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Approaches to Understanding Sustainable Peace: Qualitative Causal Loop Diagrams and Quantitative Mathematical Models

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Abstract

Scholarly research on peace has overwhelmingly focused on negative peace, or the absence of conflict, aggression, violence, and war. We seek to understand holistic peace systems, the political, economic, and social systems that sustain peaceful societies. We show how two methods can help us understand the properties and dynamics of such complex peace systems. Each method provides insights from different perspectives to help understand sustaining peace. The causal loop diagram helps us to identify the peace factors and the connections between them. The mathematical model helps us determine the quantitative results of the interactions between all the peace factors. Using these methods, we found that there is no single "leverage" factor that is the lynchpin in creating sustainable peace. Rather, the small effects of a large number of positive peace factors that support peace can collectively overcome the stronger emotional response to the negative conflict factors that jeopardize peace.

Keywords

peace studies, positive peace, sustaining peace, causal loop diagrams, mathematical modeling, social psychology, methodology

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Generating and maintaining peace, within communities, nations, and the world is a vital component for achieving human fulfillment and happiness. Previous research studies on peace have focused primarily on negative peace, or the absence of conflict, aggression, violence, and war (Goertz, Diehl, & Balas, 2016). Recently, there has been a growing movement on studying peace holistically by determining the conditions necessary to generate and sustain peace in the world. This new approach to sustainable peace examines the political, economic, and social systems that sustain peaceful societies and how they are supported by local, national, regional, and international actors.

These previous approaches have used primary anthropological assessments, social psychological studies, numerical data from databases, surveys, and expert opinions to identify the elements that characterize peaceful societies. For example, the anthropological and social psychological studies have identified the importance of an overarching social identity, interconnections among subgroups, interdependence, socialization of peaceful values, conflict management mechanisms, and visionary leadership for achieving peace (Coleman & Deutsch, 2012; Diehl, 2016; Fry, 2005; Goertz et al., 2016; Mahmoud & Makoond, 2017). Data from international organizations, nation states, foundations, and other sources have been used to quantify indicators of peace from measures of well-functioning government, equitable distribution of resources, free flow of information, good relations with neighbors, high levels of human capital, acceptance of the rights of others, low levels of corruption, and sound business environment (Institute for Economics & Peace, 2018). Although these approaches identify the elements of a positive peace system, they do not clarify how a peace system arises as the emergent property of the interactions between those separate elements.

These systems of peace depend on a large number of factors that strongly influence each other. How can we conceptualize such a complex system, determine the most important influences within it, and predict the consequences of different interventions? We describe new approaches to peace studies being developed by the Sustainable Peace Systems Mapping Initiative, convened by the Advanced Consortium on Cooperation, Conflict, and Complexity (AC4) at The Earth Institute at Columbia University. We show that a hybrid approach of a qualitative system analysis using causal loop diagrams and a quantitative system analysis using mathematical modeling and computer simulations can together provide a valuable new perspective on understanding sustainable peace. This hybrid approach may also prove equally useful to better analyze and understand a wide range of other complex social systems in families, companies, or nations.

In complex social systems, the interaction between all the elements can look like a tangled ball of twine. The high-level properties of the system as a whole can also be significantly different from the low-level properties of the interactions between the elements. For example, low-level individual timing choices can lead to a high-level traffic jam or low-level individual conversations can lead to high-level linguistic changes in vocabulary or grammar (Garud, Simpson, Langley, & Tsouka, 2015). How can we make sense of such a multicomponent, multilayered, entangled, and dynamic system? Here, we describe two methods that can help us understand such systems: qualitative causal loop diagrams and quantitative mathematical models. Each method provides a different perspective to give us insights into the properties of the system. We show that these methods can inform studies of the conditions needed to generate and sustain peace in the world.

Simple and Complex

Simple: One Cause–One Effect

We are used to seeing clear examples of a single isolated, well-defined cause leading to a single isolated, well-defined effect. What could be simpler? Your cue stick sends a white billiard ball, of a certain size, weight, speed, and direction of motion, rolling on surface with very little friction, into a red billiard ball. For more than 300 years, thanks to Isaac Newton (and others), we can accurately predict and confirm by measurement, the speed and direction of both the white and red billiard balls after their elastic (energy conserving) collision. One cause, one effect.

You set up a small electrical circuit with a few elements, little plastic-covered cylinder things, technically called resistors, inductors, and capacitors. You plug it into the alternating current outlet from your wall. The voltage and current vary in time, in a rhythmic and completely predictable way, for each of those elements.

You pour an equal amount of the solutions of an acid and a base of equal strength together and so they neutralize each other. The solution pH is 7.0, nearly exactly, you measured it with your digital pH meter. Just what you learned about in chemistry, just what you expected.

The *Staphylococcus aureus* bacteria, which normally rests without any other consequences on the surface of your skin, is pushed deep into you when the stinger of that buzzing bee stung into your hand. The redness in your skin is spreading, slowly, up your arm. No problem, the antibiotic dicloxacillin that your doctor prescribes kills the bacteria, and over the next few days the redness fades away. The cause of the infection was clear, the cause of its successful end was equally clear.[1]

Complex: Emergent System Properties

In the examples above, a clearly identifiable single cause leads to a clearly predictable and identifiable single outcome. This does that. You can forget about the rest of the universe. Simple. We are so used to seeing, or thinking that we are seeing, such simple examples, that we can come to think that this is the way the whole world works. It is not.

Many, may be most, real physical, biological, and social entities are very different from those "simple" examples. They are true systems, meaning that they consist of a large number of strongly interacting components. The properties of the whole system "emerge" or "self-organize" from its parts and yet those macro system properties are typically strikingly different from the properties of the micro interactions between its parts (Kelso, 1995). The flow of sodium ions through ion channels in the cell membrane in an action potential seems far removed from that feeling of falling in love. Positive and negative "feedback loops" of interactions can make it hard to untie the tangled ball of effects and so we may not be able to identify a single cause with a single effect. This has been well documented in the politics of international relationships (Goldstein & Freeman, 1990; Jervis, 1997). The link between cause and effect is made even more difficult to discern if there are also subsystems, with contrasting types of interactions or goals. Also, typically, such systems may have "attractors," a limited number of sets of values of the variables that the system returns to, if disturbed. The tendency of social systems to continually return to attractors of violent or dysfunctional states has been identified as a leading characteristic of intractable conflicts (Coleman, 2011; Vallacher et al., 2013). Such systems also tend to be "non-linear," meaning that changes in some values do not necessarily lead to proportionate changes in other values. Rather, a small change in a parameter may produce a surprisingly large change in the whole system, called a "bifurcation" (Strogatz, 1994). Sometimes changes in the micro properties can lead to dramatic, "unanticipated consequences" in the whole system. The nonlinearity in the interactions of the components can lead to "sensitivity to initial conditions," also known as "chaos" or the "butterfly effect" (Schuster, 1988). If a butterfly beats its wings in Beijing it triggers an ever-larger cascading set of events in the atmosphere that ultimate bring a storm to New York City (Gleick, 2008). Even though each small step is deterministic and predictable, over the long run, the state of the system is not predictable. Real-world systems also tend to be "self-adapted," morphing themselves in response to their own actions and the environment around them, dynamic rather than fixed and static (Holland, 1999).

Understanding Systems

The challenge is how do we conceptualize such real-world systems in order to understand them. This is our challenge in understanding sustainable peace. In addition, we also want our understanding to suggest how to intervene in order to generate or strengthen peace and what will be the consequences of those interventions. We review two important ways that we have used to think about systems, each with its own advantages and limitations. What is really interesting is that neither of these ways primarily involves words. A picture is worth a thousand words. Equations, with their solutions, can also be worth many words. Our experience in using qualitative pictures and quantitative equations together to understand sustainable peace serves as an example of how those combined techniques can also be useful in understanding other complex social systems.

Qualitative Pictures: Causal Loop Diagrams

In any system, how can we make sense of the whole system and of the role of each element in the system? One way is to make a picture.

Nearly a hundred years ago, in order to understand how organisms evolve over a rough fitness landscape, Sewall Wright (1986) proposed picturing the path of their evolution over a series of steps: boxes for the steps, arrows for the paths through them. To make evolutionary sense, he established rules on how to trace a path along the arrows (technically, making these directed, acyclic graphs). Sixty years ago, Jay Forrester (2013) generalized the boxes and arrows to represent the stimulating or inhibiting influences in any system, first applying this "system dynamics" to the economics of business cycles. The reification of these positive and negative influences from one factor to another as boxes or circles and the directed arrows between them are known as "causal loop diagrams." Linda Sweeny and Dennis Meadows (2010) developed games and exercises for such "systems thinking" for K-12 teachers. Joseph Novak (2009) developed causal loop diagrams into "concept maps" of abstract concepts as a way for students to organize and understand the material they are trying to learn.

A causal loop diagram pictures the named individual elements of a system as the "nodes" of a graph and the links between them as the "edges" of that graph. The links are causally directed from one node to another. The strength of the links may all be the same, or they can differ from each other. The links may also either be "positive" meaning that an increase in the value of the originating element increases the value in the target element, or "negative" meaning that an increase in the initiating element decreases the value in the target element. Typically, positive links are identified by a "+" sign or a color (such as blue) and the negative links by a "–" sign or a color (such as red).

The strength of a causal loop diagram is that it helps us understand how individual elements function together as a system. We can literally see the large-scale structure of the whole system. All the individual elements are clearly identified. How each element influences, or does not influence, each other element is also made clear. It allows us to trace through the effects of any one element on the whole system by following its links from that element, to the next elements it is connected to, and from those elements to the further elements that they are connected to, and so on. In this way we can build up a quasi-dynamic picture of what would happen if the value of that first element were to change. Often, sets of elements and their links form a cycle, that is, the trail of connected links return to an element from which they started. These cycles may be "positive feedback loops" also called "reinforcing loops" where the returning influence increases the value of the starting element. These cycles may be "negative feedback loops" also called "balancing loops" where the returning influence decreases the value of the starting element. These reinforcing and inhibiting feedback loops are given an essential role in understanding system properties as they determine how the flow of information or energy increases, or decreases, the values of elements or groups of elements.[2]

A causal loop diagram serves many different purposes (Vandenbroeck, Goossens, & Clemens, 2007). It is a heuristic tool that supports and promotes meaningful conversation among experts to develop new questions and hypotheses for data gathering and theory building. It is a knowledge management tool that organizes the available knowledge in an integrative way and illustrates how individual elements and groups of elements fit into large-scale structures of the system. It is a diagnostic tool that helps to identify potential gaps in current policy approaches. It is an operational tool to identify “leverage points” in a system as a starting point for policy interventions (Meadows, 1999). Perhaps, most important, it is a process tool. The diagram can be created as an interactive team exercise that forces the team to think up and think through the essential elements of a system and how they interact with each other (Burns, 2007). That is why it has been said that 90% of the value of the causal loop diagram actually resides in the process that created it, and only 10% in the finished diagram itself (Danny Burns, personal communication, 2014). This process allows the team to view and therefore frame the system from multiple perspectives. The ability to then merge these multiple perspectives into a coherent whole is a core aspect of “integrative complexity,” which research has found leads to better decision making with complex problems (Redding, 2016; Suedfeld, 2010; Tetlock, 2005).

A casual loop diagram also has limitations. Even though above we referred to the “value” of the elements, these elements have no quantitative, or even ordinal, values. It is also essentially a static representation of the interactions between the elements, while real systems display interesting and sometimes ever-changing, patterns in time. In principle, it might be possible to think through if this element changes, that element will change, which will change something else, and so on. However, in practice that is very hard to do when there are many elements. Moreover, the value of each element must depend on the values of all the other elements and their interactions, even though that value cannot be determined from the causal loop diagram. We will show below how these limitations can be addressed by developing a quantitative mathematical model from a causal loop diagram.

Visualizing Sustainable Peace Through Causal Loop Diagrams

We now illustrate the construction and interpretation of such a causal loop diagram that we developed to better understand the conditions needed for sustainable peace in the world. We developed this diagram in five steps. First, we did a comprehensive review of the published literature. Then, 225 contemporary peace researchers were invited to participate in an online survey. Seventy-four scholars from 35 disciplines completed that survey (Kyong et al., 2015) and 62% of them identified a small number of categories which defined a “core engine” of sustainable peace. Next, a workshop of 50 experts in academic peace studies, policy makers, and practitioners from the peace-building community reviewed and revised the causal loop diagram. The core faculty in the project then used the feedback from the workshop to revise and extend the diagram. The empirical literature on peace was then used to refine the relationships between the elements of the causal loop diagram. The resulting causal loop diagram is shown in Figure 1.

The creation of this causal loop diagram necessitated making some important choices. The elements identified were those that described intergroup processes rather than individual or nation state processes. Even among intergroup process some

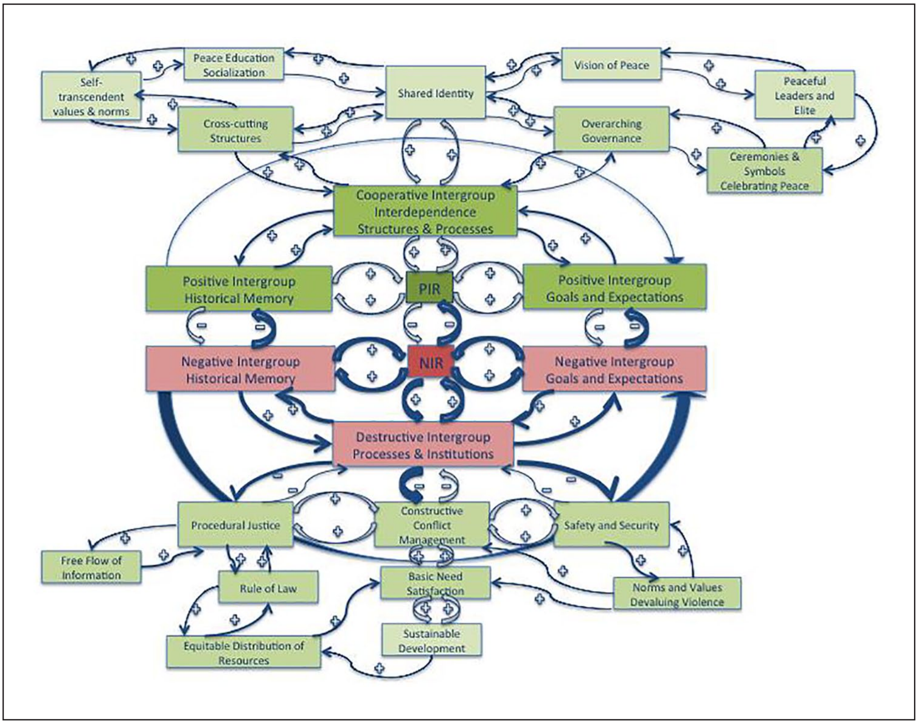

Figure 1. Causal loop diagram proposed by the Advanced Consortium on Cooperation, Conflict, and Complexity (AC4) at The Earth Institute at Columbia University for the peace factors involved in generating and maintaining sustainable peace in the world. Positive peace factors are in shades of green (light gray) and negative peace factors are in shades of red (dark gray). Positive causal links are labeled by "+," negative causal links by "−" and are directed as indicated by the arrowheads. The strengths of the causal links correspond to the thickness of the links.

elements are at lower levels of abstraction, principally behavioral or social psychology factors (such as positive or negative responses to outgroups) while some elements are at higher levels of abstraction at a societal level (such as government institutions, rule of law, and cultural mores). We believe that the causal loop diagram (and later the mathematical model generated from it) are sufficiently robust that it can plausibly describe the interactions between these processes at different levels.

We also chose elements that have broad applicability to many different sustainable peace systems. Ground-truthing exercises with local participants will be needed to determine the range of applicability of such a general model or whether more specific models with additional specific elements are needed to adequately describe different peace systems.

We also structured the topology of the causal loop diagram, that is, how the elements are connected to place positive and negative intergroup reciprocity (described below) as the most essential central elements of the system which are then surrounded by other elements in expanding layers of interactions. Other types of groupings were possible. For example, communication and cultural orientation elements could constitute their own subsystem and infrastructure elements like the rule of law or sustainable development policies their own subsystems and then those sub-systems connected to each other. Often, when we considered such hierarchical clusters, we then realized that some elements within each subgroup should be directly connected to elements within another subgroup. We made the best choices that we could between a "flat" world where each element is connected to all the other elements and a "vertical" world where only subgroups connect to other subgroups. Further data might clarify the best choice for these different topological patterns.

What was learned from the causal loop diagram proposed by Coleman et al. (2017)? (1) We identified 25 "peace factors" that are important in generating and sustaining peace. (2) We identified a "nodal focus" of two peace factors, positive and negative intergroup reciprocity (how you respond when the other group does something good for you) and a "core engine" of six additional peace factors that together define a sustainable system of peace: positive and negative intergroup historical memory, positive and negative intergroup goals and expectations, and cooperative and destructive intergroup processes and institutions. (3) We proposed positive and negative interactions between those peace factors that define 26 testable hypotheses, which we are currently testing by a meta-analysis of published studies. (4) We identified positive and negative feedback loops within this system that enhance or weaken a peace system. (5) Most important, the process of developing the causal loop diagram led the team of academic, practitioner, and community stakeholders to consider the elements and their interactions needed for peace from multiple perspectives and frameworks. In this way, as noted above, the insights and reflections gained from the interactive team process of generating the casual loop diagram provided even more value than the finished diagram itself. We also used the causal loop diagram as a starting point for "ground truthing" exercises with local communities in Afghanistan, the Basque Country, Colombia, and South Sudan (Scensei and AC4 2015).

What was *not* learned from the causal loop diagram? (1) The causal loop diagram does not specify the quantitative values for the peace factors, so that we cannot distinguish their relative importance. (2) It does not inform us about the relative values that the peace factors achieve as a result of their initial values and the strengths of the interactions between them. (3) It does not identify the most important peace factors or the most consequential interactions between them that determine the final state of the system. (4) It does not predict if there are none, or one, or multiple final states ("attractors") that the system returns to when disturbed. (5) It does tell us about the dynamics in time of the system, namely whether the values of the peace factors evolve smoothly in time to a final state, swing back and forth between different values ("limit cycles"), vary in a seeming random way with an underlying order that can be revealed ("chaos"), or fluctuates stochastically. We next show below how a rigorous mathematical model, based on the causal loop diagram, can provide some information about these issues.

Quantitative Equations: Mathematical Models

The strength of a mathematical model is that we can compute the interaction between all the elements at once and thereby study the behavior of the whole system. A mathematical model can determine the quantitative values of the elements and thereby the relative importance of each element and how each value depends on the strength of the connections between all the elements. We can also use mathematical tools to analyze the system to determine the most consequential elements and connections. We can determine the number of attractors in the system, the values of the elements in those attractors, and the dynamics in time of the system. A mathematical model yields quantitative predictions that can be compared with empirical data. Those quantitative values can be the basis for informative graphic displays and interactive interfaces that allow policy makers to explore the consequences of different interventions in the system. Perhaps the greatest strength of a mathematical model is that it frees us from thinking that a single isolated cause C leads to a single isolated effect E, because we can now compute and display how a change ripples and echoes throughout the entire system. In these ways, a mathematical model provides additional value to a causal loop diagram by revealing properties about a system that may be difficult to discern from the causal loop diagram alone.

A mathematical model also has limitations. We must define quantitative relationships between the elements and how those values evolve in time. Limited data may force us to make uncertain choices for these relationships, especially the nonlinear ones, and on the parameters on which they depend. The solution of these equations may be challenging, either analytically or numerically. Limited data may also mean that we may not be able to fully test the predictions of the model against accurate empirical data to be able to improve or validate the model. Two situations are possible. In what we call a "general model," the complexity of the model behavior is sufficient so that it has the qualitative properties of the real system, such as attractors, or self-organization, or threshold effects. Experimenting with such a mathematical model provides insight, experience, and intuition in learning what to expect from such a complex system in general, even though the model may not provide "predictive analytics" for our specific system. In what we call a "specific model," the quantitative predictions of the model are iteratively tested and improved by adjusting the model to match specific quantitative empirical data and so the model does provide quantitative predictive analytics.

A mathematical model can be implemented in many different ways, including, but not limited to, ordinary differential equations, partial differential equations, self-organizing critical systems, cellular automata, agent-based models, networks, multiplexed networks, and artificial neural networks (Strawinska-Zanko & Liebovitch, 2018). Here, we formulate a general mathematical model of a causal loop diagram by generalizing our previous models of social interactions (Fernandez-Rosales, Liebovitch, & Guzman-Vargas, 2015; Liebovitch et al., 2008; Liebovitch, Peluso, Norman, Su, & Gottman, 2011; Peluso, Liebovitch, Gottman, & Su, 2012). The quantitative value of each element x_i is given by

$$\frac{dx_i}{dt} = -|m_i|x_i + b_i + \sum_{j=1}^{n} c_{ij} \tanh(x_i). \quad (1)$$

On the left-hand side of the "equal" sign, we use a first derivative so that the values evolve smoothly in time. On the right-hand side: (1) the first term limits excessive growth of the value, (2) the second term represents internal self-stimulating or system-wide conditions, and (3) the last term is the influence from the other variables weighted by the strength of their connections c_{ij}. The hyperbolic tangent function, tanh, is used so that at low values the elements influence each other linearly, but that influence reaches a limiting threshold at high values. (Such a tanh function is typically used in connecting the nodes of an artificial neural network. In essence, the equations here form an analogy of an artificial neural network, although here the parameters of the network, and therefore its stored "memories," are set a priori rather than determined by training the network.) An important assumption in our formulation is that the strength of the connections between the variables is constant in time and independent of the values of the variables. Such time-dependent changes in the connection strengths and their nonlinear dependence on the values of the variables play an essential role in "learning" in artificial neural network models of brain function. However, in this model, we need to make these simplifying assumptions in order to keep the number of adjustable parameters and the complexity of the model tractable. We look forward to explore the importance of such "learning" in more complex models in the future.

Starting from initial conditions, such as all x_i equal to 0.1 or 1.0, we then numerically integrate this set of simultaneous equations forward in time using Euler integration[3]:

$$x_i\left(t+\Delta t\right) = x_i\left(t\right) + \Delta t\left\{-|m_i|x_i\left(t\right) + b_i + \sum_{j=1}^{n} c_{ij} \tanh\left(x_j\left(t\right)\right)\right\}. \quad (2)$$

A Mathematical Model of Sustainable Peace

We now illustrate the construction and interpretation of such a mathematical model that we developed from the causal loop diagram of the dynamics needed for sustainable peace in the world. Since negative events produce stronger and longer lasting emotional effects (Gottman, Murray, Swanson, Tyson, & Swanson, 2002), we separated the elements into "positive" peace factors that support peace and "negative" peace factors that jeopardize peace, so we could set the parameters differently for each type of element. We set the time decay constant $m_i = -0.9$ for most peace factors, but set $m_i = -0.2$ for strongly negative peace factors so that their effects decay more slowly in time. We restrict all $x_i \geq 0$ so that a negative value of a peace factor over a negative link does not produce a positive effect. We typically set $b_i = 0$ but also studied models where $b_i \neq 0$ that correspond to either self-rewarding stimulation or system-wide influence from external constrains. An example of self-rewarding stimulation for the positive intergroup reciprocity peace factor would be that when you do something good for someone from another group, you feel good about it, so you do more of

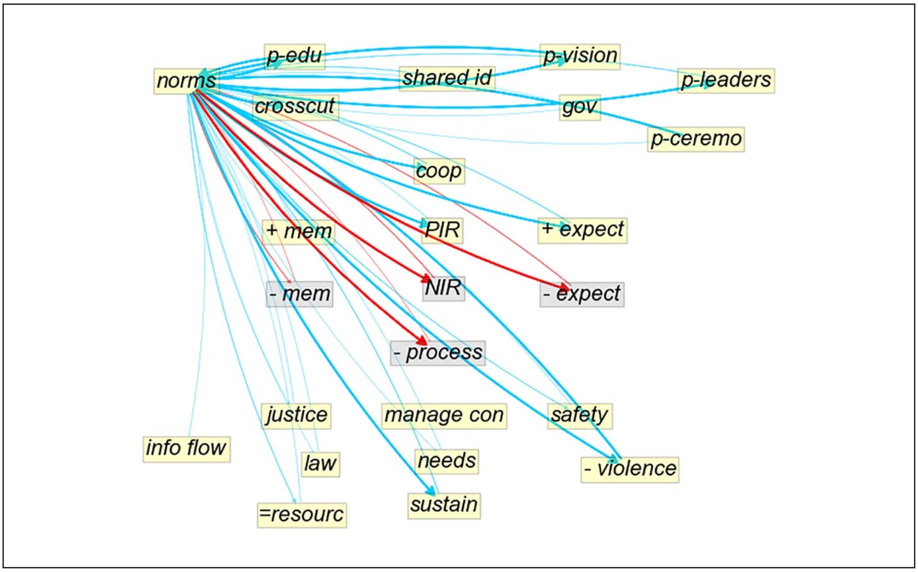

Figure 2. Mathematical model of the causal loop diagram for the peace factors involved in generating and maintaining sustainable peace. Positive peace factors are in yellow (light gray) and negative peace factors are in (dark) gray. Positive causal links are blue (light gray), negative causal links are red (dark gray), and are directed as indicated by the arrowheads. The strength of the causal links corresponds to the thickness of the links. For clarity, only the links between the peace factor "norms" and the other variables are shown. Plotted here are the initial conditions before a computation. The size of the text font is scaled to the values of its peace factor.

it. Examples of system-wide external constraints are laws or social mores. (In models in physics, b_i is called an "explicit symmetry breaking parameter.") The quantitative values of the strengths of the links c_{ij} between the peace factors were estimated from 85 published studies. We then used Equation (2) to compute how the properties of the system depended on the parameters m_i, b_i, c_{ij}, and how the long-term values of the peace factors depended on their initial values and the dynamics in time of how they reached those long-term values. A graphic visualization of the mathematical model is shown in Figure 2.

What was learned from the mathematical model? (1) We emphasize that an essential consequence of this model is that the values of the peace factors are completely determined by the parameters of the model and the initial values of the peace factors. Knowing how each peace factor influences each other peace factor is a sufficient condition that determines what the system does, how it will do it, and where it will wind up. (2) As identified in the causal loop diagram there are some positive factors that support peace, such as positive intergroup reciprocity and positive intergroup goals and expectations, and some negative factors that oppose peace, such as negative intergroup reciprocity or negative intergroup goals and expectations. For a wide range of parameters, we found that the mathematical model has only two attractors, that is, sets of values of the peace factors that the system returns to when it is pushed away from those values. Either, the positive factors that support peace are zero and the negative factors that oppose peace have high values, or the opposite case, where the factors that support peace have high values and the factors that oppose peace are zero. The system winds up either in a good place for sustainable peace or a bad place where sustainable peace is not likely. It never winds up in-between those good or bad places. (3) The values of the peace factors approach their final values smoothly, usually monotonically. The dynamics shows no evidence for continual oscillations ("limit cycles") or unpredictable behaviors ("chaos"). (4) Whether the system winds up in a good or a bad place depends most sensitively on two things: the starting values of the peace factors and the links c_{ij} between them. (5) As explained next, small effects from a large number of positive peace factors play the most important role in driving the whole system to a good place for sustainable peace.

Some of these features of the mathematical model are found in real-world conflicts. Most notably, there are sustainable systems of peace or sustainable systems of intractable conflicts that are analogous to the separate attractors of the mathematical model (Coleman, 2011; Vallacher et al., 2013). The peace or conflict system reliably returns to its previous state when moderately perturbed. It takes much more significant changes to alter the final state of the system. Our model is deterministic with fixed parameters. It may also be the case that some degree of randomness in the initial values of the variables or the strengths of the connections between them may help the system switch from one attractor to another.

If only a central set of core variables are considered, such as shown in Figure 3, the system almost always winds up in bad place where sustainable peace is unlikely. In this bad place, the negative peace factors that oppose peace have large values and the positive peace factors that support peace have values equal to zero. Although we found this result from the numerical simulations of the mathematical model, we can understand it in the following way. (Being able to "make sense" of the discoveries from a mathematical model is one way that such a model helps us gain insights into a system.) Since negative social interactions hurt deeper and last longer than the good feelings from positive social interactions, the stronger connections between the negative peace factors reinforce their own values. Then, the negative connection of those negative peace factors to the positive peace factors drives down the values of the positive peace factors. Only if this system is started very close to its values in the good place will it stay there. In the language of complex systems, the basin of attraction for the good attractor is very small and the basin of attraction of the bad attractor is very large.

If this system always goes to a bad place, how is there ever peace in the world? As the causal loop diagram was developed during this project, the findings from the evidence base in the literature as well as the social science scholars and peace practitioners kept adding more positive factors that support peace. This information led to the causal loop diagram shown in Figure 1 and the mathematical model developed from it shown in Figure 2. In this mathematical model, the system almost always winds up in a good place! The larger number of positive peace factors overwhelm the stronger

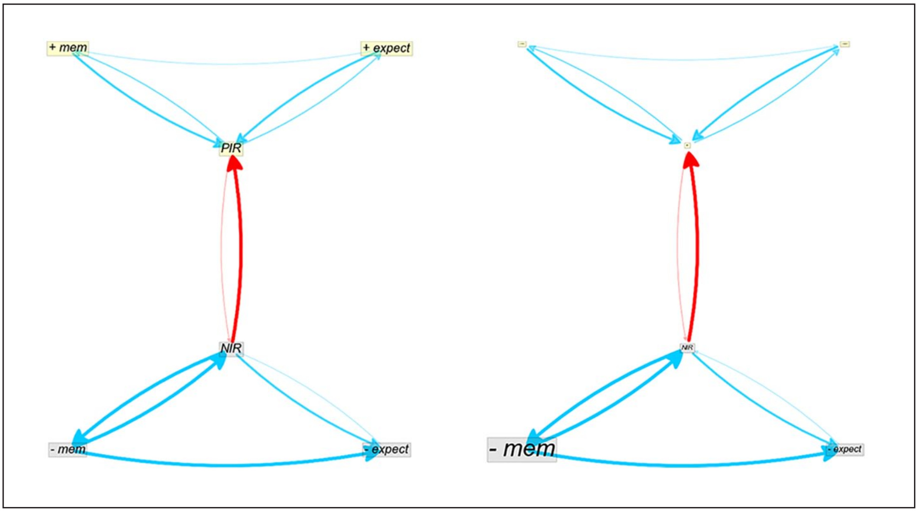

Figure 3. A mathematical model of one of the earlier forms of the core engine of the causal loop diagram of sustainable peace. The peace factors are positive and negative intergroup reciprocity, positive and negative historical memory, and positive and negative future goals and expectations. Positive peace factors are in yellow (light gray) and negative peace factors are in (dark) gray. Positive causal links are blue (light gray), negative causal links are red (dark gray), and are directed as indicated by the arrowheads. The strength of the causal links corresponds to the thickness of the links. (Left) The initial values of the peace factors are all equal. (Right) As the model is calculated forward in time the peace factors reach their final values in the attractor. Note that here the system is dominated by the negative (gray) factors. Because of the power of negative emotions, the strengths of links between the negative factors collectively reinforce each other and increase their values. The strong negative link to the positive peace factors then drives down the values of those positive peace factors.

connections between the negative peace factors. There is no single peace factor that functions as a "leverage" factor that controls the whole system. It is the collective effect of the influence of the larger number of positive peace factors that nudges the system into a good place.

What was *not* learned from the mathematical model? (1) The equations and parameters of the mathematical model are a general model, meaning that we hope that we have incorporated enough of the essential information from the causal loop diagram and other sources so that its overall qualitative properties match those found in the real world. Those properties include the existence of attractors, the existence or lack of existence of leverage points, threshold effects, and whether the dynamics are smooth, oscillatory, or chaotic. However, this is not a specific model with predictive analytics, since the quantitative predictions of this mathematical model have not been validated against quantitative empirical data. That is because we lack the quantitative empirical data to do that validation. But we are working on it. We are in the process of developing more complete operational definitions of each peace factor and using data science methods to determine their quantitative values from structured and unstructured data sets and by scraping data from social media. (2) Similarly, we also need more quantitative data on the strength of the links between the peace factors. We are also currently working on this too, by using meta-analysis to better estimate the strength of the links c_{ij} from published studies. (3) We assumed certain particular mathematical forms for the interaction between the variables (two-element but not three-element dependency and hyperbolic tangent nonlinearity) and the dynamics (first-order differential equation in time). These are actually pretty reasonable assumptions used in many other models, but we do not know how robust our conclusions based on them are to changing that nonlinearity or making the dynamics second order in time. (4) The mathematical model presented here is a "top-down" model. We defined the equations and sought to use parameter values defined by empirical measurements if available, or by our best estimates if not available. An alternative, fully data science approach, would be to use natural language processing to pull information from published articles, web pages, media, social media and then machine learning to identify the peace factors and the connections between them fully from the "bottom-up." We are currently exploring this approach, but speculate that the hardest part of this task is the natural language processing, since the computer program must "understand" the text of the sources, not just identify key words or even themes. We believe that it would be instructive and look forward to learning the similarities and differences between models created from the top-down versus bottom-up approaches.

A mathematical model is only as useful as the way it presents its information to humans so that they can make sense of it. We are also developing computer programs to make it easy for people, such as policy makers, to transform a causal loop diagram that they create into a mathematical model, visually display the results of that mathematical model, provide easy ways to change the parameters of that model, and then display the results of those interventions. First, we have developed software that transforms a causal loop diagram constructed in Microsoft PowerPoint automatically into the data files needed by the computer program that computes the mathematical model. In its current version, the program identifies the names of the variables, the strengths of the links between them through their line widths, and the positive or negative sign of the links by their color. (This can be done because a .pptx file is actually a set of Open XML text files that can be parsed in Python. See for yourself, replace the extension ".pptx" in a PowerPoint file name with ".zip" and click on it twice.) Second, we have created a graphical user interface to the mathematical model so that a policy maker, with key strokes and mouse clicks, can enter different initial values of the peace factors, change the strength of the links between them, run a calculation, and see the results in graphs of how the peace factors change in time and their final values as text boxes proportional to their final values. The program was coded in Python 3.4.1, using the GUI app Tkinter, and it runs on OSX, Windows, and Linux operating systems. Output from that program is shown in Figure 4. We have made these programs available as open source on GitHub (Liebovitch, 2018). Third, we are exploring different types of visualization, such as whether it gives the user more meaning to see and interact with the whole model at once, with some peace factors subsumed into their

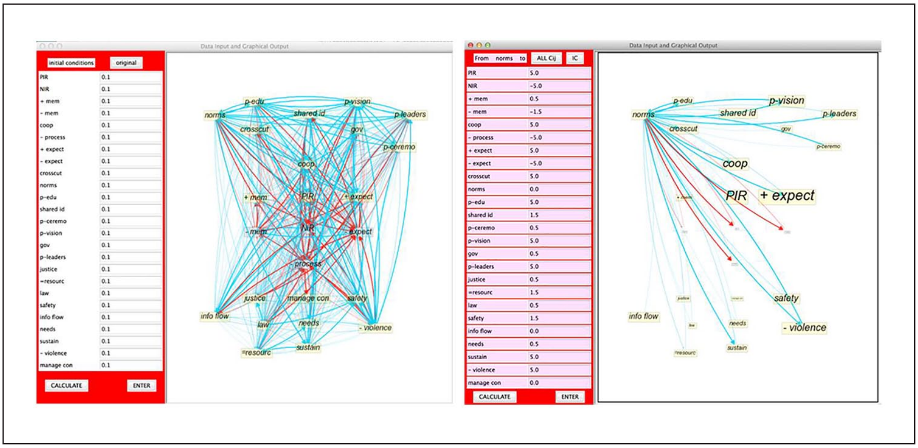

Figure 4. Graphical user interface of the mathematical model of the causal loop diagram for sustainable peace. In this model, the additional positive peace factors added to the system drive the system toward sustainable peace. (Left) The text size of the peace factors in the image is proportional to their initial values which can be set by entering a number into an entry box and a mouse click on the "enter" button. (Right) After a mouse click on the "calculate" button, the text sizes of the peace factors are now proportional to their values at long times that define the attractor. A mouse click on a peace factor brings up the input frame for changing the strength of its links and shows only the links into and out of that peace factor.

respective peace factors of the core engine to better understand how those major factors interact, or to single out small pieces of the model to play with their interactions to gain a clearer understanding of the positive and negative feedback loops often described in causal loop diagrams.

Since a mathematical model is quantitative, we can also use other mathematical tools to analyze it to identify the elements and links that are most influential in producing the system properties. Recently, many tools have been developed to analyze the properties of networks (Barabási, 2016; Newman, 2010). The causal loop diagrams and the mathematical model based on them here are both networks, that is, vertices connected by edges defined by the adjacency matrix c_{ij}. Hence, they too can be analyzed by network tools. For example, cross-impact matrix analysis of the number and strength of the links can be used to identify the roles of peace factors, as independent (few inputs, few outputs), driving (few inputs, many outputs), dependent (many inputs, few outputs), and linking (many inputs, many outputs; Asan & Asan, 2007; Nazarko, Ejdys, Halicka, Nazarko, & Kononiu, 2017). An important network measure is "centrality," which is the importance of a peace factor in terms of its connections within the network. There are many different measures of centrality including degree centrality: How many links go into or out of a peace factor and betweeness centrality: the number of times a node acts as a bridge along the shortest path between two other nodes ("Centrality"; https://en.wikipedia.org/wiki/Centrality). Our preliminary analysis of the mathematical model surprisingly showed that some of the positive peace factors in the periphery have the highest centrality measures, rather than the peace factors in the core engine. This corroborates our finding above that many positive peace factors are needed to sustain peace. The large number of positive peace factors must be widely connected to the other elements to be effective in overcoming the strong emotional effect of the negative peace factors. Many network measures do not take into account the direction, strength, or sign of the links. We are now working to generalize measures of centrality to include that information.

We have also begun to use modern data science methods to provide quantitative measures of the peace factors. For example, we collected data from Twitter feeds originating in London, Northern Ireland, and Singapore that refer to past or future events, and used a sentiment analysis to measure the emotional positive or negative valence of those tweets, as a way to estimate positive and negative intergroup historical memory and future expectations. This work is in its early stages and is still in progress.

Discussion

Maintaining peace requires a complex system of interactions between many peace factors. We want to understand how the properties of this whole system emerge from the interactions between the lower level elements of the system. In order to do that, we have explored the advantages and limitations of two methods: qualitative causal loop diagrams using graphs and quantitative mathematical models using equations. The process of creating the causal loop diagram is an important and valuable tool in identifying the elements of a system and how they are connected together. A causal loop diagram shows how each element fits into the system and provides an overview of the entire system. However, it may be difficult to think through the effects of an intervention that cascades from one element to the next. It also does not provide quantitative information on the relative importance of each element. A mathematical model, based on the causal loop diagram, can compute the interactions of all the elements together at once, provide quantitative values of the elements and hence their relative importance, and serve as the basis of an interactive simulation which policy makers can use to explore the effects of an intervention on the system. However, for such a mathematical model to provide quantitatively accurate predictions requires that it be tested and validated with known values from empirical data. Together, both casual loop diagrams and the mathematical models derived from them give us insights, from different perspectives, to help understand the macro systems properties of a complex social system and how they arise from micro lower level processes.

We used both causal loop diagrams and mathematical models to better understand systems of sustainable peace. We used the causal loop diagram as a process to identify the peace factors and their connections to each other. We used the mathematical model to compute quantitative values for those factors to determine their long-term values and relative importance. The most striking result that we found was that there was no one "leverage" factor, which if changed alters the whole system. Rather, the strong emotional content and more lasting emotional consequences of the negative peace factors will always lead the system far from peace, unless a large number of positive peace factors, perhaps each with small individual effects, act collectively to move the system toward peace. This result could mean that in different situations there could be different positive peace factors that are context-specific, but whose collective effects still result in sustainable peace.

Future Directions

Earlier we differentiated the top-down approach that is currently employed in our mathematical model versus an alternative bottom-up approach that we are working to employ using data science techniques. That same differentiation is also valid for the approach we used to construct our causal loop diagram, which involved expert-driven analysis and interpretation to define the factors that contribute to sustainable peace and the network structure. Like our mathematical model, our causal loop diagram is a general model that is context agnostic. However, based on the results of our qualitative and quantitative models we know that there are a few characteristics of peace systems that put constraints on the utility of these approaches. Specifically, we know that these systems are multidimensional, defined by multiple factors and the dynamic interactions across them. We also have evidence that idiosyncratic, context-specific factors likely determine the structure and strengths of network connections across these components. The analytical and (by extension) predictive utility of our models is thus constrained by two tensions: the general versus specific definition of a peace system, and the top-down versus bottom-up measurements of that system.

To begin to address those limitations, we are currently working toward turning our general mathematical model into a specific model by using modern data science methods to measure quantitative values of the peace factors and the strength of the connections between them so that we can test and improve the predictions of the model. This will enable us to extend the utility of our models by informing them with the idiosyncratic data required to build a specific model. This bottom-up approach to mathematical modeling should then provide the predictive analytics for policy makers to explore the effects of different interventions and thereby be more successful in their interventions and avoid "unanticipated consequences."

However, this only partially circumvents the top-down versus bottom-up tension. Because our mathematical model is informed by the outputs and structure of a causal loop diagram that itself was expert-designed and expert-interpreted, our general framework is the product of a top-down design. Whether that limits the analytical and predictive utility of a specific model remains an unknown question, as we lack a truly bottom-up design for comparability. Such a design would not only be case specific and informed by real-world data collected from the case, but the peace factors and network structure and strengths would also need to be identified from the bottom-up, rather than interpreted and interpolated by experts.

In order to overcome this final limitation, we are currently also designing a participatory approach to measuring sustainable peace that recognizes the multidimensionality of the phenomenon, appreciates the idiosyncratic nature of it, and understands the dynamic structural aspects of the network of factors that affect a peace system. Because we have evidence from our mathematical model that the general structure of the causal loop diagram (the inner valence of variables that comprise the core engine of sustainable peace) is an analytically powerful and context-agnostic framework, we are designing a multidimensional index around those dimensions of a peace system. We are likewise designing a survey instrument that can be administered to a variety of stakeholders within a specific peaceful society to collect data on the factors that various sectors of society perceive as relevant to and influential of sustainable peace in their own context. The survey results can then be utilized to populate the data needed to construct the multidimensional index of sustainable peace for a particular society. Moreover, by tracking the survey in a longitudinal design, it should be possible to identify the dynamics that influence the degree of peacefulness for a society. This approach would make the first of two crucial steps to constructing a bottom-up model.

The second step involves identifying the topology of factors and the structure of the network in the outer valence of the causal loop diagram. We have designed and piloted early iterations of a participatory causal loop diagramming methodology to elicit the network structure and strength of relationships from stakeholders in a peaceful society (Donahue, Rucki, Coleman, & Fisher, 2017; Fisher, Redding, Straw, & Mazzaro, 2015). However, the methodology is currently purely elicitive, meaning that both the factors themselves and the network structure are generated through the modeling process, making the factors that are elicited idiosyncratic to a given modeling process. By merging the survey and multidimensional index described above with the modeling methodology we have piloted, we should be able to standardize the factors included in a modeling process for a given society and focus explicitly on the network structure and strength of the connections. With the bottom-up factors identified through a stakeholder survey and the bottom-up structure generated through participatory modeling, we would then have the inputs required to build a truly bottom-up and case-specific model that can be compared against our other modeling outputs to fully assess the analytical and predictive utility of our models of sustainable peace.

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Notes

1. Actually, as we struggled to find examples of purely simple systems, we realized that even these examples are not really that simple. If you struck that white billiard ball into a racked triangle of billiard balls it is not likely that you could predict where all the billiard balls would wind up (Freiberger, 2014). If that simple electrical circuit includes a "varactor diode" whose capacitance varies with voltage, the current flowing in the circuit could vary quite strangely and unpredictably (Linsay, 1981). If the acid and base are not infinitely well stirred, their interaction will happen only at the interfaces where they touch and so the pH will vary both over space and over time (Kopelman, 1988). If those usually innocent staph on your skin have been evolving under selective pressure from too many products that you have been using with unnecessary antibiotics or they have been trading resistance factors with their friends, that bee sting–induced MRSA (methicillin-resistant *Staphylococcus aureus*) infection is going to be a much bigger deal for you ("MRSA infection," 2015; http://www.mayoclinic.org/diseases-conditions/mrsa/basics/definition/con-20024479). The problem here is both that those "simple" examples actually do consist of many smaller interacting parts and those systems are also interacting with the world outside of them so you cannot so easily separate them from that world. In reality, many things are more complicated than our cartoons of them. The fact that we (sometimes) believe those cartoons is more a reflection of how we blind ourselves to reality to serve our preconceived notion of thinking that one simple cause leads to one simple effect.
2. Interestingly, there are quite a number of other possible connection topologies, such as three-element feed-forward loops and single-input modules, which are not commonly noted in causal loop diagrams, although they play important functional roles in the networks of gene regulation and biochemical pathways (Alon, 2007).
3. Although it plays a suspenseful role in the movie *Hidden Figures* in matching elliptical and parabolic trajectories so that astronaut John Glenn can safely return to earth, we are aware that Euler integration is a simple method for a sophisticated calculation. We use it here because, with an appropriate step size, in our experience, it is simpler and more stable than fourth-order Runge–Kutta or predictor–corrector numerical integration methods.

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