added to both the numerator and denominator in the case of battle victories, beliefs increase, whereas the opposite is true for losses. Depending on how aggressively agents update their beliefs, moreover, divergence from the true distribution is also possible. For example, a combatant with a $\phi_i > 1$ might have a small success on the battlefield, but conclude that it accomplished more than it did, thereby resulting in a higher aggregate belief about its own share of the overall distribution of resources than it actually has.

With the inclusion of incomplete information, Eq. (2) will no longer result in zero investment, because $\dot{\rho}_i \neq \rho_i$ and, therefore, frequently $\dot{\rho}_i - \sigma_i \neq 0$. In such a case, rather than never engaging in battle, agents would fight each other with battles occurring based on Eqs. (3) and (4). In this case, a cycle of negotiations and battles would occur over time. The inclusion of incomplete information paints a more accurate picture of the civil war process and some of the results of the model are based on this scenario. Empirically, however, there are other factors that are important to capture and that this paper seeks to analyze more fully—aggressiveness and adaptation—which comprise the primary focus of the model analysis.

2.3. Aggressiveness and Adaptation

Some combatants might still prefer to pursue violence regardless of the size of the share that is offered to the combatant. Let $\theta_i \in U[-0.1, 0.1]$ represent an agent's aggressiveness for engaging in violence.[8] Once a level of aggressiveness is introduced, Eq. (2) changes to

$$\omega_i = \dot{\rho}_i - \sigma_i + \theta_i \tag{8}$$

and investment is determined by this rule. I assumed above that if $\rho_i - \sigma_i < 0$ then no investment occurred. Now that aggressiveness is introduced, if $\rho_i - \sigma_i < 0$, then the negative investment can act to offset an agent's aggressiveness (if $\theta_i > 0$). Combatants often engage in violence for reasons independent of the goal of receiving the share of the distribution of resources they think they deserve. The existing literature identifies several factors affecting a group's aggressiveness that fit this notion, including identity and religion. For example, in Chechnya during the late 1990s and early 2000s, Shamil Basayev's Islamic fundamentalist faction was far more prone to use violence than Aslan Maskhadov's faction, regardless of the circumstances. Arguably, some combatants might never be satisfied with a settlement even if they control all relevant resources (high aggressiveness). On the other hand, other groups in civil war torn societies might actively press for peace, even if it means that they might not benefit as much (low aggressiveness). Thus, levels of aggressiveness are distributed uniformly around zero to capture both types.

In order to examine adaptation, I incorporate a selection mechanism that allows individual agents to adapt (1) their resource levels, π_i, (2) their aggressiveness, θ_i, and (3) their rules for updating beliefs, ϕ_i. Selection occurs at the end of each episode throughout the run and a single episode consists of k battles and negotiations. Agents are reproduced based on their fitness relative to others, based on the following steps. First, replicas of the actors in the current episode constitute the initial set of actors in the successive episode. Second, a new agent is created that replaces one of the least-fit agents. The reproduced agent is assigned a new level of resources ($\pi_i \leq$ the strongest existing actor). Third, with a small probability (<0.3), reproduced agents inherit from the fittest agent the value for weighting new information, ϕ_i, as well as aggressiveness, θ_i.[9] Finally, mutation is also introduced by redrawing a level of capability for the fittest agent. Such a change, although not likely to be dramatic, has the potential to create shifts in the distribution of resources.[10]

The logic underlying this simple selection mechanism is that combatants can be defeated and, in their place, new groups can enter and participate as combatants. Alternatively, less-fit combatants might change strategies and reemerge with a different (often greater) support base. In this sense, the system is adaptive. (Hereafter, the selection mechanism is used to capture adaptive behavior and all references to this mechanism indicate my focus on adaptation.) It also allows for the possibility of sudden shifts in the distribution of resources, which is key because in civil wars, rebels are dependent on the population for resources and support [16].

[8] *θ_i is fixed across t unless changed through a selection process, which I discuss below.*

[9] *I also lower the probability to <0.2 and there is no noticeable change in the results.*

[10] *To be precise, I draw a random number from a normal distribution with the agent's capability level as the mean, and with a small standard deviation surrounding this mean. Thus, resources could increase or decrease for the strongest actor. (Varying the exact standard deviation has no significant effect on the outcome.)*

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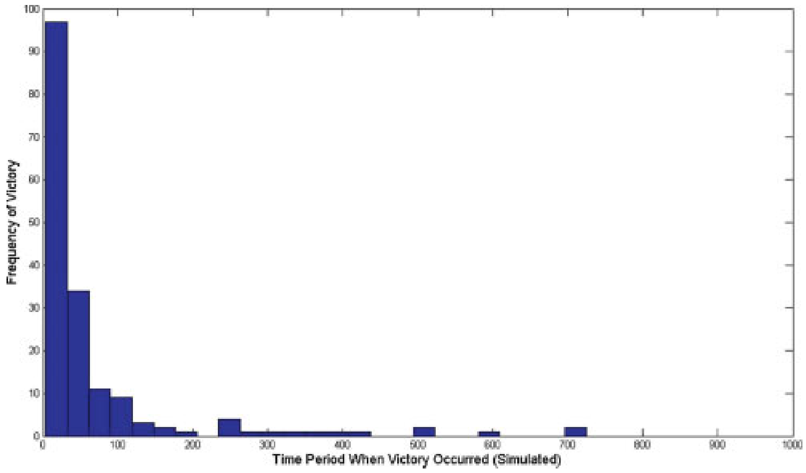
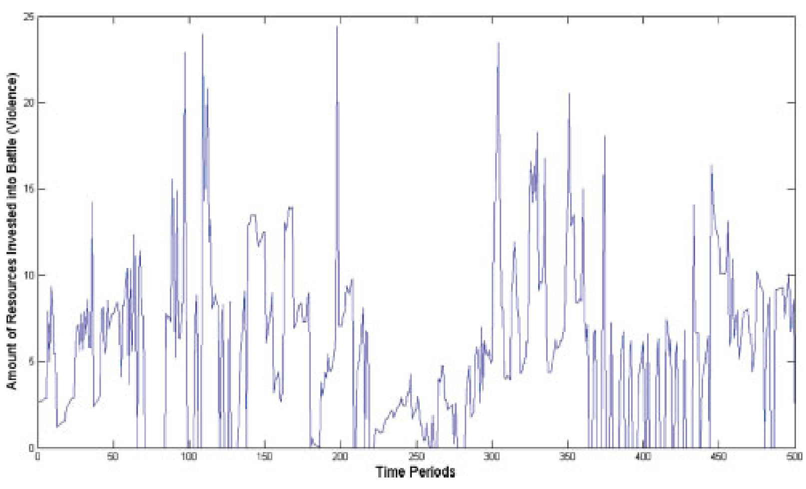
FIGURE 1



Simulated distributions of times at which victory occurs. In this experiment: number of agents = 3, episode = 0, $\theta \in U[-0.1, 0.1]$, $\Pi = 100$, and $\phi \in U[0, 2]$. The X axis represents the period in the run at which victory occurs and the Y axis captures the number of runs that ended at this time period. Each period represents one negotiation attempt and one battle. The figure shows that when victory occurs, it frequently occurs very early in the war. There are incidents of victories that occur much later, but they are rare. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

FIGURE 2



Aggregate investment of resources in battle. In this run: number of agents = 5, episode = 6, $\theta \in U[-0.1, 0.1]$, $\Pi = 100$, and $\phi \in U[0, 2]$. The X axis captures the periods in the run and the Y axis shows the aggregate amount of resources invested by the agents. This figure illustrates the punctuated equilibrium dynamics that occur once adaptation is possible. Although this is a single run, it is representative of others that allow adaptation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

This source of support has the potential for fluctuations over time based on success or failure on the battlefield.

3. MODEL FINDINGS

Consistent with the overview of the model, I first consider the effects of increasing the number of agents without a selection mechanism or a level of aggressiveness under conditions of incomplete information. Following this, I introduce aggressiveness, but no selection mechanism. Then, I examine the opposite scenario with a selection mechanism, but no aggressiveness. Then, I interact the two and consider several variations on this basic framework.

Because a single run can provide unique results, each separate experiment is conducted as a "batch" that repeats individual runs 250 times with the same initial parameter inputs. Unless specified as a single run of the model, each experiment discussed below is a batch. I consider several key outcomes measured as follows. First, I report the mean number of times that spikes in the investment of resources exceed 10, 20, and 30% of total resources to capture periods of concentrated violence. (To reiterate, I use the terms "investment of resources" and "violence" interchangeably.) Second, I report the percentage of time that an agent is "dominant." Dominance refers to a state in which a single agent controls at least 90% of the total resources. Related, I also discuss the occurrence of victory, which is when a single agent controls all resources, and there is no further investment in battle. Finally, I also report the percentage of time that there exists relative agreement or "settlement," which is when at least two agents have resources that they could invest in battle, but total investment (by all agents) is lower than 5% of overall resources.

Throughout the results section, I primarily refer to various figures, but also note the specific locations of raw results in Tables A1–A3 in Appendix A. Appendix B reports some findings of sensitivity analysis of the key results in the model.

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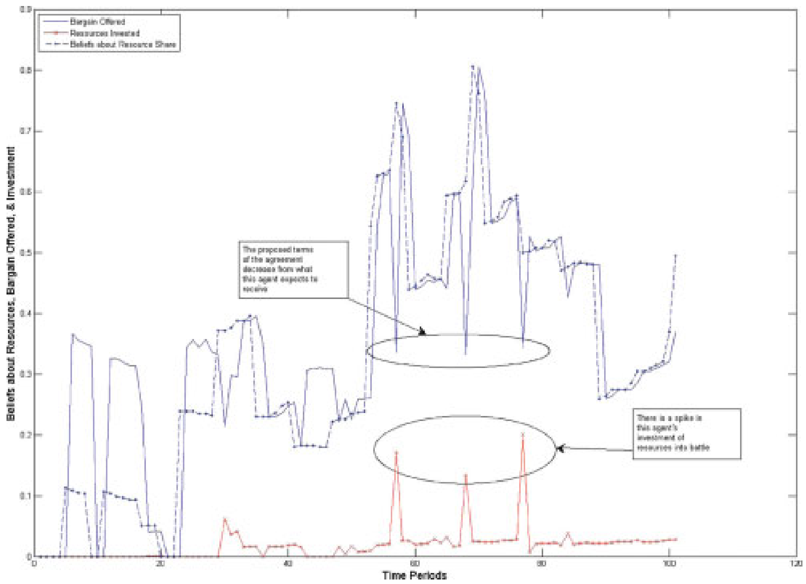
FIGURE 3



The interaction of beliefs about resources, bargain offered, and resources invested. In this run: number of agents = 5, episode = 6, $\theta \in U[-0.1, 0.1]$, $\Pi = 100$, and $\phi \in U[0, 2]$. The *X* axis shows periods in the run and the *Y* axis represents beliefs, bargains offered, and the amount of resources invested as a percentage of the agent's total resources. Only 100 of the 1000 time periods are shown for illustration purposes. This run simply illustrates that when an agent's belief about the share of the distribution of resources is correlated with what the agent is offered, investment of resources in battle is low. In this case, the agent receives an offer that is consistent with its share of the distribution. When the share of the resources and the bargain offered are uncorrelated, however, investment is higher because the offer does not meet the agent's expectations. (See portions of the run noted above.) [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

3.1. Civil Wars without Adaptation

When there is incomplete information, but no selection mechanism or propensity for aggressive behavior, one of the strongest results is that there is little violence generally, and very few "spikes" in violence in particular. For any given number of agents, the mean number of spikes exceeding the low threshold is never higher than two (Table A1, experiments 1–7).

Because the absence of aggressiveness is highly unlikely empirically, I also examine runs in which there is no selection mechanism (no adaptation), but there is a propensity for aggressive behavior, $\theta \in U[-0.1, 0.1]$. In these cases, there are between 15–40 spikes in the level of violence depending on the number of participating actors and dominance is more frequently a state of the system (see Table A1, experiments 8–14). Victory is also a frequent outcome in the experiments especially when agents are allowed to be aggressive. Figure 1 displays the time periods at which victory is achieved in a batch run of the model where agents are aggressive, but there is no selection mechanism whereby the characteristics and set of actors can change. In this case, wars frequently end in early victories.

Claim 1. *When the set and characteristics of agents do not (or cannot) change over time, wars are likely to end in settlement if actors have benign intentions and victory if actors have some propensity for violence.*

3.2. Individual Runs and the Effects of Adaptation

To analyze the effects of adaptation, I begin by discussing the dynamics of several individual runs that provide intuition for dynamics underlying the results of the aggregate runs. Once adaptation is introduced via the selection mechanism, the results change significantly. When agents are able to adapt, runs of the model frequently result in punctuated equilibrium dynamics, rather than victories early in the war. (In a model of civil violence, Epstein also finds punctuated equilibrium dynamics [6].) Figure 2 is a snapshot from a single run in which there are a number spikes in the levels of resources invested into battle (violence) by agents. In some cases, spikes in violence appear when there was no preceding violence, whereas other spikes extend from existing, lower-level violence.

Because the interaction topology is complex, exact patterns generating the spikes are difficult to predict, ex ante. The spikes in violence generally occur, however, for a couple of reasons. They occur following periods in which selection occurs, as the set of agents and their characteristics can change leading to greater uncertainty and different configurations of agent belief updating capacities and propensities for aggressive behavior. If an agent is dominant, furthermore, then violence often increases following selection because the dominant agent invests large amounts of resources to crush the new opposition quickly, similar to repression strategies in some political regimes. Furthermore, agents make unacceptable proposals about the distribution of agreement terms and, as a result, other actors invest resources ($\dot{\rho}_i - \sigma_i > 0$). This frequently occurs when agents have inaccurate beliefs about the distribution of resources. To illustrate, Figure 3 displays, for a single run of the model, one agent's beliefs about its share of the distribution of resources (dashed-dotted line), the bargain it is offered (solid line), and its level of investment of resources in battle (starred line) over a short period of

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time. The amount of resources invested is, by definition, a function of agent beliefs about resources and the bargain the agent is offered. When the bargain offered correlates with beliefs about an agent's share of resources, agents invest fewer resources in battle than if beliefs and the bargain offered are inversely correlated.

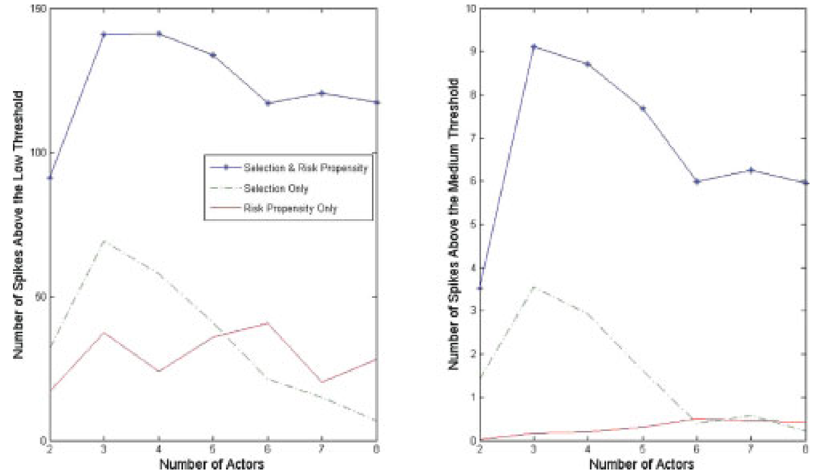
3.3. Aggregate Runs and the Effects of Adaptation

With an explanation of several individual runs as a backdrop, consider the aggregate results to analyze the effects of allowing adaptation via the selection mechanism every k time periods ($k = 6$ for the main results). Figure 4 shows comparative statics of the number of spikes exceeding the low and medium thresholds as the number of agents increases from two to eight for three sets of experiments: selection with no aggressiveness, aggressiveness with no selection, and the two interacted. The results for the low and medium thresholds show that the interactive effect of a selection mechanism and aggressiveness is much higher than simply the combined additive effect (see Tables A1 and A2, experiments 8–28).

Interestingly, although spikes in the level of violence are highest when selection and aggressiveness are interacted, Figure 5 shows that the percentage of time in which there is relative agreement is also relatively high when the two are interacted. Periods of settlement are highest when selection occurs alone, but when selection and aggressiveness are interacted, the percentage of time in a state of relative agreement or settlement is still roughly 50%. When agents only have a propensity for aggressiveness, and spikes in violence are low, levels of dominance are quite high, whereas periods of relative settlement are low.

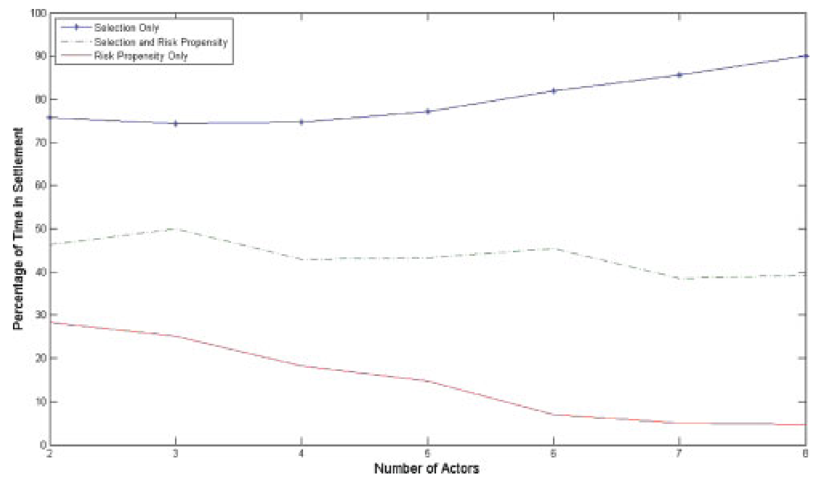
Selection allows agents to avoid complete domination by allowing them to adapt and increase their resources and, much of the time, violence remains at low levels with no one agent dominant. In other words, violence remains at very low levels much of the time, but when

FIGURE 4



Spikes in the investment of resources. In these experiments: number of agents =2–8, selection $= 6$, $\theta \in U[-0.1, 0.1]$, $\Pi = 100$, and $\phi \in U[0, 2]$. These plots show comparative statics for changes in the number of spikes exceeding the low (left pane) and medium (right pane) thresholds, as the number of actors increases. When selection is present and agents have a propensity for aggressive behavior, the number of spikes in violence is significantly higher than either alternative produces on its own. It also shows the nonmonotonic relationship as the number of actors increases. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

FIGURE 5



Percentage of time in settlement. In these experiments: number of agents =2–8, selection varies, θ varies, $\Pi = 100$, and $\phi \in U[0, 2]$. This plot illustrates the relationship between the number of actors and the percentage of time that aggregate investment is both below 5% and no single agent has more than 90% of the resource distribution. It illustrates the possibility that even when there are many spikes in the levels of violence over time, they can occur during times of relative agreement. The number of spikes (see Figure 4) when both a selection mechanism and aggressiveness are present is fairly high. Yet examining this plot shows that these spikes occur when the levels of relative agreement or settlement are also relatively high (compared to the case in which there is aggressiveness only). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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violence does occur, it frequently spikes high. These results suggest the following:

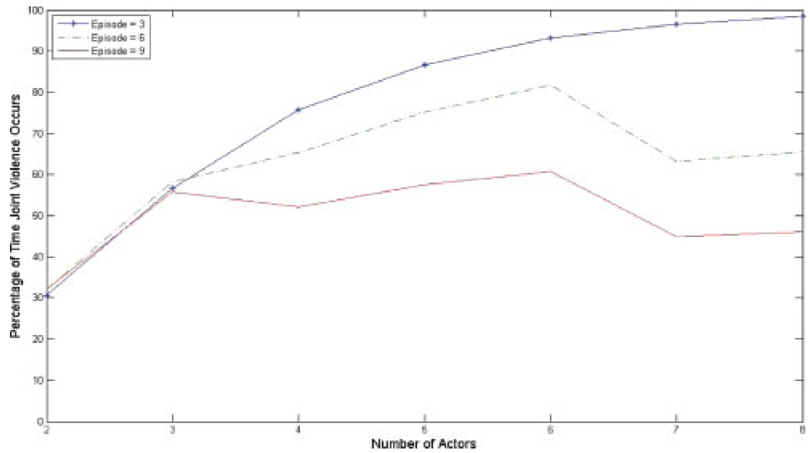
Claim 2. *When combatants are adaptive, violence frequently occurs amidst periods of relative agreement and can spike high (punctuated equilibrium dynamics). On the other hand, the possibility of adaptation prevents any one agent from becoming dominant very often.*

Thus, adaptation suggests tradeoffs in the possible outcomes. From a normative perspective, sharp outbursts of violence are terrible, but dominance of a single group might be also. If a single group becomes dominant, then other groups in society might be subject to a repressive regime.

Given my emphasis on the selection mechanism, I also vary the frequency of selection to three and nine time periods per episode. When selection occurs more and less frequently, the number of spikes is lower in most cases (see Table A1, experiments 22–28; Table A2, experiments 29–42), suggesting that simply incorporating more frequent adaptation does not deterministically produce more violence. Instead, there appears to be some frequency of adaptation that is most conducive to violence, which in these experiments is in the middle range. The results do show clearly, however, that when selection occurs more frequently, the percentage of time in settlement also increases, and periods of dominance almost disappear. When selection occurs less frequently, on the other hand, periods of dominance increase substantially, whereas periods of settlement decrease.

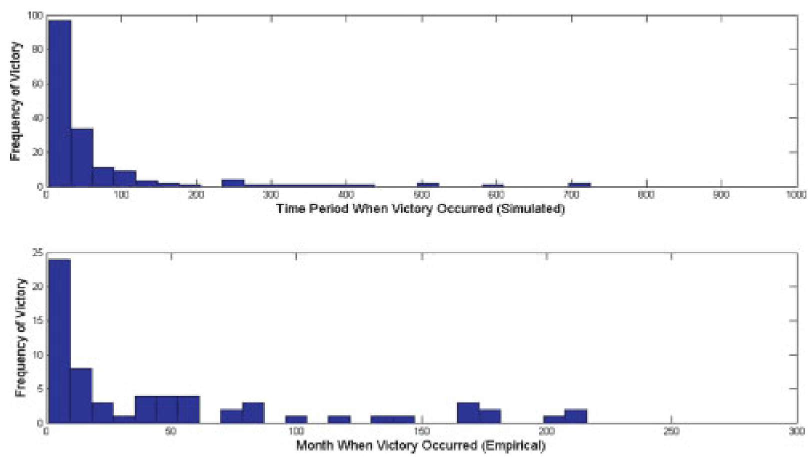
As adaptation occurs more frequently, furthermore, violence between two or more actors becomes far more common than no violence or one-sided violence. Empirically, one-sided violence refers to behavior such as riots, pogroms, genocide, or even some violent protests, whereas violence between two or more actors refers to actual battles between the parties. Figure 6 illustrates the comparative statics as the number of actors increases. When selection occurs more frequently, the percentage of time that multiple agents are engaged in battle increases substantially. Thus, the faster conflict systems adapt and evolve, the more frequent is broad participation in violence.

FIGURE 6



Percentage of time in joint violence. In these experiments: number of agents =2–8, selection frequency varies, $\theta \in U[-0.1, 0.1]$, $\Pi = 100$, and $\phi \in U[0, 2]$. This plot illustrates the relationship between the number of actors and the percentage of time that joint (two or more actors) violence occurs, as opposed to periods of nonviolence or one-sided violence. The plot indicates that joint violence is increasingly likely as adaptation occurs more frequently. Similar to Figure 4 there is a nonmonotonic effect where joint violence is most likely at middling levels. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

FIGURE 7



Simulated and empirical distributions of times at which victory occurs. The top pane is identical to Figure 1 and contains simulated data on the frequency and timing of victories. The bottom pane shows data on the duration of wars that end in victory based on data from Doyle and Sambanis [19]. Comparing the plots, it appears that the empirical data are generally consistent with the shape of the simulated data. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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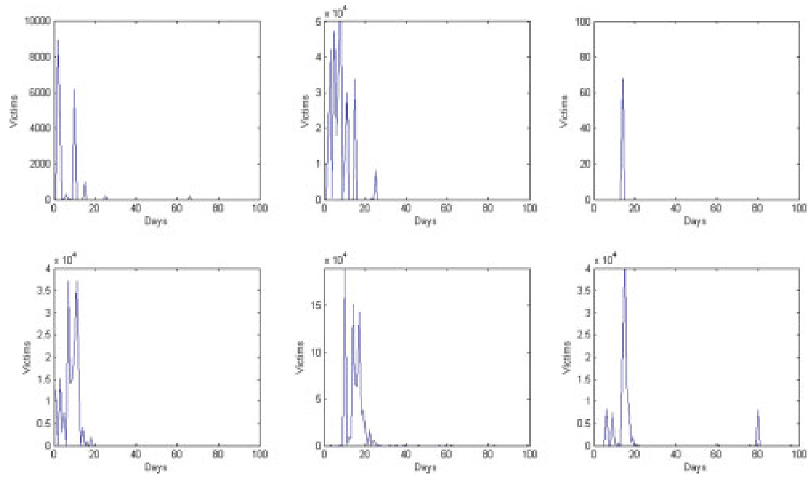
FIGURE 8



Victims in the Rwandan genocide. This figure plots data on deaths during the first 100 days of the Rwandan genocide based on data from Davenport and Stam [20]. There are 11 prefectures in Rwanda, and this plot shows data from six of 11 prefectures; data from the other five are all very similar. The violence was carried out swiftly with high numbers of deaths in the earliest days and very little violence following later. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Finally, although not the thrust of this paper, Figures 4 and 6 both show that there are nonmonotonic effects between the number of actors and (1) spikes in violence and (2) participation in violence respectively. Current theories of civil war dynamics and resolution have found a simple monotonic relationship whereby resolution becomes more difficult as the number of actors increases (for example, see [17]). Yet the results of each set of experiments examined here suggest that the opposite might be true—outbursts of violence are not simply a monotonically increasing function of the number of actors. Thus, theories of civil war that assume only two actors, for example [18], might only apply to wars with precisely two actors, rather than the entire set of civil war cases with which most theories are tested [18].

4. ASSESSING THE PLAUSIBILITY OF THE MODEL

Conceptualizing civil war as an adaptive system illustrates several key dynamics that inform current scholarly work and have testable implications. The thrust of this paper is theoretical, but to demonstrate the plausibility of the model and illustrate the testable implications, I show several empirical examples below that address Claims 1 and 2. These examples clearly do not "test" the model, but are useful illustrations of the applicability of some of the theoretical results. Because Claims 1 and 2 yield distinct results, they usefully characterize how adaptability affects patterns of conflict. Figure 7 (top) displays the simulated data from Figure 1. Figure 7 (bottom) shows the number of months to victory based on empirical data from Doyle and Sambanis [19].

Both figures show a high number of victories occurring early in the wars with the rest of the victories skewed to the right. Empirically, the mean number of months to achieve victory is 50.46 with a standard deviation of 61.47, whereas the mean number of months to reach a negotiated agreement is 124.21 with a standard deviation of 127.35. These results (simulated and empirical) suggest that, when victories occur, they tend to take place very early in most cases (i.e., the spike early in both figures). It is possible that the patterns of violence are a function of agent inability to adapt to the changes in the war. In the model experiments, most violence occurs very early (in the first 100 time periods) and only rarely surfaces later. In most cases, one agent becomes dominant quickly and the others are not able to adapt in order to engage in violence.

An examination of the days in which violence occurred during the Rwandan genocide lends support to these results. Figure 8 shows the number of victims over the course of the first 100 days of the genocide in six different prefectures measured by Davenport and Stam [20]. Much of the violence occurs early, but is characterized by a number of spikes, and in a couple of cases there are spikes in the violence later on.[11]

Because patterns of violence are frequently characterized by punctuated equilibrium dynamics (Proposition 2), adaptability is a possible explanation for the dynamics. Consider the following statistics on civilian deaths in the Iraq war from April 2003 to September 2005 measured by the Iraq Body Count group [21]. Figure 9 displays data on casualties after April 9, the day typically associated with the defeat of Iraqi conventional forces. Given that my focus is on civil war, it is more accurate to include only those dates following the defeat of the conventional forces, around when the insurgency began.[12] Interestingly, Figure 9 shows that there are relatively few casualties at any given point in time, but periods of relative nonviolence are punctuated by high spikes in the level of

[11] *Clearly investment of resources into battle (from the formal model) and actual deaths (from the empirical data) are not identical. Yet, the investment of resources in battle is designed to proxy levels of violence and death occurring between combatants.*

[12] *Whether the insurgency officially began on April 10 is not very likely, but it is clear that shortly after the defeat of conventional forces the insurgency began—probably no later than May 2003.*

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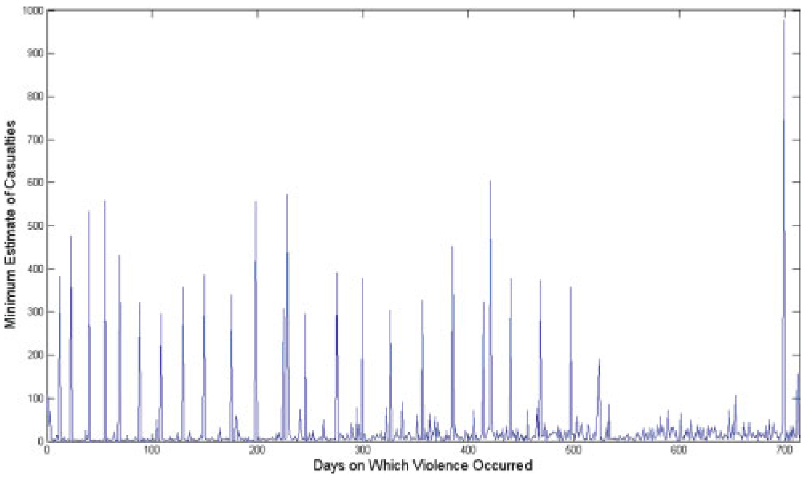
FIGURE 9



Civilian deaths in iraq between April 10, 2003 and September 2005. This plot shows the minimum estimate of casualties suffered in the current Iraq war between the dates specified and is based on data from *Iraq Body Count* [21]. The plot begins with data on April 10, 2003 as this is immediately following the defeat of conventional forces, and somewhere near the beginning of the insurgency. Much of the time there is relatively little violence, but these periods are punctuated with high spikes in the level of violence. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

violence. Arguably, the insurgents in Iraq have been highly effective at adapting over time.

Finally, these dynamics illustrate an important, but underemphasized, empirical regularity: many civil wars tend to fluctuate between periods of war and periods of peace. Often war subsides while combatants negotiate or attempt to implement terms of an agreement only to revert back to war for a time. Thus, lulls in violence (between spikes) often reflect moves towards peace by the various parties rather than just interludes between fighting. This recursive process is common in many civil wars, as is illustrated by the Sierra Leone case in Table 2. Most analyses of civil war tend to compartmentalize the peace process focusing on a single period of time in which there is a move from war to peace, or vice versa, or on a particular stage of the process (e.g., reaching negotiations). Likely, extant work relies on static conceptualizations of war and peace, because dynamic, recursive processes become too complicated for existing methodological techniques. Computational methods allow for a more systematic treatment of multi-actor, multi-stage processes that more closely match the empirical data-generating process. The punctuated equilibrium dynamics highlight the fluid and recursive process that characterizes many civil wars and suggest that empirical analysis should focus more explicitly on these characteristics.

5. CONCLUSION

This paper seeks to capture systematically some of the complexities of civil wars and associated peace processes using an agent-based computational model. Because adaptation is addressed only indirectly in the civil war literature, I have focused on learning and adaptation through various stages of the peace process. The model presented here suggests that one explanation for the empirical regularity of long civil wars [1] is that combatants are adaptive.

TABLE 2

Recursive Dynamics in the Sierra Leone Civil War

Sierra Leone (1991–1997)	
Year	Phase of War (or Peace)
1991	War
1992	Negotiations
1992	War
1995	Negotiations
1995	War
1996	Negotiations
1996	Peace Agreement
1997	Negotiations

Despite developing a model that is, arguably, truer to form than extant models of civil war, clearly there are aspects that I leave out. Rather than overcomplicate the model with every possibility, I attempt to keep the model as simple as possible [22]. Factors such as economics, the "indivisibility" of settlement terms, and culture are, therefore, captured only indirectly at best. Key model changes, such as allowing a percentage of the overall resources to decrease through battle, might provide interesting insights. Nevertheless, the model yields several testable claims that offer useful insights for scholars of civil war resolution. Preliminary data analysis, furthermore, demonstrates the plausibility of the model, though more rigorous tests would be necessary to validate the claims of the model. Further empirical work could be usefully devoted to measuring and analyzing the evolutionary context of wars including the changing set and characteristics of actors over time.

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APPENDIX A. TABLES OF RESULTS FOR ALL EXPERIMENTS

TABLE A1

Model Results without Selection

Experiment	Agents	Spikes in violence: Low	Spikes in violence: Med	Spikes in violence: High	Outcomes: % Dominance	Outcomes: % Settle	Joint violence % of Time
			Baseline: Selection ($k = 0$); Aggressiveness ([0])				
1	2	1.32	0.27	0.02	5	94	0
2	3	2.75	0.08	0.03	3	95	1
3	4	1.64	0.20	0.02	6	93	3
4	5	1.54	0.22	0.11	4	95	2
5	6	1.88	0.34	0.10	5	94	3
6	7	1.40	0.20	0.11	6	94	1
7	8	1.35	0.28	0.14	3	96	1
			Selection ($k = 0$); Aggressiveness ($U[-0.1, 0.1]$)				
8	2	16.79	0.03	0.00	65	28	10
9	3	37.48	0.17	0.02	65	25	15
10	4	23.82	0.20	0.03	76	18	10
11	5	35.94	0.30	0.08	78	15	15
12	6	40.51	0.50	0.15	84	7	13
13	7	20.14	0.44	0.10	88	5	8
14	8	28.29	0.44	0.20	88	5	11

TABLE A2

Model Results with Selection

Experiment	Agents	Spikes in violence: Low	Spikes in violence: Med	Spikes in violence: High	Outcomes: % Dominance	Outcomes: % Settle	Joint violence % of Time
			Selection ($k = 6$); Aggressiveness ([0])				
15	2	31.86	1.40	0.02	10	76	0
16	3	69.09	3.56	0.14	0	74	21
17	4	57.72	2.92	0.24	0	75	43
18	5	40.89	1.62	0.13	0	77	63
19	6	21.20	0.39	0.02	0	82	76
20	7	14.96	0.57	0.05	0	86	82
21	8	6.79	0.22	0.02	0	90	89
			Selection ($k = 6$); Aggressiveness ($U[-0.1, 0.1]$)				
22	2	91.08	3.52	0.16	19	46	32
23	3	140.78	9.12	0.64	2	50	59
24	4	141.15	8.70	0.66	8	43	65
25	5	133.69	7.68	0.57	6	43	75
26	6	116.98	5.98	0.41	5	45	82
27	7	120.52	6.26	0.48	17	39	64
28	8	117.28	5.95	0.47	17	39	66

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TABLE A3

Model Results Varying the Frequency of Selection

Experiment	Agents	Spikes in violence: Low	Med	High	Outcomes: % Dominance	% Settle	Joint violence % of Time
Selection ($k = 3$); Aggressiveness ($U[-0.1, 0.1]$)							
29	2	94.29	4.67	0.12	14	52	31
30	3	143.70	9.31	0.43	0	55	57
31	4	135.76	7.07	0.52	0	50	76
32	5	105.26	3.11	0.16	0	52	87
33	6	70.59	1.05	0.03	0	54	93
34	7	64.31	1.13	0.04	0	54	97
35	8	43.26	0.50	0.03	0	57	99
Selection ($k = 9$); Aggressiveness ($U[-0.1, 0.1]$)							
36	2	86.65	2.98	0.12	25	43	32
37	3	142.35	8.12	0.66	8	44	56
38	4	123.11	5.98	0.49	23	35	52
39	5	123.41	6.10	0.59	21	36	58
40	6	122.44	5.94	0.60	20	37	61
41	7	100.15	4.50	0.35	36	30	45
42	8	103.18	4.85	0.29	35	31	46

APPENDIX B. SENSITIVITY ANALYSIS

In addition to the results reported in the paper and the tables in Appendix A, I also varied a number of other parameters to understand better the range of outcomes. In most cases, the key results reported in the paper do not change significantly. Two parameter changes do have an impact on the number of spikes in violence, and I alluded to them already in the text.

First, I changed the ranges for the aggressiveness parameter to $\theta \in [-0.2, 0.2]$ and $\theta \in [0, 0.2]$. Unsurprisingly, these changes increase the number of spikes that exceed the low threshold. The number of spikes exceeding the medium and high thresholds increase as well, but not much. This result is unsurprising because the low threshold is set at 10% of overall resources. Allowing agents to have a greater propensities for aggressiveness—the amount they invest every time regardless of a negotiation offer—increases the base level of violence. In the extreme case, if θ continued to vary until the upper bound reached 1, then agents would invest up to all of their resources every time irrespective of the bargain offered them. Although increasing aggressiveness has an effect on spikes in violence, this does not detract from the central focus of the model. When agents adapt, they can adopt the aggressive traits of more successful agents. Thus, the level of the aggressiveness is part of the adaptation process itself.

Second, the amount that beliefs differ from the true distribution of resources also has an effect on the number of spikes in violence. As beliefs move closer to the true distribution, investment of resources into battle also tends to decrease, as do spikes in violence. Increasing the distance between beliefs and the true distribution, on the other hand, has the effect of creating even more spikes. This is also unsurprising given the way the model is set up in that under conditions of complete information, violence is at its lowest. Moreover, examining Eq. (2) shows that when agent beliefs deviate significantly from the true distribution of resources, their assessments of how much to invest will be inaccurate.

Given that changes occur in both directions for these two parameters (spikes increase or decrease with different belief levels) and because aggressiveness is part of the adaptation process, the values used in the analysis appear to be reasonable benchmarks for both aggressiveness and beliefs. They allow an examination of the effects of incorporating adaptation into the model and facilitate useful insights about the civil war process.

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