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INTERNATIONAL COOPERATION

Detecting reciprocity at a global scale

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Reciprocity stabilizes cooperation from the level of microbes all the way up to humans interacting in small groups, but does reciprocity also underlie stable cooperation between larger human agglomerations, such as nation states? Famously, evolutionary models show that reciprocity could emerge as a widespread strategy for achieving international cooperation. However, existing studies have only detected reciprocity-driven cooperation in a small number of country pairs. We apply a new method for detecting mutual influence in dynamical systems to a new large-scale data set that records state interactions with high temporal resolution. Doing so, we detect reciprocity between many country pairs in the international system and find that these reciprocating country pairs exhibit qualitatively different cooperative dynamics when compared to nonreciprocating pairs. Consistent with evolutionary theories of cooperation, reciprocating country pairs exhibit higher levels of stable cooperation and are more likely to punish instances of noncooperation. However, countries in reciprocity-based relationships are also quicker to forgive single acts of noncooperation by eventually returning to previous levels of mutual cooperation. By contrast, nonreciprocating pairs are more likely to exploit each other's cooperation via higher rates of defection. Together, these findings provide the strongest evidence to date that reciprocity is a widespread mechanism for achieving international cooperation.

INTRODUCTION

The international system lacks a single sovereign capable of enforcing cooperative agreements (1–4). Therefore, stable intercountry cooperation relies, in part, on countries' self-interest for its propagation (5).

Because reciprocity in repeated games incentivizes cooperation (6–9), even in the absence of external enforcers, reciprocity may provide a crucial explanation for bilateral cooperation across a wide variety of international domains, including trade (10), the maintenance of international law (11), the avoidance of war (12), and protecting the environment (13). In addition, recent experimental studies show that bilateral reciprocity between pairs of actors can sustain cooperative contributions to a shared public good (14). Therefore, bilateral reciprocity may even underlie some instances of multilateral cooperation, such as global emissions agreements.

Moreover, both evolutionary models (6, 9, 15–19) and laboratory experiments (7, 8, 20) show that simple strategies of reciprocity, such as Tit-for-Tat, can become widespread in a population—at least when actors place a sufficiently high value on the payoff for future cooperation (8, 20). Because states are long-lived actors that typically interact for indefinite periods of time, scholars have hypothesized that Tit-for-Tat-like reciprocity may similarly emerge as a prevalent strategy in international relations (1, 12, 15, 21). If so, cooperative reciprocity should be detectable across a large number of country pairs. Furthermore, while Tit-for-Tat is a reciprocity-based strategy derived for specific types of games (for example, the prisoner's dilemma), we expect more generalized notions of reciprocity (22, 23) to drive international cooperation as well.

Yet, despite the central role of reciprocity in theories of international cooperation, no study has conclusively detected reciprocity-driven cooperation in a large number of country pairs. To be certain, many studies have used a variety of methods to detect Tit-for-Tat

reciprocity between small sets of countries, usually on the order of two or three (21, 24–29). However, these findings do not speak to whether these relationships are highly prevalent in the manner implied by theoretical models.

Meanwhile, a few recent studies have shown that interactions between many country pairs are consistent with models of reciprocity, as states' cooperation toward one another is temporally correlated (30, 31). However, these studies do not investigate whether the dynamics of reciprocity help stabilize cooperation between country pairs. Therefore, these studies do not indicate whether reciprocity actually represents a mechanism for widespread, stable cooperation. Similarly, past research has found cooperation in large-scale international institutions, such as the World Trade Organization, and argued that such cooperation may be theoretically explained by in-kind reciprocity between member states (32). Yet, this observation is very different from demonstrating that dynamics of bilateral reciprocity are detectable within these institutions and, furthermore, that such dynamics drive cooperation.

Beyond the usual difficulties in detecting influence in observational data, detecting reciprocity in the international system has at least two additional challenges. First, reciprocity requires cooperation between states to be coupled, such that cooperation by state *A* toward state *B* influences cooperation by state *B* toward state *A* and vice versa. Unfortunately, many existing methods, usually based on Granger causality, are ill-suited to detecting such coupling because they require the influence of each variable to be linearly separable (33). A second challenge is that many models for detecting reciprocity can reach the wrong conclusion if they ignore the fact that relations between pairs of states typically exist within a broader web of interstate relations (27, 30, 31, 34, 35). These methodological difficulties, when combined, may help explain why empirical research has yet to confirm many of the predictions made by evolutionary models of international cooperation.

Here, we address these methodological issues by using convergent cross mapping (CCM), which is a recently developed method for detecting mutual influence in coupled systems, first introduced by Sugihara *et al.* (33). This method has been shown to detect coupling in systems where Granger causality-based methods fail (33, 36) and can still detect mutual influence when pairs are embedded in a larger network of

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interactions (33, 37, 38). Using this method, we are able to detect reciprocity in at least 47 state pairs. We show that the cooperative dynamics in these state pairs are consistent with evolutionary models of reciprocity. Specifically, we demonstrate the willingness to sustain cooperation and to forgive minor instances of noncooperation in reciprocity-based relationships.

RESULTS

Applying CCM to the directed Goldstein time series of country *A*'s level of cooperation with country *B*, and vice versa, identifies pairs of countries exhibiting "CCM reciprocity" [that is, $CCM(A, B) \geq 0.25$ and $CCM(B, A) \geq 0.25$]. If countries *A* and *B* have CCM reciprocity, then country *A*'s treatment of country *B* "CCM causes" country *B*'s treatment of country *A* and vice versa. Examples of reciprocating country pairs are often nearby spatially, such as Russia and Ukraine, which share a border, but the reciprocity between China and the United Kingdom demonstrates how an increasingly connected world allows influence to span distance as well (see Fig. 1D). In total, we detect 47 country pairs exhibiting CCM reciprocity.

Mathematically, CCM reciprocity is not necessarily direct reciprocity because CCM influence may not preserve valence (that is, does cooperation breed cooperation in kind?). However, compared to nonreciprocating country pairs, CCM reciprocity indicates country

pairs that are more likely to cooperate regardless of recent interactions (see Fig. 2, A and B) and are more likely to engage in conflict in response to recent conflict (see Fig. 2D). Moreover, Fig. 2A shows that the dynamics of cooperation differentiate between reciprocity- and nonreciprocity-based relationships. Compared to rates of cooperation on aggregate, countries in reciprocity-based relationships are more likely to cooperate in response to cooperation by the other state, whereas countries that are not in reciprocity-based relationships are less likely to cooperate in response to cooperation. Therefore, countries in reciprocity-based relationships appear to bolster and reinforce each other's cooperation through increased willingness to meet cooperation with cooperation. On the other hand, countries in nonreciprocity-based relationships are more likely to exploit other states' cooperation due to decreased rates of cooperation in kind.

It is also the case that country pairs in reciprocating relationships are more likely to mirror the specific type of cooperation or conflict that is directed at them (see Fig. 3). This preservation of valence further indicates that CCM reciprocity serves as a plausible proxy for direct reciprocity. It is also important that valence is preserved for both verbal interactions (Fig. 3, C and D) and material cooperation and conflict (Fig. 3, A and B). This suggests that our results are not purely explained by "cheap talk," which is abundant in international relations (39, 40), but also rely on more "costly" material interactions. Additional comparisons are provided in section S3, including response to recent

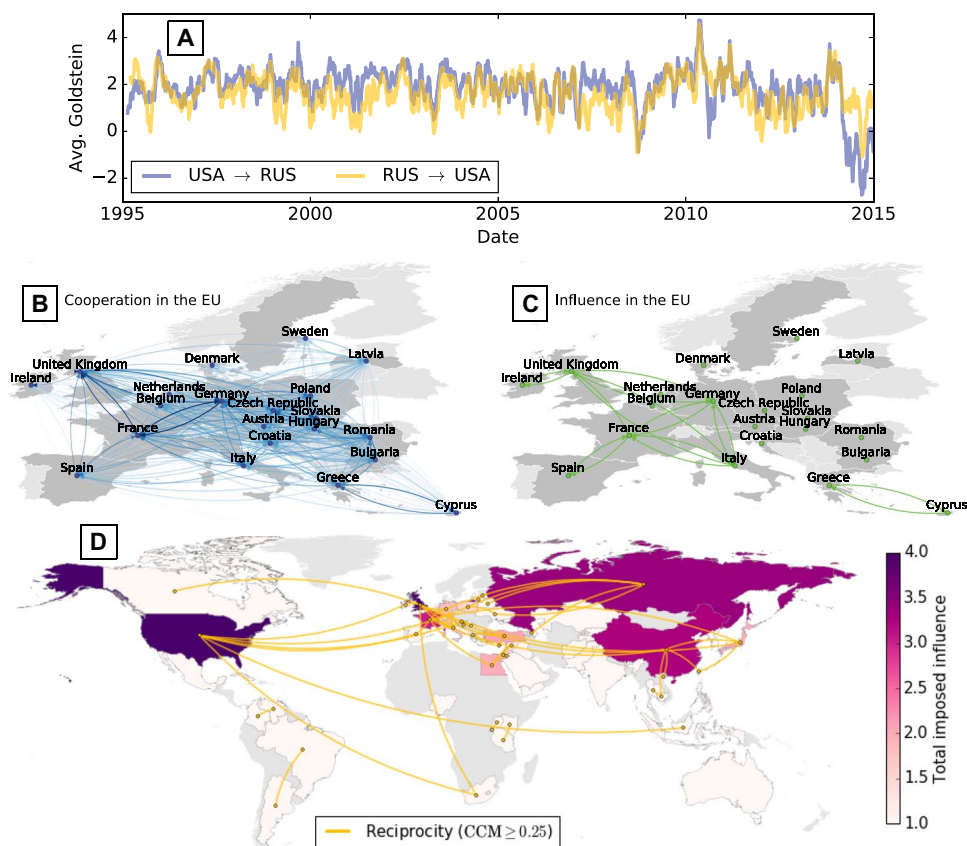


Fig. 1. Mapping cooperation, influence, and reciprocity in the European Union (EU) and around the world. (A) The directed Goldstein time series for the United States (USA)–Russia (RUS) relationship. The time series have been smoothed using a 30-day moving average for visualization purposes. (B) A network representing overall attitude of EU countries, the amount of interaction between nations (darker edges indicate more actions), and how cooperative interactions are on average (edge width). (C) A network representation of influence among EU nations [that is, $CCM(A, B) \geq 0.25$]. (D) Countries are colored according to their total imposed influence on others, and yellow lines connect pairs of countries exhibiting reciprocity. Gray countries had insufficient data for CCM analysis.

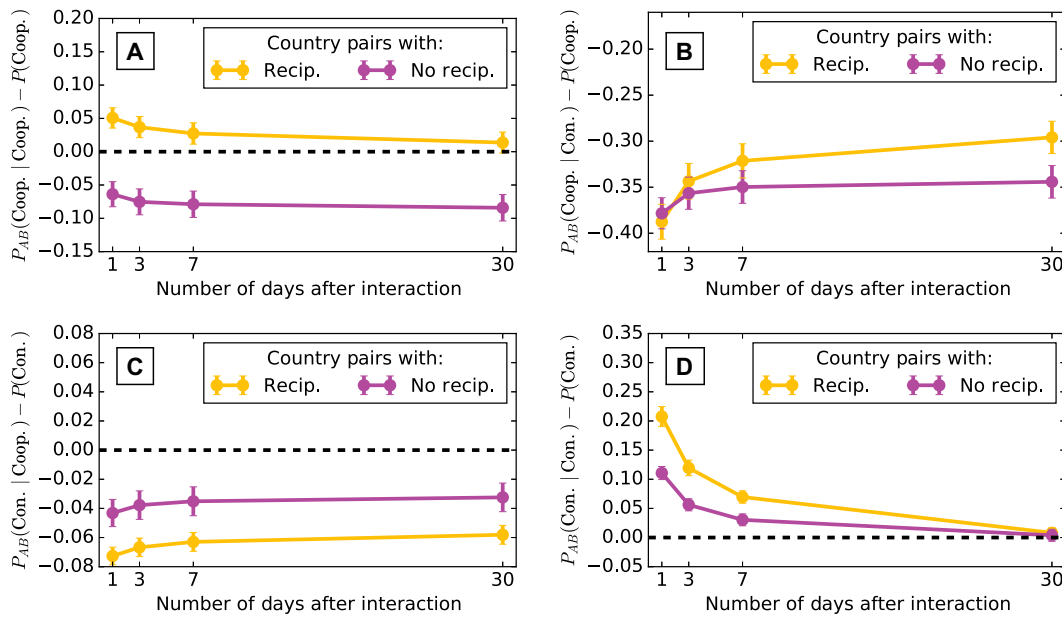


Fig. 2. Country pairs exhibiting reciprocity are cooperative on average but reciprocate conflict. Given an observation of cooperation (left) or conflict (right), reciprocating country pairs are more likely to cooperate (A and B) regardless of recent interaction, less likely to conflict given recent cooperation (C), but more likely to reciprocate conflict (D) in the cumulative interactions of the following day, 3 days, and 7 days (x axis). Each point represents the average rate of cooperation or conflict between countries A and B, denoted by P_{AB} , for reciprocating country pairs (yellow) or nonreciprocating country pairs (purple), and error bars represent the standard error. Probabilities (y axis) have been shifted according to the aggregate probabilities of cooperation or conflict, respectively, across the entire Integrated Crisis Early Warning System (ICEWS) data set.

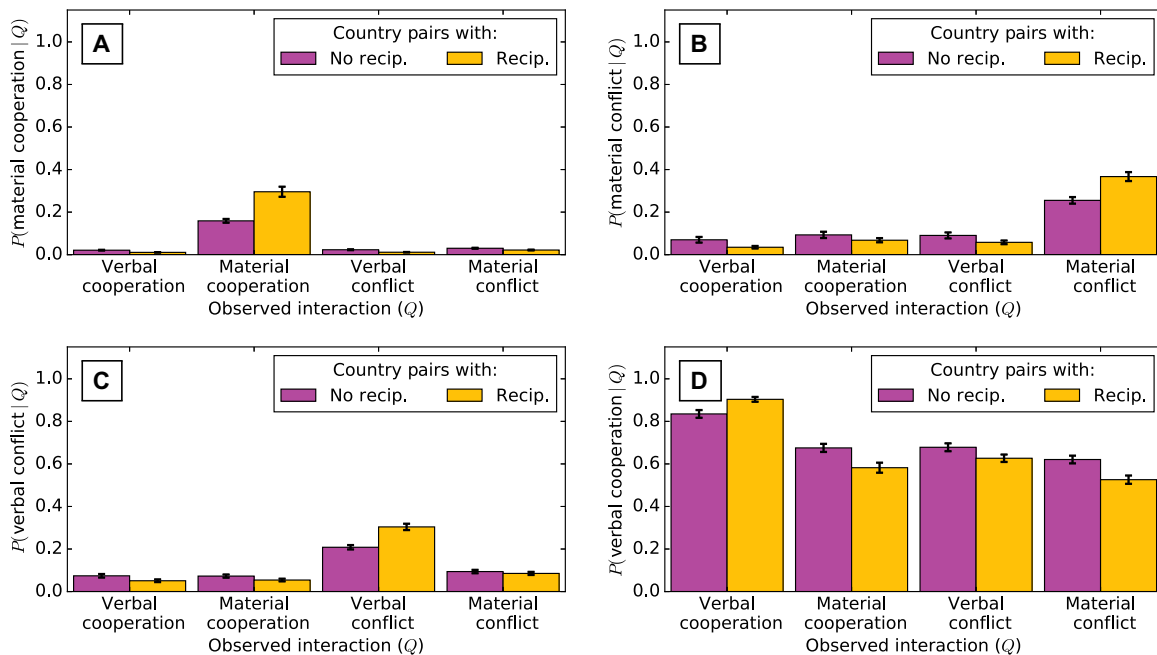


Fig. 3. CCM reciprocity indicates mirroring of specific interaction types. Given an observed interaction type (x axis, denoted by Q) between a country pair with (yellow) or without (purple) CCM reciprocity, we plot the probability (y axis) of (A) material cooperation, (B) material conflict, (C) verbal conflict, and (D) verbal cooperation in the day following the interaction (see section S3 for additional time windows).

cooperation or conflict compared to aggregate cooperation/conflict on a pair-by-pair basis and response by quad class interaction type.

A willingness to sustain cooperation and forgive transgressions can be crucial for the evolution of cooperation (16, 20)—especially when there is a chance that players will mistake the intent or nature

of each other’s actions (20). These strategies may therefore be especially important in international cooperation, where there is a high risk that such misperceptions will occur (41, 42). It is therefore interesting to see that reciprocating country pairs are more willing to sustain cooperation (see Fig. 2A) and more likely to return to

cooperating several days after conflict (see Fig. 2B). These findings demonstrate that reciprocity is characterized by higher levels of forgiveness even when faced with noncooperation.

Although we can study the relationship of a country pair in isolation, these dyadic relationships also exist as part of a web of interstate relations (27, 30, 31, 34, 35). In particular, previous work has considered international relations as a network and examined network properties, such as degree centrality (43, 44), in relation to a country's willingness to adopt international environmental policy. CCM can be used to construct a "network of influence" (see Fig. 4A) where each country is a node, and country *A* is connected to country *B* with a directed link if $CCM(A, B) \geq 0.25$. The global network of influence not only highlights the prevalence of two-cycles (we have already noted that there are 47) but also points to the existence of more complicated structures comprising pathways along which influence might propagate. For example, we find 15 three-cycles in the network of influence (see Fig. 4B), which suggests the possibility for generalized reciprocity (22, 23), in addition to direct reciprocity, as a factor in international relations.

On aggregate, how do shared levels of cooperation relate to reciprocity? Country pairs with greater shared influence [that is, $(CCM(A, B) + CCM(B, A))/2$] also exhibit a greater correlation between their directed Goldstein time series (see Fig. 4C). Similar to our results in Fig. 3, this relationship is broadly consistent with models of Tit-for-Tat reciprocity, where players respond in kind to each other's previous actions. However, CCM influence is also not the same thing as a simple

correlation in each country's level of cooperation toward the other. There are country pairs that exhibit high levels of CCM influence but have a relatively low correlation between their directed Goldstein time series. One reason this may occur is if countries use more complex strategies to determine whether to defect or return to cooperation. For example, if countries use forgiving strategies that wait for several transgressions before retaliating (16, 20, 41, 42), this can weaken the correlation between their directed Goldstein time series. Another reason is a potential asymmetry of influence (see section S5 for example country pairs) between pairs of countries exhibiting asymmetries in military and/or economic power. For example, the relationship between the United States and Taiwan is thought to be hierarchical such that the weaker partner unconditionally cooperates with U.S. defense policy in the region (45). In this situation, Taiwan's cooperation toward the United States may be less influenced by the United States' cooperation toward it even though it is influenced by U.S. directives on regional defense policy. This analysis suggests that forgiving strategies may ease the transition from an asymmetrical relationship into one based on reciprocity.

DISCUSSION

Together, the findings in this study help resolve a long-standing question about the global presence of reciprocity in cooperative international relations. Markers of reciprocity are detectable in a sizable

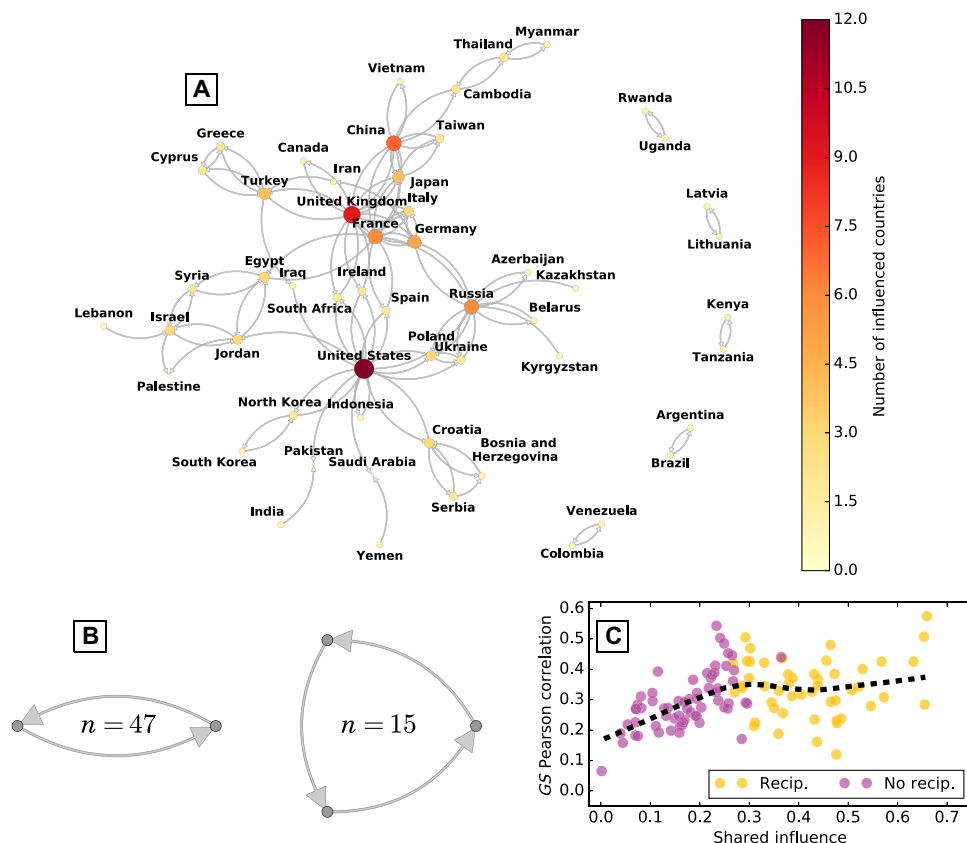


Fig. 4. Generalizing reciprocity from country pairs in isolation. (A) The global influence network. Countries are represented by nodes. An arrow connects country *A* to country *B* if $CCM(A, B) \geq 0.25$. Node size and color reflect the node's out-degree. (B) The number of two and three cycles in the global influence network. (C) Country pairs with higher shared influence [that is, $(CCM(A, B) + CCM(B, A))/2$; x axis] have increasingly correlated attitudes toward each other (y axis). Marker colors indicate whether the country pair has reciprocity [that is, $CCM(A, B) \geq 0.25$ and $CCM(B, A) \geq 0.25$; yellow] or not (purple). The black dashed line represents a LOWESS (locally weighted scatterplot smoothing) regression fit.

number of country pairs, and reciprocity is associated with patterns of cooperation that mirror patterns found in both simulation-based studies (6, 9, 15–17) and experiments involving individual human decision-makers (7, 8, 20). Combining these observations, we conclude that reciprocity is a widespread mechanism for achieving international cooperation.

With this conclusion in mind, we note that our methods may miss short time scale relationships between nations that interact sporadically, thus implying that our finding of 47 reciprocity-based relationships is a lower bound for the true number of international relationships based around direct reciprocity. Detecting sporadic reciprocating relationships will require new methods that may be applied to sparse data and relationships spanning shorter time periods. These methods would allow for investigations into the creation or destruction of reciprocity-based relationships and an understanding of sparser reciprocity-based international interactions, which have been observed in case studies (29).

Our observation of many reciprocity-based relationships by studying country pairs in isolation suggests that more generalized notions of reciprocity may also influence cooperation in international relations. Although the interactions shared between a pair of countries likely contain the bulk of information about cooperation between those countries, additional contextual information may be embedded in the relationships these countries maintain with shared third parties. We believe that future work investigating the network effects of cooperation might uncover further evidence of generalized reciprocity, thus further supporting our conclusion that reciprocity is widespread in international relations.

Motivated by Wang *et al.* (46), we demonstrate the robustness of our analysis to several potential sources of bias in the ICEWS data (see section S2). New alternative event data sets may benefit from recent improvements in machine learning for event classification, but these data sets do not yet span sufficiently long time periods to apply our methods. The maturation of these new data sets will allow new insight into reciprocity's role in international relations.

In addition to informing long-standing questions in the social sciences, our findings may inform policy choices. In recent decades, some policymakers have questioned the centrality of reciprocity to the maintenance of international cooperation and have placed greater emphasis on unilateral action by international superpowers (47). Our findings support the claim that powerful countries exert a high level of influence on cooperation in the international system. However, much of this influence is mutual, meaning that such cooperation is still determined, in part, by in-kind reciprocity rather than by the unilateral actions of a particular state. Furthermore, in agreement with simulated and experimental cooperation games, our evidence suggests that reciprocity leads to stable cooperation even in the face of minor transgressions, thus highlighting the benefits of enduring the costs of a reciprocity-based relationship through forgiving reciprocity-based strategies. Therefore, even policymakers in powerful countries should be mindful of the fact that unilateral noncooperation in areas like trade or the environment may engender a costly, negative response from many of the countries with whom they regularly interact.

MATERIALS AND METHODS

Data set

The ICEWS (48) is an event data set consisting of coded interactions between sociopolitical actors (that is, cooperative or hostile actions between individuals, groups, sectors, and nation states) during the

span of years from 1995 to 2015. Events were automatically identified and extracted from news articles by the BBN ACCENT event coder. These events were essentially triples consisting of a source actor, an event type [according to the Conflict and Mediation Event Observations (CAMEO) taxonomy of events, explained below], and a target actor. Geographical-temporal metadata were also extracted and associated with the relevant events within a news article.

CAMEO event categories represent a standardized encoding of types of interactions between sociopolitical actors. Furthermore, each event type, e , is associated with a real-valued interaction Goldstein score, g_e , between -10.0 (conflictive) and 10.0 (cooperative) (49) (that is, $g_e \in [-10, 10]$). CAMEO events contain a hierarchical structure; the highest abstraction consists of only four classes, called quad classes, which are verbal cooperation, material cooperation, verbal conflict, and material conflict. See section S1 for the distribution of quad classes, the distribution of Goldstein scores for CAMEO events occurring in the ICEWS data, and the resulting distribution of Goldstein scores occurring after weighting the CAMEO event type by rate of occurrence in the ICEWS data set.

Measuring international cooperation

We measured temporal changes in conflict and cooperation between a pair of countries as follows: Given the complete set of CAMEO event types, C , we calculated the average Goldstein score for a collection of interaction events from ICEWS, E , according to

$$GS(E) = \sum_{e \in C} \frac{g_e \cdot f_E(e)}{\sum_{e \in C} f_E(e)} = \sum_{e \in C} g_e \cdot p_E(e) \quad (1)$$

where $f_E(e)$ is the frequency of event e in E and $p_E(e)$ is the probability of observing an event of type e in E .

Following work with similar data (50, 51), we applied this calculation to the collection of events between a pair of countries on each day. As a result, we produced a time series capturing the temporal fluctuations of cooperation in that relationship.

Specifically, to capture the dynamics between country A and country B over time, we calculated the average Goldstein score for the events in the ICEWS data set with source country A and target country B on each day. We denote the collection of events and dates detailing the directed relationship between country A and country B using $E_{A,B}$.

Several existing works highlight the open-ended question regarding how to aggregate temporal data when calculating average Goldstein scores (51). However, we will focus on daily time series here because daily interactions are the finest temporal resolution available in the ICEWS data set.

The resulting Goldstein time series can be noisy. For plotting purposes, we used a 30-day moving average to smooth out time series so as to reveal the dominant trends (see Fig. 1A for an example of relationship time series). However, all measurements and calculations were carried out using the raw unsmoothed time series. Finally, we used linear interpolation to fill time periods with missing data or no data, but we did not consider time series with gaps exceeding 100 days or interactions involving countries without data on at least half of all days in the data set (see fig. S4A for the distribution of maximum gap lengths for time series considered in this study). As a robustness check, we demonstrated that key results about reciprocating country pairs remain true when using cubic interpolation instead of linear interpolation (see fig. S4, B to I).

Measuring influence with CCM

Using these temporal patterns of cooperation and conflict, to what extent does country *A*'s level of cooperation with country *B* influence *B*'s level of cooperation with *A* and vice versa? Although "influence" may have a more general meaning in other settings, we take the term to represent a causal relationship between the cooperation levels of country pairs. CCM (33, 52) is a new method for detecting dynamical causality, or influence, from time series and has been used for causal inference from dynamical systems in ecology (36), in empirical studies of social media (38), and in empirical studies of neuroscience (37). CCM uses the closeness of points in one time series to reconstruct a second time series; if the reconstructed time series accurately models the empirical time series according to Pearson correlation [typically $CCM(A, B) \geq 0.25$ for noisy empirical data (33)], then we conclude that the second time series causally influences the first time series (see section S2 for calculation and sections S2.1 to S2.3 for details on varying the CCM influence threshold). As an example, Fig. 1 (B and C) demonstrates the attitudes and influence from directed Goldstein time series among European Union nations based on interactions from 1995 to the end of 2014. In addition to the comprehensive description provided by Sugihara *et al.* (33, 52), we provided a detailed description of CCM applied to a classic dynamical system and to ICEWS data in section S2.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/4/1/eaao5348/DC1>

section S1. Summarizing ICEWS

section S2. Measuring influence using CCM

section S3. Characterizing instances of reciprocity

section S4. Varying thresholds for CCM reciprocity

section S5. Country pairs with asymmetric influence

fig. S1. The distributions of Goldstein scores by CAMEO event type occurring in the ICEWS data set.

fig. S2. The distribution of CAMEO quad classes in the ICEWS data set.

fig. S3. The number of events per day during the entire ICEWS data set.

fig. S4. Gaps in interactions between country pairs are small.

fig. S5. An example from dynamical systems.

fig. S6. Examples of shadow manifolds.

fig. S7. Using nearest neighbors of shadow manifolds to recover variable dynamics.

fig. S8. Using CCM to infer causality between using United States (USA) treatment of Saudi Arabia (SAU) and Saudi Arabia's treatment of the United States ($E = 200$, $\tau = 1$).

fig. S9. The number of pairs of countries exhibiting CCM reciprocity (*y* axis) during four 5-year time periods (*x* axis) as we vary the minimum influence threshold (that is, minimum Pearson correlation of CCM reconstruction, indicated by color).

fig. S10. CCM causation decreases with increased artificial noise.

fig. S11. The effects of biased news data ($\lambda = 0.00$).

fig. S12. The effects of biased news data ($\lambda = 0.10$).

fig. S13. The effects of biased news data ($\lambda = 0.20$).

fig. S14. The effects of biased news data ($\lambda = 0.30$).

fig. S15. The effects of biased news data ($\lambda = 0.40$).

fig. S16. The effects of biased news data ($\lambda = 0.50$).

fig. S17. The effects of biased news data ($\lambda = 0.60$).

fig. S18. The effects of biased news data ($\lambda = 0.70$).

fig. S19. The effects of biased news data ($\lambda = 0.80$).

fig. S20. The effects of biased news data ($\lambda = 0.90$).

fig. S21. Main results using CCM analysis with $E = 200$ and $\tau = 2$.

fig. S22. Main results using CCM analysis with $E = 200$ and $\tau = 3$.

fig. S23. Main results using CCM analysis with $E = 200$ and $\tau = 4$.

fig. S24. Main results using CCM analysis with $E = 200$ and $\tau = 5$.

fig. S25. Country pairs exhibiting CCM reciprocity are more likely to reciprocate cooperation or conflict.

fig. S26. The patterns of behavior in the day following an interaction.

fig. S27. The patterns of behavior in the three days following an interaction.

fig. S28. The patterns of behavior in the week following an interaction.

fig. S29. The patterns of behavior in the month following an interaction.

fig. S30. The effects of varying the CCM threshold for causality.

fig. S31. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.15$] are connected using yellow edges.

fig. S32. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.20$] are connected using yellow edges.

fig. S33. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.25$] are connected using yellow edges.

fig. S34. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.30$] are connected using yellow edges.

fig. S35. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.35$] are connected using yellow edges.

fig. S36. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.40$] are connected using yellow edges.

fig. S37. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.45$] are connected using yellow edges.

fig. S38. Pairs of countries exhibiting CCM reciprocity [that is, $CCM(A, B) \geq 0.15$ and $CCM(B, A) \geq 0.50$] are connected using yellow edges.

table S1. Nations ordered by total imposed influence.

table S2. The Pearson correlation for proportion of interactions of each quad class between a pair of countries to the shared influence for that pair of countries.

table S3. Country pairs ordered by increasing absolute difference in directed influence [that is, $CCM(A, B) - CCM(B, A)$].

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