

Population is the main driver of war group size and conflict casualties

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The proportions of individuals involved in intergroup coalitional conflict, measured by war group size (W), conflict casualties (C), and overall group conflict deaths (G), have declined with respect to growing populations, implying that states are less violent than small-scale societies. We argue that these trends are better explained by scaling laws shared by both past and contemporary societies regardless of social organization, where group population (P) directly determines W and indirectly determines C and G. W is shown to be a power law function of P with scaling exponent X [demographic conflict investment (DCI)]. C is shown to be a power law function of W with scaling exponent Y [conflict lethality (CL)]. G is shown to be a power law function of P with scaling exponent Z [group conflict mortality (GCM)]. Results show that, while W/P and G/P decrease as expected with increasing P, C/W increases with growing W. Small-scale societies show higher but more variance in DCI and CL than contemporary states. We find no significant differences in DCI or CL between small-scale societies and contemporary states undergoing drafts or conflict, after accounting for variance and scale. We calculate relative measures of DCI and CL applicable to all societies that can be tracked over time for one or multiple actors. In light of the recent global emergence of populist, nationalist, and sectarian violence, our comparison-focused approach to DCI and CL will enable better models and analysis of the landscapes of violence in the 21st century.

population scaling | war group size | conflict casualties | conflict investment | conflict lethality

Numerous recent publications have addressed the long-term history of human violence to understand both its evolutionary significance (1–3) and how differing social institutions and organizational principles impact the frequency and severity of coalitional violence or warfare (4, 5). It is variously argued that the modern world is less violent than what was the case for much of human prehistory (6–10) or alternatively, that the development of modern state institutions and economic forms has spurred increases in violence (11, 12). These debates focus largely around two variables: (i) the frequency with which conflicts occur and (ii) the proportion of any given social group (the unit from which a war group is drawn for purposes of this paper) that is engaged in violence and what proportions of those engaged or exposed are killed by violent acts.

Ethnographic data suggest that, in small-scale societies, both participation in coalitional violence (proportional war group size) (Fig. 1) and the proportion of those killed are often higher than comparable rates observed in modern state conflict (5, 8). Some researchers consequently argue (i) that more individuals were exposed to violence in the past than at present (5) and (ii) that prehistoric violence was less constrained than modern violence, with fewer limits on the individuals and how many individuals were targeted and potentially killed (5, 6, 8).

Prior studies have shown that both size and frequency of conflicts obey a log–log scaling law (13–15) and that population size and casualties follow a similar logarithmic relationship (16). These prior studies have focused only on periods of major or active conflict. Here, we expand on these results by examining the relationship between proportional participation in conflict [the ratio of war group size (W) to population (P)] and

resulting deaths [overall group conflict deaths (G) as a proportion of war group size]. Notably, we find that, when modern states not actively engaged in conflict are included, a strong sublinear log–log relationship exists between population size and war group size, while casualties are driven by war group size and are not directly driven by population. The relationship between war group size and casualties is supralinear, suggesting that large populations (usually states) generate more casualties per combatant than in ethnographically observed small-scale societies or in historical states.

Modeling Scaling Relationships Between Population, War Group Size, and Conflict Casualties or Deaths

We propose that trends in size and proportions of both W and G are better explained by scaling relationships between P, W, G, and conflict casualties (C). In other words, we argue that population size is a significant driver of conflict investment, casualties, and deaths. By population (P), we mean the total number of individuals in the social unit (settlement, society, ethnic group, polity, city, kingdom, empire, state, or nation state) from which a war group is drawn and within which the casualties are generated. Decreasing proportions of W/P and G/P in more complex societies as opposed to small-scale societies might be the incidental product of the organizational needs and logistical constraints of different populations rather than the outcome of any measurable decrease in overall violence, increased investment in processes and institutions, and/or the “profitability of peace.” The scaling laws outlined here are analogous to allometric scaling properties observed in biological and social systems. For

Significance

Recent views on violence emphasize the decline in proportions of war groups and casualties to populations over time and conclude that past small-scale societies were more violent than contemporary states. In this paper, we argue that these trends are better explained through scaling relationships between population and war group size and between war group size and conflict casualties. We test these relationships and develop measures of conflict investment and lethality that are applicable to societies across space and time. When scaling is accounted for, we find no difference in conflict investment or lethality between small-scale and state societies. Given the lack of population data for past societies, we caution against using archaeological cases of episodic conflicts to measure past violence.

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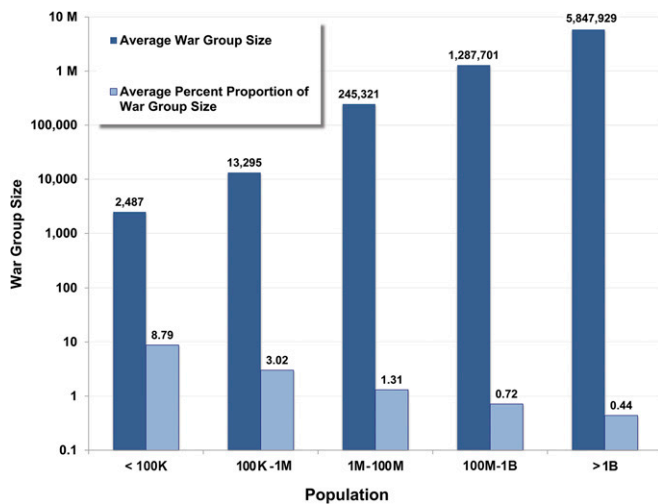


Fig. 1. Comparison of trends in average numbers and percent proportions of war group size by population categories from Dataset S1 ($n = 223$).

example, the relationship between mammalian body mass and physiology has been observed to follow power law functions, where processes, such as metabolic rates, slow down as body mass increases (e.g., Kleiber's Law) (17). Hence, large-bodied mammals have proportionally slower metabolic rates in comparison with small-bodied mammals that have higher metabolic rates. Similar relationships also underlie the energy intake as a proportion of body mass, where small-bodied mammals need to consume proportionally higher quantities of food to maintain optimal function, while larger mammals consume proportionally lower quantities of food (17). Other studies have noted similar scaling laws in the relation of material resources or social activity and sizes of cities and settlements. Strong power law relationships

have been shown to exist between city populations and energy use, infrastructure, wealth, patents, and pollution (18). We argue that similar scaling laws drive the relationships between populations, war group sizes, and casualties. The various terms and abbreviations that we use are listed and defined in Table 1.

Prestate or nonstate small-scale societies face situations of conflict brought about by a range of factors, including ecological or economic imbalance, resource scarcity, and revenge claims (5, 8). In these societies, conflict needs are not managed through any centralized authority but rather through combat readiness training undergone by members of a group as socially structured rites of passage. Consequently, in times of war, in small-scale societies, such as the Yanomamo (19), Mae Enga (20), or the Bari (21), a high proportion of subadult and adult members of these societies can be called on for either defense or attack (5). The logistical constraints of maintaining such war groups are largely expedient and do not fall on any particular managerial institution within these societies. In the periods between conflicts, the members of war groups resume their noncombat activities (e.g., farming, pastoralism, crafts production, and trade). Hence, we expect that, in such societies, the expedient W/P would be high. Indeed, most observations of functioning war groups within small-scale societies would be made precisely in times of conflict, when all combat-trained/-ready individuals are called to war or placed on standby, akin to contemporary societies with compulsory or expedient draft/military service.

In more complex and stratified societies with large P numbering in the tens or hundreds of thousands, millions, or billions, conflict needs are met through specialized war groups (military, army) that are financed and maintained by managerial elites through taxation or other forms of redistribution. The need for training, arming, feeding, clothing, and housing such groups places considerable constraints and limits on the size of war groups that may be maintained by any given society. These constraints may be mitigated by emergent or ongoing conflict, and maintaining adequate numbers for defense or attack needs would be largely dependent on

Table 1. Terminology and abbreviations

Symbol	Description
Conflict	We follow the definition of Wrangham and Glowacki (2) [<i>SI Definitions of Terms and Understanding Current Debates on Evolution of Violence (Table S1 Provides Multiple Definitions and Associated Sources)</i>]: "Relationships in which coalitions of members of a group seek to inflict bodily harm on one or more members of another group; 'groups' are independent political units. This definition is broader than many because it includes all kinds of fighting, whether in a surprise attack (raid or ambush), chance meeting or planned battle."
C	Conflict casualties: the number of casualties (deaths) from any conflict. We do not include those missing or wounded in action in C
CW	Proportion of conflict casualties to war group size
CL	Conflict lethality: relative measure of number of conflict casualties accounting for scale in war group size
DCI	Demographic conflict investment: relative measure of number of individuals involved in conflict accounting for scale in group population
G	Overall group conflict-related deaths in a conflict requiring massive personnel and resource investment
G/P	Proportion of overall group conflict-related deaths to group population
GCM	Group conflict mortality: relative measure of number of conflict-related deaths in massive conflicts accounting for scale in group population
P	Group population: total number of individuals in the social unit (settlement, society, ethnic group, polity, city, kingdom, empire, state, or nation state) from which a war group is drawn and within which the casualties are generated
W	War group size: the total number of individuals involved in conflict-related activities, either for the society as a whole or for a single conflict
W/P	Proportion of society involved in coalitional violence
Small scale	Societies with low populations (generally <10,000) that rely on foraging or subsistence-level agriculture and/or pastoralism
State-level societies	Societies with large populations (generally >>10,000) that rely on diversity of subsistence and surplus formation activities, including agriculture, large-scale manufacturing, and/or industry and who have institutionalized specialized groups for economic, political, conflict, and other activities

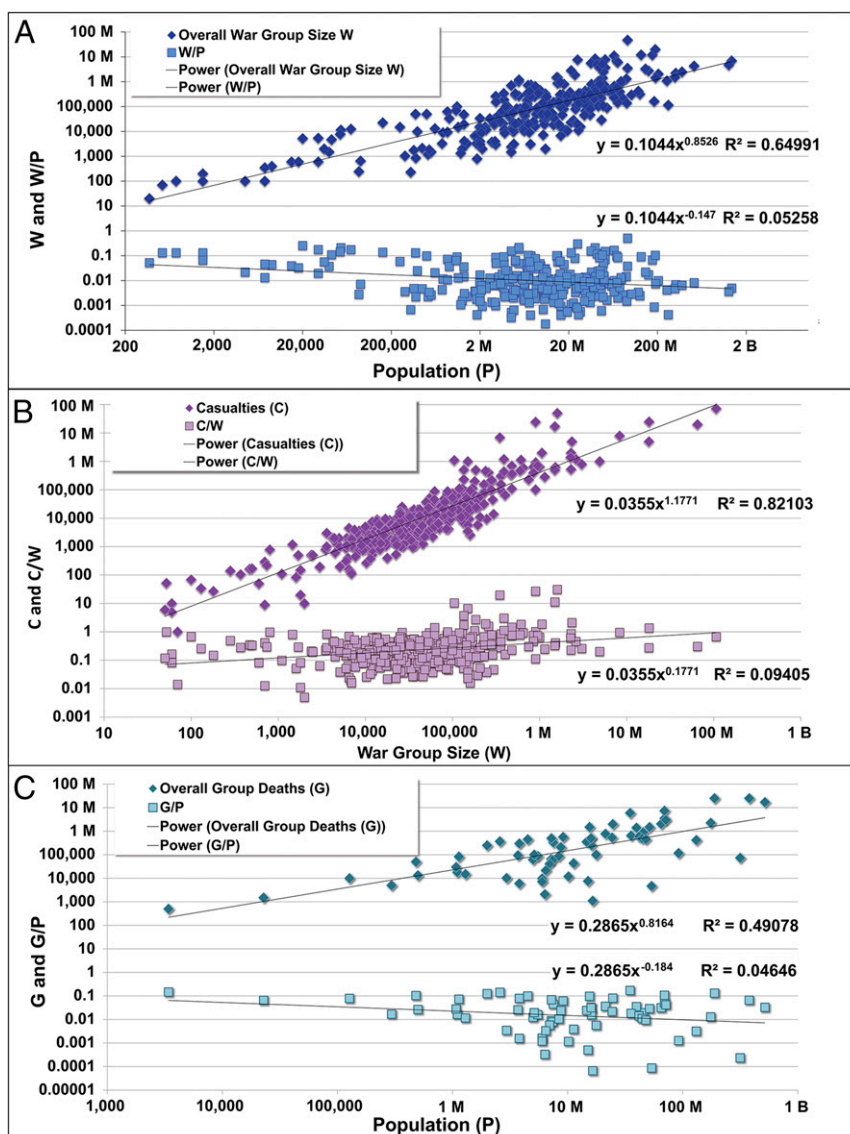


Fig. 2. Log–log distributions show the scaling relationships between P (population) and W (war group size), between W and C (conflict casualties), and between P and G (overall group conflict deaths). (A) Scaled distribution of P vs. W and W/P from [Dataset S1](#) ($n = 295$). (B) Scaled distribution of W vs. C and CW from [Dataset S2](#) ($n = 430$). (C) Scaled distribution of P vs. G and G/P for World War I and World War II from [Dataset S4](#) ($n = 65$).

available resources. Hence, we expect that, in larger stratified and state-level societies, W would increase according to a scaling relationship with P , subject to logistical constraints and conflict needs. However, there would be a decrease in W/P .

We would also expect a similar decrease in the proportion of G to P . However, this is a far more difficult calculation. Social

groups might be involved in multiple conflicts, and W_j for individual conflict j within any group might vary from small raiding or sabotage parties to large invasion forces based on both expedient needs and logistical constraints. Given that groups do engage in multiple conflicts simultaneously, it is hard to compare deaths from conflicts, such as the English Civil War, the Punic

Table 2. Regression results of $\ln P$ vs. $\ln W$ across and within social categories to understand variation in war group size (W) and DCI (X) based on Eq. 1 [$W = K(P)^X$] and [Datasets S1](#) and [S5](#)

Type of society	DCI	95% CI	K	Adjusted R^2	R	N
All	0.86	0.78, 0.93	0.10	0.65	0.81	295
Small scale	0.96	0.74, 1.18	0.08	0.84	0.92	18
All states	0.96	0.86, 1.01	0.02	0.58	0.76	277
21st Century states	1.07	0.95, 1.19	0.02	0.57	0.76	228
20th Century state conflicts	1.09	0.85, 1.32	0.01	0.65	0.81	50
NMC data 19th to 21st century states	0.98	0.97, 0.99	0.02	0.71	0.84	12,870

All relationships are significant at $P < 0.001$.

Table 3. Regression results of LnW vs. LnC across and within social categories to understand trends in conflict casualties (C) and CL (Y) based on Eq. 2 [$C = M(W)^Y$] and Dataset S2

Type of conflict	CL	95% CI	M	Adjusted R^2	R	N
All	1.18	1.12, 1.25	0.04	0.82	0.91	430
Small scale	1.01	0.60, 1.42	0.14	0.58	0.76	21
All states (historical and contemporary)	1.21	1.15, 1.27	0.03	0.79	0.89	393
Contemporary states	1.23	1.02, 1.44	0.02	0.85	0.92	27

All relationships are significant at $P < 0.001$.

Wars, or World War I or II, that preoccupy the resources of entire societies for multiple years on multiple fronts with deaths from small skirmishes or raids that might or might not be parts of a larger conflict. For example, a small-scale society i with $P_i = 300$ and $W_i = 100$ might send 10 warriors on a raiding party conflict j . Therefore, $W_i/P_i = 0.33$, and $W_j/P_i = 0.03$. A large nation state i with $P_i = 10,000,000$ and $W_i = 50,000$ might send a unit j of 5,000 troops as part of a global peacekeeping force. Therefore, $W_i/P_i = 0.005$ (overall army), and $W_j/P_i = 0.0005$ (unit). In either case, would the casualties be calculated based on proportion of the raiding party or active unit sent to battle (C_j/W_i) or the overall war group size (C_j/W_i)? Would G/P be calculated as a proportion of all conflict-related deaths within a time period to average population? Furthermore, when we examine a scaling relationship between P and G , do we consider the proportions of conflict casualties of individual battles and skirmishes (e.g., Battle of the Bulge, Stalingrad, D-Day) or the total overall conflict (World War II)?

Given these difficulties, we propose that it is more appropriate to compare total W involved with resulting total C summed over the total duration of a conflict, whether small or large. Doing so eliminates the impact of short-term fluctuations in combatant levels and provides a measure that can be consistently used to compare lethality of small raids/assaults, ambushes, single battles, longer wars, and seasonal conflict in preindustrial contexts. To ensure that time averaging does not impact the results, we examined the correlation between annual war group sizes and annual casualties for 58 conflicts (*SI Metadata and Caveats*, Fig. S1, and Dataset S3). We find no significant differences in scaling relationships or conflict lethality (CL) between annual and total war group size levels and casualties as shown in Dataset S2 (Dataset S8, 5.1–5.3).

We suggest that the generation of war groups, conflict casualties, and group conflict deaths are emergent outcomes of organizational interactions and energy-based activities that scale directly or indirectly in relationship to group population.

We model these relationships (Eqs. 1, 3, and 5) based on the general power law function $Y = \alpha(X)^\beta$. Here, we are primarily interested in β as the primary scaling factor that determines the relationship between Y and X ; α reflects the proportions of X^β and functions as a normalization constant. The expected proportions W/P , C/W , and G/P (Eqs. 2, 4, and 6) are then derived from Eqs. 1, 3, and 5.

War group size (W) is modeled as a power law scaling function of group population (P) as presented in the equation

$$W = K(P)^X. \quad [1]$$

K is a normalization constant and represents the proportion of P^X involved. The exponent X serves as a measure of how many individuals are being committed to the unit's war group, hereafter known as demographic conflict investment (DCI) in relation to P . The proportion of W to P is modeled from [1] as shown in the equation

$$\frac{W}{P} = K(P)^{X-1}. \quad [2]$$

Conflict casualties (C) are modeled as a power law function of conflict war group size (W) as presented in the equation

$$C = M(W)^Y. \quad [3]$$

M is a normalization constant and represents the proportions of W^Y killed in the conflict, while the exponent Y serves as a measure of CL in relation to W .

The proportion of C to W is modeled from [3] as shown in the equation

$$\frac{C}{W} = M(W)^{Y-1}. \quad [4]$$

Group conflict deaths (G) are also modeled as a power law function of group population size (P) as presented in the equation

$$G = O(P)^Z. \quad [5]$$

Here, O is a normalization constant and represents the proportions of P^Z killed in the overall conflict, while the exponent Z serves as a measure of group conflict mortality (GCM) in relation to P .

The proportion of G to P is modeled from [5] as shown in the equation

$$\frac{G}{P} = O(P)^{Z-1}. \quad [6]$$

Hence, based on the proposed scaling laws (Eqs. 1, 3, and 5):

Log transformation of $W = K(P)^X \rightarrow \text{Ln}W = X(\text{Ln}P) + \text{Ln}K$ (hence, if $X > 0$, $\text{Ln}P$ would be strongly and positively correlated with $\text{Ln}W$);

Log transformation of $W = M(W)^Y \rightarrow \text{Ln}W = Y(\text{Ln}W) + \text{Ln}M$ (hence, if $Y > 0$, $\text{Ln}W$ would be strongly and positively correlated with $\text{Ln}C$); and

Log transformation of $G = O(P)^Z \rightarrow \text{Ln}G = Z(\text{Ln}P) + \text{Ln}O$ (hence, if $Z > 0$, $\text{Ln}P$ would be strongly and positively correlated with $\text{Ln}G$).

Table 4. Regression results of LnP vs. LnG across recent and contemporary conflicts to understand trends in Group conflict deaths (G) and GCM (Z) based on Eq. 5 [$G=O(P)^Z$] and Dataset S4

World wars	GCM	95% CI	O	Adjusted R^2	R	N
World War I and World War II	0.82	0.61, 1.03	0.29	0.49	0.72	65
World War I	0.62	0.14, 1.15	4.82	0.26	0.51	20
World War II	0.89	0.65, 1.12	0.11	0.56	0.76	45
Smaller conflicts (United States and United Kingdom)	-0.31	-1.32, 0.71	178,971	0.01	0.09*	47

All relationships are significant at $P < 0.001$ unless marked * $P > 0.1$.

Table 5. Central tendencies and variation of DCI (X) for overall societies and different subgroups within Datasets S1 and S5 using Eq. 7

Type of society	Average DCI (X) (K = 0.1)	95% CI	N
All	0.85	0.84, 0.86	295
All states	0.85	0.84, 0.86	277
Small scale	0.94	0.89, 0.98	18
World War I and World War II	0.95	0.92, 0.97	48
20th/21st Century states with military service/conflict	0.91	0.89, 0.93	133
20th/21st Century states without military service/conflict	0.76	0.75, 0.78	95
NMC data 19th to 21st century states	0.86	0.86, 0.87	12,870

We expect to find the following.

- i) As P increases, W will increase following the proposed power law scaling relationship with P (Eq. 1), and W/P will decline with respect to P (Eq. 2).
- ii) As W increases, C will increase following the proposed power law scaling relationship with W (Eq. 3), and C/W will decline with respect to W (Eq. 4).
- iii) As P increases, G will increase following the proposed power law scaling relationship with P (Eq. 5), and because of decline in W/P with respect to P, there will be a commensurate decline in G/P with respect to P (Eq. 6).

Results

We explore the hypothesized log–log scaling relationships between group population (P), war group size (W), and proportion of war group size (W/P) (Eq. 1, Fig. 2A, and Datasets S1 and S5); between war group size (W), conflict casualties (C), and proportion of conflict casualties (C/W) (Eq. 3, Fig. 2B, and Dataset S2); and between P, overall group conflict deaths (G), and proportion of group conflict deaths (G/P) for World Wars I and II (Eq. 5, Fig. 2C, and Dataset S4). The results show that strong and significant log–log correlations exist along the proposed power law relationships between P and W, W and C, and P and G. Specifically, our data suggest the following.

- i) As P increases, W increases sublinearly, with $X < 1$, following Eq. 1 (very strong positive: $r = 0.82$, $P < 0.001$), and W/P also declines, with $X - 1 < 0$, following Eq. 2 (weak negative: $r = -0.23$, $P < 0.001$) (Fig. 2A).
- ii) As P increases, G increases sublinearly, with $Z < 1$ following Eq. 5 (strong positive: $r = 0.72$, $P < 0.001$), and G/P declines, with $Z - 1 < 0$ following Eq. 6 (weak negative $r = -0.22$, $P < 0.001$) (Fig. 2C).

However, we find that, as W increases, C also increases but supralinearly, with $Y > 1$ following Eq. 3 (very strong positive: $r = 0.91$, $P < 0.001$) (Fig. 2B). Consequently, we find that, as W increases, C/W also increases, with $Y - 1 > 0$ following Eq. 4 (weak positive: $r = 0.31$, $P < 0.001$) (Fig. 2B).

This increase in C/W with respect to W is an unexpected result. We expected to find that, in more specialized war groups characteristic of complex societies with large populations, there would be increasing numbers of noncombatant and support personnel who would not contribute to the casualty figures. The relatively lower proportions of active combatants in state conflicts were expected to correlate with declining C/W with respect to W.

The variation in the distribution of W, C, and G (Fig. 2) is captured in both the normalization constants K, M, and O and the exponents X, Y, and Z. If K, M, and O represent the proportions of P^X , W^Y , and P^Z that are affected by conflict involvement, conflict casualties, and group deaths, respectively, then X, Y, and Z represent the DCI, CL, and GCM, respectively.

To explore the value of DCI, CL, and GCM as standalone measures of conflict investment, lethality, and mortality, we regressed the data in Fig. 2. We also break down the analysis by type of social organization to see differences in DCI and CL between states and small-scale societies. The results for the regression values of DCI: X, CL: Y, and GCM: Z and normalization constants K, M, and O by social organization are shown in Tables 2–4.

The regression analysis enabled parsing the impact of scale of social organization on conflict investment and casualties. There are strong overall log–log correlations between P and W (Fig. 2A and Dataset S8, 1A.1), W and C (Fig. 2B and Dataset S8, 1B.1), and P and G (Fig. 2C and Dataset S8, 1C.1) for all data points in Datasets S1, S2, S4, and S5. The regression results (Dataset S8, 1A.1–1C.4) indicate similarly strong log correlations ($P < 0.001$) for these variables within the subcategories in Datasets S1, S2, and S4.

Small-scale societies show the same DCI ($X = 0.96$) as state-level societies ($X = 0.96$). However, they show greater variation of DCI [$0.74 < X < 1.18$, 95% confidence interval (95% CI)] than state-level societies ($0.86 < X < 1.01$, 95% CI) (Table 2). Small-scale societies also show a higher proportion (K) of P^X involved in W ($K = 0.08$, $0.01 < K < 0.67$, 95% CI) than state-level societies ($K = 0.02$, $0.004 < K < 0.1$, 95% CI) (Dataset S8, 1A.2 and 1A.3).

Small-scale societies show unexpectedly lower overall CL ($Y = 1.01$) and greater variance for CL ($0.60 < Y < 1.42$, 95% CI) than all state-level conflicts ($Y = 1.21$, $1.15 < Y < 1.27$, 95% CI) or contemporary state conflicts ($Y = 1.23$, $1.02 < Y < 1.44$, 95% CI) (Table 3). However, small-scale societies also show greater proportions (M) of W^Y contributing to C ($M = 0.14$, $0.20 < M < 1.14$, 95% CI) (Dataset S8, 1B.2) than do all states ($M = 0.02$, $0.01 < M < 0.04$, 95% CI) (Dataset S8, 1B.3) and contemporary states ($M = 0.03$, $0.001 < M < 0.34$, 95% CI) (Dataset S8, 1B.4).

For World Wars I and II, we see that, while World War I shows lower GCM ($Z = 0.62$) than World War II ($Z = 0.89$), the proportion (O) of P^Z in World War I is much higher ($O = 4.82$) than that World War II ($O = 0.11$) (Table 4). When we consider smaller conflicts for the United States and the United Kingdom (Dataset S4), we find no significant correlation between P and G ($r = 0.09$, $P = 0.24$) (Dataset S8, 1C.4). This finding is not surprising, as the conflict casualties for each of these conflicts would be correlated with the total size of the specific W engaged in these battles and not the overall P or even the overall W of the United States or the United Kingdom.

It is clear that varying values of the normalization constants (K, M, and O) affects the size of the exponents (X, Y, and Z), and there are strong negative correlations between K and X ($r = -0.72$), M and Y ($r = -0.99$), and O and Z ($r = -0.97$). We addressed this issue by applying the values of K, M, and O as constants derived from the overall regressions of P vs. W for K, W vs. C for Y, and P vs. C for Z (Tables 2–4). Thus, we maintain the general proportions of P^X , W^Y , and G^Z derived from the regression but also transfer all of the variability in the scaling relationship to X, Y, and Z for all societies and conflicts to calculate relative measures of DCI, CL,

Table 6. Central tendencies and variation of CL (Y) for overall societies undergoing conflict and different subgroups within Dataset S2 using Eq. 8

Type of conflict	Average CL (Y) (M = 0.04)	95% CI	N
All	1.17	1.16, 1.18	430
Small scale	1.22	1.09, 1.34	21
All states	1.16	1.15, 1.17	409
Historical state	1.16	1.15, 1.17	382
Contemporary state	1.16	1.13, 1.21	27

Table 7. Central tendencies and variation of GCM (Z) for World War I and World War II within Dataset S4 using Eq. 9

World Wars	Average GCM (Z)		N
	(O = 0.29)	95% CI	
World War I and World War II	0.82	0.80, 0.84	65
World War I	0.79	0.74, 0.84	20
World War II	0.83	0.80, 0.86	45

and GCM and their variations within and between social organization categories and through time (*Materials and Methods, SI Metadata and Caveats*, and *Dataset S6*).

For every society i , we calculate X_i for all P_i and W_i from *Datasets S2, S4, and S5* with $K = 0.1$ (from regressing P vs. W) to calculate mean and SD of X for the various social categories as seen in Table 5. Here, X_i would be a relative measure of DCI for society i within our dataset ($n = 295$) (*Dataset S2*) and the National Material Capabilities (NMC) (22, 23) dataset ($n = 12,870$) (*Dataset S5*) as shown in the following equation:

$$DCI_i = X_i = \frac{\text{Ln}(\frac{W}{K})}{\text{Ln } P}, \text{ where } K = 0.10. \quad [7]$$

For every conflict j , we calculate the value of Y_j for all W_j and C_j with $M = 0.04$ (from regression of W vs. C) to calculate mean and SD of Y for the various social categories as seen in Table 6. Here, Y_j would be a relative measure of CL within our dataset ($n = 430$) as shown in the following equation:

$$CL_j = Y_j = \frac{\text{Ln}(\frac{C}{M})}{\text{Ln } W}, \text{ where } M = 0.04. \quad [8]$$

For every country l involved in World Wars I and II, we calculate Z_l for all P_l and G_l with $O = 0.29$ (from regression of P vs. G) to calculate mean and SD of Z for the two conflicts as seen in Table 7. Here, Z_l would be the relative GCM suffered by each nation involved in the two world wars with respect to national population within our dataset ($n = 65$) as shown in the following equation:

$$GCM_l = Z_l = \frac{\text{Ln}(\frac{G}{O})}{\text{Ln } P}, \text{ where } O = 0.29. \quad [9]$$

The results are shown in Tables 5–7. Small-scale societies seem to show higher average DCI (0.94) and CL (1.22) than the average DCI (0.86) and CL (1.16) in state-level societies (Tables 5 and 6 and *Dataset S8, 2A.2–2A.4 and 2B.1–2B.3*), thereby affirming the argument that DCI and CL decrease with growing population and complexity.

However, we add an important caveat. The data for P and W for small-scale societies were collected at the time of active conflict, whereas many contemporary states in *Dataset S1* ($n = 95$) are not in active conflict situations or in preparation for conflict, a factor that would significantly affect DCI. We do not have data for small-scale societies not in conflict. We also observe that small-scale societies have higher variance for both DCI ($0.89 \leq X \leq 0.98$, 95% CI) and CL ($1.09 \leq Y \leq 1.34$, 95% CI) than state societies ($0.84 \leq X \leq 0.86$, 95% CI) and CL ($1.15 \leq Y \leq 1.17$, 95% CI). Levene's Tests for Equality of Variance show that the two samples do not have equal variance ($P < 0.0001$) (*Dataset S8, 2A.2–2A.4, 2B.2, and 2B.3*).

We controlled for situational context by comparing DCI for small-scale societies ($n = 18$, average DCI = 0.94) with DCI of 20th and 21st century states undergoing actual conflict and/or those with military draft or compulsory conscription ($n = 133$, average DCI = 0.91). Taking into account the high variance in both DCI and CL for small-scale as opposed to state-level societies, we find no significant difference in DCI between small-scale societies and contemporary so-

cieties engaged in preparation, buildup, or active conflict using t tests ($P = 0.14$) (*Dataset S8, 3.1*); t tests also show no significant difference ($P = 0.68$) between the average DCI of the multiple nations involved in the two world wars (average DCI = 0.95) and the average DCI of small-scale societies ($X = 0.94$) (*Dataset S8, 3.2*). Similarly, t tests show no significant differences in average CL between contemporary states and small-scale societies (*Dataset S8, 3.3*) ($P = 0.34$).

Discussion

Our results suggest that, as P increases, W also increases following the proposed power law relationship between P and W and that W/P declines as expected. Hence, there is a scaled positive log–log sublinear relationship between group population and war group size, where the proportion of war group size to population declines with growing population and complexity. However, there is no difference in DCI between small-scale societies observed during times of conflict and contemporary or recent state-level societies preparing for or engaged in active conflict.

As P increases, G also increases sublinearly following the proposed power law relationship between P and C , and G/P declines as expected, as noted by Falk and Hildebolt (16). However, we suggest that this relationship for states is significant only in the case of all-encompassing conflicts, such as the world wars or major international conflicts (e.g., the Iran–Iraq War). We find no significant correlation between P and C in the case of smaller individual conflicts in state societies (Table 4; *SI Metadata and Caveats* and *Datasets S4 and S8, 1C.4*). Hence, there is a scaled positive log–log sublinear relationship between populations of nations engaged in massive conflict and the conflict casualties of the overall conflict. While we only present results of the two world wars, given the sublinear scaling relationship between population and war group size, it follows that the proportions of overall casualties even of such all-encompassing conflicts would decline with respect to group population as populations increase.

However, we find that, as W increases, C increases supra-linearly following the proposed power law relationship with W and that C/W also increases. This supralinear trend showing increase in both absolute numbers and proportions of casualties to war group size is unexpected. The supralinear increase in conflict casualties (C) and proportions of casualties with respect to war groups (C/W) in any individual conflict might be caused by increased CL because of more effective weaponry (16, 24, 25). A more likely explanation is that, in large societies with established public infrastructure, high numbers of noncombatant deaths might arise because of postconflict infrastructure collapse after revenue depletion, diversion of resources to conflict efforts, and targeted annihilation of enemy groups that might include civilians and noncombatants. For example, the Biafra War of 1954–1957 is estimated to have involved 150,000 total combatants and resulted in around 1 million conflict-related deaths. However, the actual combatant deaths are estimated to range from 50,000 to 75,000. The rest of the casualties reported were noncombatants, primarily older male adults, women, and children who died in the ensuing famines, food shortage, and collapse of public health infrastructure (26). The collapse of infrastructure and targeted annihilation of enemy groups would also explain the high numbers of civilian deaths in World War I, World War II, Vietnam, or the numerous civil wars and rebellions in China (An Lushan 755–763 CE, Taiping 1850–1864 CE) (*Dataset S2*). Thus, factoring in noncombatant deaths from conflict-related infrastructure collapse within state-level conflicts could account for the increase in C/W , even as W/P declines with growing P . Hence, we find a scaled positive log–log supralinear relationship between number of combatants in a war group and the number of casualties of any conflict regardless of whether it is a single battle or a long, drawn-out war (Fig. 2B, *SI Metadata and Caveats*, Fig. S1, and *Dataset S8, 5.1–5.3*). However, there is no significant difference in CL between small-scale and state-level societies engaged in active conflict.

In short, small-scale societies do not have to maintain standing war groups but rather, can call on trained individuals for defense or attack, who then would resume other nonmartial activities during

nonconflict times. These expedient war groups tend to be trained in conflict through socially structured rites of passage and as such, do not demand the managerial efforts or energy costs that are incurred by specialized war groups in state-level societies. Furthermore, our data on such societies were drawn specifically during times of conflict and thus, may show levels of DCI that are not characteristic of small-scale societies for most of their normal daily practices. However, if we agree that these expedient war groups in small-scale societies are akin to drafted war groups or conflict era war groups in state-level societies, we see no differences in DCI between small-scale societies or such contemporary states. Similarly, we see that, while small-scale societies do show greater average CL than state-level societies, the greater variation in CL in small-scale societies does not enable us to differentiate small-scale societies as having statistically significantly more lethality than state-level societies.

Hence, while the probability of any random individual in a society being involved in any conflict or being a casualty of a conflict decreases with growing populations and complexity, we suggest that this trend is better explained by the power law scaling relationships between P , W , C , and G that seem to hold across societies, regardless of population size or the type and nature of institutions within any society past or present. We do observe that, in contemporary societies with compulsory military draft, such as Switzerland, Singapore, Russia, North Korea, South Korea, or Israel, or in societies undergoing ongoing large conflicts, such as the world wars, probability increases significantly, although actual proportions with respect to group populations might remain low. In the next two sections, we show how the scaling laws lead to more robust and effective indicators of group militarization and conflict intensity measured through DCI and CL.

DCI as a Robust Measure of Diachronic Conflict Investment and Intensity. DCI (or X) is a robust measure of militarization and conflict investment. We find that DCI is strongly correlated (Table 8; $r = 0.84$; $r_s = 0.83$) with the most commonly used measure of investment in conflict: the global militarization index (GMI) (27) (*Materials and Methods*). While GMI is applicable only to modern industrialized and monetized states, DCI can be applied at any population scale and to any type of economic or social system. It can, therefore, be used to track changes in conflict investment over time for any geographic or temporal context provided that P and W can be reliably measured or estimated.

We showed this by using Eq. 7 to calculate DCI for 20 contemporary states from Dataset S5 (see Dataset S6). DCI plotted over time, measured by the relationships between group population and the size of the war group, effectively captures changes caused by individual conflicts, including internal strife, and can also be used to track convergence and divergence in DCI of allies, adversaries, and expedient or formal diplomatic groups among contemporary nations (Fig. 3, Fig. S2, and Dataset S6).

We can effectively use changes in DCI for the United States, the United Kingdom, and Russia/Union of Soviet Socialist Republics (USSR) to map small and large conflicts for these countries from 1816 to 2014 (Fig. 3 and Table 9). The trends show that, before 1914, DCI of the United States was relatively low (and was largely concerned with its own internal and external stability). Apart from the American Civil War (1861–1865), the Mexican-American War (1845–1847), and the Spanish-American War (1898–1899), the DCI of the United States did not exceed 0.7 for most of the 19th century. While it rose to high levels commensurate with European nations during World War I (US DCI = 0.96), between World War I and

Table 8. Parametric and nonparametric correlation between GMI and DCI scores and ranks

Test	Correlation coefficient	95% CI	P
Pearson's r	0.84	0.79, 0.89	<0.00001
Spearman's Rho	0.82	0.75, 0.87	<0.00001
Kendall's Tau	0.64	0.57, 0.69	<0.00001

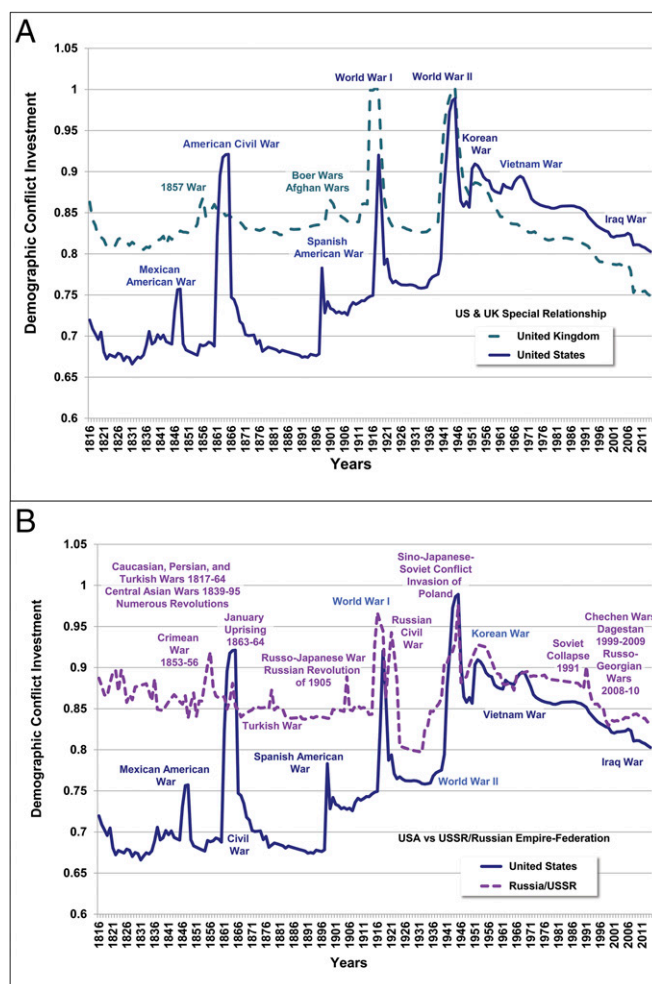


Fig. 3. Long-term trends in DCI (X) to show divergence and convergence among allies and adversaries from Dataset S6. (A) The United States–the United Kingdom alliance 1816–2014. (B) The United States–USSR/Russia adversarial interaction 1816–2014.

World War II, the US policies under Presidents Wilson, Harding, Coolidge, and Hoover were focused on distancing the United States from European conflicts. This focus and a lack of any local or regional conflict within the United States and neighbors between 1920 and 1940 as well as the Great Depression might have led to a decline in DCI from the high DCI levels of World War I. However, during and after World War II, the US DCI rose to levels similar to those of other participating nations and continued tracking with DCI of other key nations through the Cold War. We compare how the US DCI converges and diverges by calculating correlation of DCI between allies (the United States–the United Kingdom) and adversaries (the United States–USSR/Russia) within historical epochs (Table 9).

There is a low correlation between the United States and the United Kingdom and almost none between the United States and the Russian Empire before 1914. The correlation rises appreciably between 1914 (start of World War I) and 1945 (end of World War II), by the end of which the United States was an active and dominant member of the global conflict landscape in alliance with the United Kingdom ($r = 0.71$, 1914–1945) and in an adversarial relationship with Russia/USSR ($r = 0.53$, 1914–1945). After 1945, the DCIs of both the United Kingdom (ally) and the USSR (adversary) show almost identical correlations with the DCI of the United States between 1946 and 1992 ($r = 0.78$). After 1993, the DCI correlation between the United States and the United Kingdom increases rapidly ($r = 0.95$) as the two allies

Table 9. Pearson correlations (r) of DCI (X) for the United States–the United Kingdom and the United States–USSR/Russia from 1816 to 2014 (Dataset S6)

Time period	DCI: United States–United Kingdom	DCI: United States–Russia/USSR
	Pearson's r	Pearson's r
Before World War I	0.47	−0.08
1914–1945	0.71	0.53
1946–1992	0.78	0.78
1993–2014	0.95	0.61

engage in multiple conflict partnerships (Afghanistan, Iraq). However, as the Russian Federation was not considered a North Atlantic Treaty Organization (NATO) threat after the collapse of the USSR, there is a decline in the United States–Russian DCI correlation ($r = 0.61$). We can also see trends in DCI (X) for different groups of 20th/21st century nation state ally–adversarial relationships (Iran–Iraq–Egypt–Israel, India–Pakistan–China–North Korea–South Korea); formal alliances, such as NATO; and civic bodies: the United Nations Security Council Permanent Members over time, also calculated per Eq. 7, from Dataset S6 (Fig. S2).

While a full analysis and time series modeling of the trends in Fig. 3 (Fig. S2) are beyond the scope of this paper, we can draw some primary inferences from a preliminary inspection of these data.

- i) DCI is remarkably sensitive at identifying changing conflict needs and shows fluctuations even for small engagements, especially in earlier periods, where personnel are the primary investment rather than technology.
- ii) Trends in DCI show some decreasing demographic investment in conflict over time, suggesting that most modern nations have reached optimal sizes of armies that they can and desire to sustain at any time subject to population conflict needs, other economic or cultural considerations, or investments in conflict technology rather than personnel, all of which may contribute to declining DCI.
- iii) Increases in DCI at the time of major conflict are significant indicators of conflict investment, regardless of technology, as states tend to increase numbers of combatants in the field during active combat. This is especially pertinent given the lessons from the Iraq War (2003–2011), Afghanistan (2001 to present), and Syria (2011 to present) that clearly show that technology may not easily replace “boots-on-the-ground.”

CL as a Robust Measure of Diachronic Conflict Casualties and Combat Intensity. Finally, we examine CL over time by looking at trends in Y calculated from Eq. 8 over time and at differences in average and variation of CL within Dataset S2 (Fig. 4 and Table 10). Just as the exponent X can serve as a robust measure of DCI for comparative purposes, the exponent Y may also serve as a robust measure for CL, as it accounts for the scaling factor of war group size (and indirectly, of population).

As seen in Fig. 4, the data do not reveal a discernable trend in CL through time. To explore if different time periods results in different CL, we binned the data into various temporal categories of multiple centuries. Results from changes in average CL over 500-y blocks are shown in Table 10.

Although there are diachronic fluctuations in average CL (Table 10), these differences are not statistically significant or temporally consistent, regardless of how time blocks are pooled for averaging (Dataset S8, 5.1–5.3). We propose CL as a robust measure for evaluating combat intensity for societies across space and time. As it accounts for the scaling effect of war group size on casualties, it is hence more applicable for comparative analysis of conflicts in societies across different scales of social organization and through time as opposed to proportions of casualties with respect to group population.

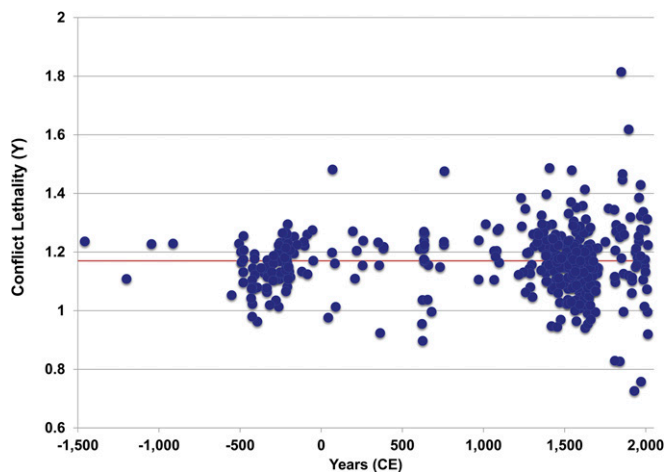


Fig. 4. Distribution of CL (Y) over time ($n = 430$) (Dataset S2). The red line indicates the general CL (1.17) derived from the regression.

Conclusion

On the basis of our modeling and analyses of the relationships between population, war group size, and resulting casualties, we find that war group size scales with population as proposed. We have derived a robust quantifiable measure of DCI that is applicable across all scales of population and over time, which can, in principle, be used to map both local and global changes in conflict investment. Use of the DCI accounts for the scaling effect of population and provides a means of assessing how relatively demographically invested in conflict any particular societies or groups of societies may be, regardless of size or time. We suggest that this measure is, therefore, an appropriate means of comparing rates of potential conflict-related violence over time to assess whether one period, place, or time is characterized by increased or decreased violence in comparison with another spatiotemporal context. DCI is thus similar to other measures of conflict investment, such as the GMI, but it is easier to calculate as it is based solely on population and war group size and thus, applicable to any temporal, regional, social, economic, or demographic context.

We also find that number of casualties scales with war group size within any particular conflict. We have derived a robust quantifiable measure of CL that is applicable across all scales of population and over time, which can, in principle, be used to map both local and global changes in CL. Use of the exponent CL is not dependent on unknown populations, but it accounts for the scaling effect of war group size and thus, provides a means of assessing how relatively lethal any particular conflict may be, regardless of social organization, conflict size, or time. We propose this measure as a more appropriate means of comparing conflict-related lethality over time to assess whether conflicts in one period, place, or time are characterized by increased or decreased lethality in comparison with another spatiotemporal context.

However, the relationship between population and conflict casualties given by the GCM is tenuous and only shows statistical

Table 10. Average CL across 500-y periods (Datasets S2 and S8, 5.1)

Historical period	Average CL	95% CI	N
Pre-500 BCE	1.18	1.11, 1.25	7
500–0 BCE	1.15	1.14, 1.17	85
0–500 CE	1.17	1.10, 1.24	15
500–1000 CE	1.17	1.12, 1.22	24
1000–1500 CE	1.19	1.17, 1.21	89
1500–1900 CE	1.17	1.15, 1.18	179
1900–2015 CE	1.15	1.10, 1.22	31

significance when considering massive conflicts involving most resources and attention of the involved state-level societies. Hence, we caution against its use as a measure of group violence if based on smaller conflicts and skirmishes. Consequently, in the absence of reliable data on population or war group sizes, we question to what degree isolated finds of extreme violence in the past [for instance, those found at Jebel Sahaba (Sudan, approximately 11,600 B.P.) (28), Nataruk (Kenya, approximately 10,000 B.P.) (29), or Schöneck Kilianstädten (Germany, approximately 7,000 B.P.) (30)] can be extrapolated to infer overall levels of violence in prehistory (31, 32) or to make comparisons with modern ethnographically or historically documented conflicts with more reliable documentation of population and war group size (5, 6).

Based on our results, we conclude that trends in proportions of war group size or casualties in relationship to population are, in fact, described by deeper scaling laws driving group social organization subject to contingencies, such as logistical constraints, expedient needs, and technology. These contingencies may place lower and upper limits on both (i) the size of the war group needed and sustained by any society at a given point in history, and (ii) how many casualties will result from any conflict within and between societies and account for the variation of the dependent variables around the trends revealed in the regression analyses. However, the scaling relationships show clear log-log trends that are highly significant and follow similar scaling relationships observed within biological and social systems (13–15, 17, 18).

Indeed, while the probability of being involved in conflict as a member of a war group or as a casualty of conflict in large and/or contemporary societies is lower than in small-scale societies, it might not be driven by any better or worse angels of our nature. This probability might merely be an emergent outcome of differential logistical constraints and group populations. This probability may also change rapidly based on group conflict needs, expedience, and contingency. The demographic investment of any society in its own conflict issues or the lethality of any conflict then is not a matter of proportions but of scale.

In closing, we draw specific attention to the alarming rise of nationalism and the growing conflicts within and between 21st century nation states, leading to reemergence of arms races among prominent contemporary actors. Various nations and their allies have repeatedly come into closer confrontation with others ever since the conflicts, rebellions, and insurgencies in the Middle East and North Africa following the Iraq War (2003–2011), Arab Spring (2011), and the Syrian Civil War (2011 to present). We expect to see various nations aiming to boost their war capabilities through increase in defense expenditure as well as DCI. We might also see increased CL if, during armed conflict, warring groups prioritize national or group interests over cooperative or détente alliances, accords, and agreements. The approach presented here would enable future modeling efforts that might help conflict scholars, policymakers, and practitioners to better anticipate trends in conflict buildup and understand CL; to reduce the attritional effects of massive violence on local, regional, and global social economies; and ultimately, to make sense of the conflict landscape of the next decade.

Materials and Methods

Scaling Models and Derivations. Eqs. 1, 3, and 5 were constructed based on the power law function that describes scaling relations in social and biological systems: $Y = \alpha X^\beta$. This function enables modeling and testing of the proposed scaling relationships between independent and dependent variables P vs. W, W vs. C, and P vs. G: $Y = \alpha(X)^\beta$. Hence, $W = K(P)^X$, $C = M(W)^Y$, and $G = O(P)^Z$. This function also enables the derivation of Eqs. 2, 4, and 6, where proportions (W/P, C/W, and G/P) can be modeled $Y = \alpha(X)^\beta$, $Y/X = \alpha(X)^\beta/X$, and $Y/X = \alpha(X)^{\beta-1}$. Hence, $W/P = K(P)^{X-1}$, $C/W = M(W)^{Y-1}$, and $G/P = O(P)^{Z-1}$. The calculation of values for the β exponent was based on the

logarithmic transform of $Y = \alpha X^\beta$, leading to Eqs. 7–9 that maintain α as a constant so that all of the variation in the correlation of Y and X is captured in β :

$$Y = \alpha(X)^\beta \rightarrow \ln Y = \ln(\alpha(X)^\beta) \rightarrow \ln Y = \beta \ln X + \ln \alpha \rightarrow \beta = \frac{\ln Y - \ln \alpha}{\ln X} \rightarrow \beta = \frac{\ln(\frac{Y}{\alpha})}{\ln X}$$

Hence, $DCI = X = \ln(W/K)/\ln P$, where $K = 0.10$; $CL = Y = \ln(C/M)/\ln W$, where $M = 0.04$; and $GCM = Z = \ln(G/O)/\ln P$, where $O = 0.29$. We could have held K, M, and O to be one. In that case,

$$DCI = \frac{\ln W}{\ln P} \quad CL = \frac{\ln C}{\ln W} \quad GCM = \frac{\ln G}{\ln P}$$

However, since DCI, CL, and GCM are relative measures, as long as K, M, and O are constant, there is no change in the trends of DCI, CL, or GCM through time or with population. Furthermore, maintaining the values of K, M, and O derived from the regression preserves the notion that these values reflect the overall proportions of P^X , W^Y , and P^Z that contribute to overall W, C, and G, respectively, across societies.

Metadata. Data on P, W, C, and G were gathered from various scholarly sources (Dataset S9) and are organized in Datasets S1–S6. When different sources presented different estimates for P, W, C, or G, the geometric mean of the different values was used in the analysis to ensure against overestimation. *SI Metadata and Caveats* and Dataset S9 have specific information on caveats and sources for the different datasets as well as our analysis of correlations between annual war group size and conflict casualties and between total war group size and conflict casualties (*SI Metadata and Caveats* and Fig. S1).

Statistical Analysis. All figures were constructed using Microsoft Excel along with trend lines, regression equations, and R^2 values. The statistical analysis (Dataset S8) was performed using IBM SPSS Statistics, Version 24. Regression analysis of $\ln P$ vs. $\ln W$, $\ln W$ vs. $\ln C$, and $\ln P$ vs. $\ln G$ seen in Tables 2–4 along with 95% CIs for regression coefficients (K, M, O and X, Y, Z) and bootstrapping to account for low sample size in some of the subcategories are in Tables 2–4 and Dataset S8, 1A.1–1C.4. Central tendencies, t test, and ANOVA of X and Y are in Tables 5–7 and 10 and Dataset S8, 3.1–3.4 and 5.1–5.3. Parametric and nonparametric correlation of Bonn International Center for Conversion (BICC) GMI and DCI are in Table 8 and Dataset S8, 6.1–6.3.

Testing the Validity of DCI Against Known GMI. The BICC has developed the GMI, which is a sophisticated military index that calculates the relative weight and importance of the military apparatus of one state in relation to its society as a whole based on data from 152 contemporary states. The GMI as developed by the BICC is based on many factors under a proprietary methodology that includes military expenditure and health access. We developed our own ranking based on DCI of the 173 contemporary states in Dataset S1 (Dataset S7). We compare our DCI rankings of 151 states within these 173 states for the year 2014 with the BICC GMI rankings of the same 151 states using Spearman's Rho ($r_s = 0.83$, $P < 0.00001$), Kendall's Tau ($t = 0.64$), and Pearson's Correlation of BICC GMI scores with DCI X values ($r = 0.84$, $P < 0.00001$) as seen in Table 8 and Datasets S7 and S8, 6.1–6.3. All of the correlation results suggest significant and strong agreements between BICC GMI and DCI. Given that DCI can be applied to all societies, from small-scale groups to industrial states, it is an easier and more applicable alternative to GMI.

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