Complexity theory applied to policy worldwide

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Abstract

In our increasingly complex, interdependent world, it is important to recognize how policy changes in one part of the world can have important effects in another. Complex systems science has the ability to describe dependencies and infer their policy implications. One of the central methodologies of complex systems is multiscale analysis, which can be used to identify aspects of systems that have impact on a large scale and are therefore particularly relevant to policy. The New England Complex Systems Institute has used this method to demonstrate the significant role U.S. energy and market policies have played in the bouts of social unrest in the Middle East and elsewhere. This was done by connecting riots with rising food prices and showing that food prices increased as a direct result of federally mandated conversion of corn into ethanol and deregulation of speculation on commodity markets. Additional examples include the role of banking deregulation in the economic crisis, stock market deregulation in market crashes, the role of demographic geography in ethnic violence, and the impact of global transportation on pathogen evolution and the Ebola epidemic. Effective national and international policies should be considered using the insights of complex systems science to evaluate global consequences.

I. INTRODUCTION

Globalization, including transportation, communication, economic and social integration, imply that seemingly local policies can have far-reaching consequences. Under these conditions what appear to be autonomous decisions by national authorities can have global impacts. How can we identify those impacts? Dependencies in networks and the patterns of behavior that are caused by them are the subject of complex systems science [1, 2]. Complex systems are systems in which the collective behavior does not satisfy the central limit theorem, i.e. components are neither independent nor fully dependent. One of the central methodologies of complex systems science, multiscale analysis [3–5], can be used to identify the complex relationships between the behavior of parts and the whole. The overall complexity of a system, or the amount of information required to describe a system, can be analyzed as a function of scale. If the parts of a system are independent, then the whole system exhibits fine scale random behavior. If the parts are correlated, the system has large scale coherent behavior. If the parts are interdependent, the system can perform complex behaviors that can be characterized to identify key properties.

Focusing on the largest scale behaviors in relation to finer scale component behaviors enables understanding how external forces and internal self-organization together comprise the behavior of the system. The impact of policy interventions, past and intended, can be characterized. Policies that change a particular behavior must have the necessary scale of intervention, while those that change complex behaviors must have the necessary ability to respond to different conditions—an effective intervention must be at least as complex as the target system.

The literature on complex systems science has become large with both scientific studies and applications to real world problems [6]. The following sections will illustrate how complex systems science and multiscale analysis have been used by the New England Complex Systems Institute to develop important insights and inform policy making decisions in our complex interdependent world. In Section II, we describe the role of spiking food prices in political instability, including the Arab Spring. In Section III, we identify U.S. ethanol mandates and commodity market deregulation as the primary causes of the rising food prices that sparked unrest. In Section IV, we outline how we can characterize panic in equity markets and its impact on market behavior. Section V describes the consequences of interdependence for systemic risk and the financial crisis. In Section VI, we consider the role of ethnic geography on ethnic tension and violence, using peaceful Switzerland as a case study to show how peaceful coexistence can be achieved. Finally, in Section VII, we show how increasing global transportation actually changes the types of diseases that are present, leading to vulnerability to extinction through outbreaks of highly lethal, rapidly spreading diseases. The Ebola epidemic of 2014 is an example of the risks that we are facing. Section VIII provides a brief summary.

II. THE FOOD CRISES AND POLITICAL INSTABILITY IN NORTH AFRICA AND THE MIDDLE EAST [7]

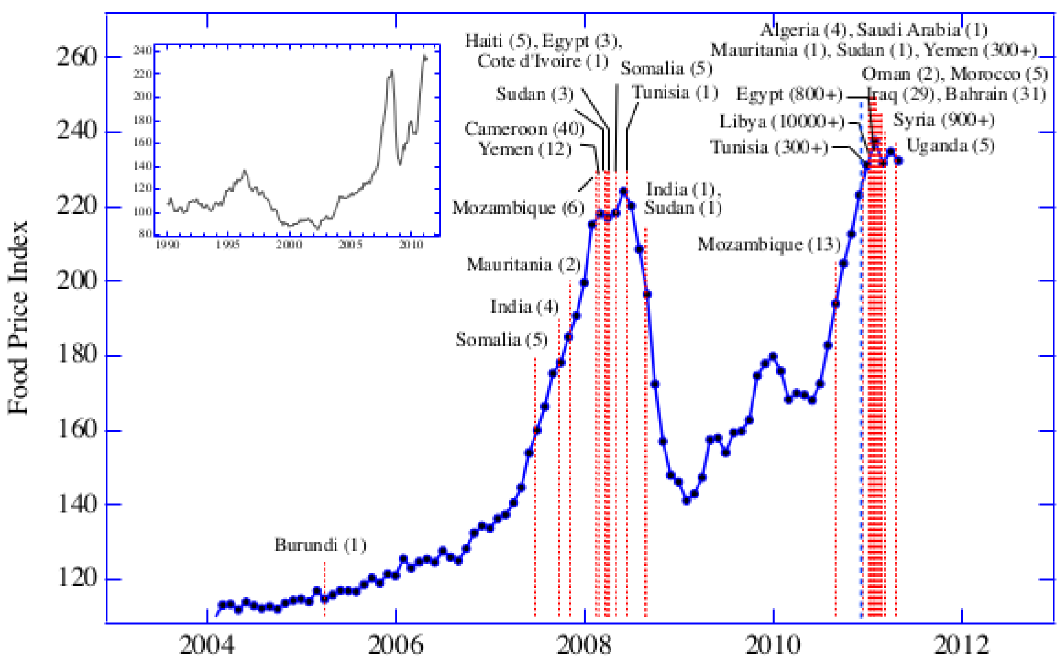

FIG. 1: Time dependence of FAO Food Price Index from January 2004 to May 2011. Red dashed vertical lines correspond to beginning dates of "food riots" and protests associated with the major recent unrest in North Africa and the Middle East. The overall death toll is reported in parentheses. Blue vertical line indicates the date, December 13, 2010, on which we submitted a report to the U.S. government, warning of the link between food prices, social unrest and political instability. Inset shows FAO Food Price Index from 1990 to 2011.

In 2011 protest movements became pervasive in countries of North Africa and the Middle East. These protests were associated with dictatorial regimes and were often considered to be motivated by the failings of the political systems in the human rights arena. We demonstrated that food prices are the precipitating condition for social unrest and identified a specific global food price threshold for unrest. We projected that, even without sharp peaks in food prices, within just a few years the trend of prices would reach the threshold. This pointed to a danger of spreading global social disruption. Our predictions have been realized [8].

Historically, there are ample examples of "food riots" with consequent challenges to authority and political change, notably in the food riots and social instability across Europe in 1848, which followed widespread droughts. While many other causes of social unrest have been identified, food scarcity or high prices often underlie riots, unrest and revolutions. Today, many poor countries rely on the global food supply system and are thus sensitive to global food prices. This condition is quite different from the historical prevalence of subsistence farming in undeveloped countries, or even a reliance on local food supplies that could provide a buffer against global food supply conditions. It is an example of the increasingly central role that global interdependence is playing in human survival and well-being. We can understand the appearance of social unrest in 2011 based upon a hypothesis that widespread unrest does not arise from long-standing political failings of the system, but rather from its sudden perceived failure to provide essential security to the population. In food importing countries with widespread poverty, political organizations may be perceived to have a critical role in food security. Failure to provide security undermines the political system's very reason for existence. Once this occurs, the resulting protests can reflect the wide range of reasons for dissatisfaction, broadening the scope of the protest and masking the immediate trigger of the unrest.

Human beings depend on political systems for collective decision making and action and their acquiescence to those systems, if not enthusiasm for them, is necessary for the existence of those political systems. The complexity of addressing security in all its components, from protection against external threats to the supply of food and water, is too high for individuals and families to address themselves in modern societies [1]. Thus, individuals depend on a political system for adequate decision making to guarantee expected standards of survival. This is particularly true for marginal populations, i.e. the poor, whose alternatives are limited and who live near the boundaries of survival even in good times. The dependence of the population on political systems engenders its support of those systems, even when they are authoritarian or cruel, compromising the security of individuals while maintaining the security of the population. Indeed, a certain amount of authority is necessary as part of the maintenance of order against atypical individuals or groups who would disrupt it [7]. When the ability of the political system to provide security for the population breaks down, popular support disappears. Conditions of widespread threat to security are particularly present when food is inaccessible to the population at large. In this case, the underlying reason for support of the system is eliminated, and at the same time there is "nothing to lose," i.e. even the threat of death does not deter actions that are taken in opposition to the political order. Any incident then triggers death-defying protests and other actions that disrupt the existing order. Widespread and extreme actions that jeopardize the leadership of the political system, or the political system itself, take place. All support for the system and allowance for its failings are lost. The loss of support occurs even if the political system is not directly responsible for the food security failure, as is the case if the primary responsibility lies in the global food supply system.

The role of global food prices in social unrest can be identified from news reports of food riots. Fig. 1 shows a measure of global food prices, the UN Food and Agriculture Organization (FAO) Food Price Index and the timing of reported food riots in recent years. In 2008 more than 60 food riots occurred worldwide in 30 different countries, 10 of which resulted in multiple deaths, as shown in the figure. After an intermediate drop, even higher prices at the end of 2010 and the beginning of 2011 coincided with additional food riots (in Mauritania and Uganda), as well as the larger protests and government changes in North Africa and the Middle East known as the Arab Spring. There were comparatively fewer food riots when the global food prices were lower. Three of these, at the lowest global food prices, are associated with specific local factors affecting the availability of food: refugee conditions in Burundi in 2005, social and agricultural disruption in Somalia and supply disruptions due to floods in India. The latter two occurred in 2007 as global food prices began to increase but were not directly associated with the global food prices according to news reports. Two additional food riots in 2007 and 2010, in Mauritania and Mozambique, occurred when global food prices were high, but not at the level of most riots, and thus appear to be early events associated with increasing global food prices.

These observations are consistent with a hypothesis that high global food prices are a precipitating condition for social unrest. More specifically, food riots occur above a threshold of the FAO price index of 210 ($p<10^{-7}$, binomial test). The observations also suggest that the events in North Africa and the Middle East were triggered by food prices. Considering the period of time from January 1990 to May 2011 (Fig. 1 inset), the probability that the unrest in North Africa and the Middle East occurred by chance at a period of high food prices is $p<0.06$ (one sample binomial test). This conservative estimate considers unrest across all countries to be a single unique event over this period of just over twenty years. If individual country events are considered to be independent, because the precipitating conditions must be sufficient for mass violence in each, the probability of coincidence is much lower.

A persistence of global food prices above this food price threshold should lead to persistent and increasing global unrest. Given the sharp peaks of food prices we might expect the prices of food to decline shortly [7]. However, underlying the peaks in Fig. 1, we see a more gradual, but still rapid, increase in food prices during the period starting in 2004. It is reasonable to hypothesize that when this underlying trend exceeds the threshold, the security of vulnerable populations will be broadly and persistently compromised. Such a threat to security should be a key concern to policymakers worldwide. Social unrest and political instability of countries can be expected to spread as the impact of loss of security persists and becomes pervasive, even though the underlying causes are global food prices and are not necessarily due to specific governmental policies. While some variation in the form of unrest may occur due to local differences in government, desperate populations are likely to resort to violence even in democratic regimes. We successfully predicted a breakdown of social order as a result of loss of food security, based upon historical events and the expectation that global population increases and resource constraints will lead to catastrophe.

III. THE FOOD CRISES: A QUANTITATIVE MODEL OF FOOD PRICES INCLUDING SPECULATORS AND ETHANOL CONVERSION [9]

In 2007 and early 2008 the prices of grain, including wheat, corn and rice, rose by over 100%, then fell back to prior levels by late 2008. A similar rapid increase occurred again in the fall of 2010. These dramatic price changes have resulted in severe impacts on vulnerable populations worldwide and prompted analyses of their causes. Among the causes discussed are (a) weather, particularly droughts in Australia, (b) increasing demand for meat in the developing world, especially in China and India, (c) biofuels, especially corn ethanol in the

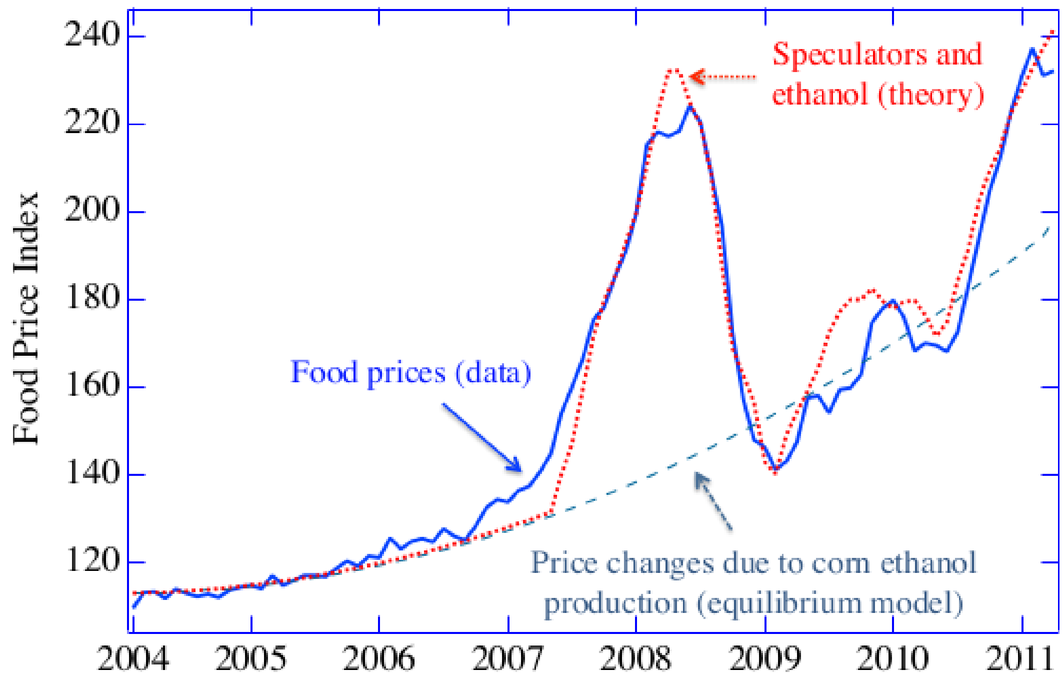

FIG. 2: Food prices and model simulations - The FAO Food Price Index (blue solid line), the ethanol supply and demand model (blue dashed line) — where dominant supply shocks are due to the conversion of corn to ethanol so that price changes are proportional to ethanol production — and the results of the speculator and ethanol model (red dotted line) — which adds speculator trend following and switching among investment markets, including commodities, equities and bonds.

US and biodiesel in Europe, (d) speculation by investors seeking financial gain on the commodities markets, (e) currency exchange rates, and (f) linkage between oil and food prices. Many conceptual characterizations and qualitative discussions of the causes suggest that multiple factors are important. However, quantitative analysis is necessary to determine which factors are actually important and which are not. While various efforts have been made, no analysis thus far has provided a direct description of the price dynamics. We have produced a quantitative model of price dynamics demonstrating that only two factors are central: speculators and corn ethanol. We introduced and analyzed a model of financial speculator price dynamics describing speculative bubbles and crashes. We further showed that the increase in corn to ethanol conversion can account for the underlying price trends when we exclude speculative bubbles. A model combining both the shock due to increasing ethanol conversion and speculators quantitatively matches food price dynamics. Our results imply that changes in commodity market regulations that eliminated restrictions on investments and government support for ethanol production have played a direct role in global food price increases.

The analysis of food price changes immediately encounters one of the central controversies of economics: whether prices are controlled by actual supply and demand, or are affected by speculators who can cause "artificial" bubbles and panics. Commodity futures markets were developed to reduce uncertainty by enabling pre-buying or selling at known contract prices. In recent years "index funds" that enable investors (speculators) to place bets on the increase of commodity prices across a range of commodities were made possible by market deregulation. The question arises whether such investors, who do not receive delivery of the commodity, can affect market prices. One thread in the literature denies the possibility of speculator effects in commodities. Others affirm a role for speculators in prices, but there has been no quantitative description of their effect. The rapid drop in prices in 2008, consistent with bubble/crash dynamics, increased the conviction that speculation is playing an important role. Still, previous analyses have been limited by an inability to directly model the role of speculators. This limitation has also been present in historical studies of commodity prices. For example, analysis of sharp commodity price increases in the 1970s found that they could not be due to actual supply and demand. The discrepancy between actual prices and the expected price changes due to consumption and production was attributed to speculation, but no quantitative model was provided for its effects. More recently, statistical (Granger) causality tests were used to determine whether any part of the price increases in 2008 could be attributed to speculative activity. The results found statistical support for a causal effect, but the magnitude of the effect cannot be estimated using this technique.

We developed a model relating speculation to prices and analyzed its price dynamics. The model describes trend-following behavior and can directly manifest bubble and crash dynamics. In our model, when prices increase, trend following leads speculators to buy, contributing to further price increases. If prices decrease, the speculators sell, contributing to further price declines. Speculator trading is added to a dynamic model of supply and demand equilibrium. If knowledgeable investors believe supply and demand do not match (as inferred from available information), there is a countering (Walrasian) force toward equilibrium prices. When prices are above equilibrium these investors sell, and when below these investors buy. The interplay of trend following and equilibrium restoring transactions leads to a variety of behaviors depending on their relative and absolute strengths. For a sufficiently large speculator volume, trend following causes prices to depart significantly from equilibrium. Even so, as prices further depart from equilibrium the supply and demand restoring forces strengthen and eventually reverse the trend, which is then accelerated by the trend following back toward and even beyond the equilibrium price. The resulting oscillatory behavior, consisting of departures from equilibrium values and their restoration, matches the phenomenon of bubble and crash dynamics. The model clarifies that there are regimes in which speculators have distinct effects on the market behavior, including both stabilizing and destabilizing the supply and demand equilibrium.

Aside from the high price peaks, the underlying trends of increasing food prices match the increases in the rate of ethanol conversion. We constructed a dominant supply shock model of the impact of ethanol conversion on prices, accurately matching underlying price trends and demonstrating that the supply and demand equilibrium prices would be relatively constant without the increase in corn to ethanol conversion. We then combined the effects of speculators and corn to ethanol conversion into a single model with remarkably good quantitative agreement with the food price dynamics. The unified model also captures the way speculators shift between equities and commodities for maximum projected gains. Final results are shown in Fig. 2.

IV. PREDICTING ECONOMIC MARKET CRISES USING MEASURES OF COLLECTIVE PANIC [10]

In sociology [11–14], panic has been defined as a collective flight from a real or imagined threat. In economics, bank runs occur at least in part because of the risk to the individual from the bank run itself — and may be triggered by predisposing conditions, external (perhaps catastrophic) events or even randomly. Although empirical studies of panic are difficult, efforts to distinguish endogenous (self-generated) and exogenous market panics from oscillations of market indices have met with some success, though the conclusions have been debated. Market behavior is often considered to reflect external economic news, though empirical evidence has been presented to challenge this connection. Efforts to characterize events range from the Hindenburg Omen to microdynamic models and to the demonstration that market behaviors are invariant across many scales. Panic can be considered a criti-

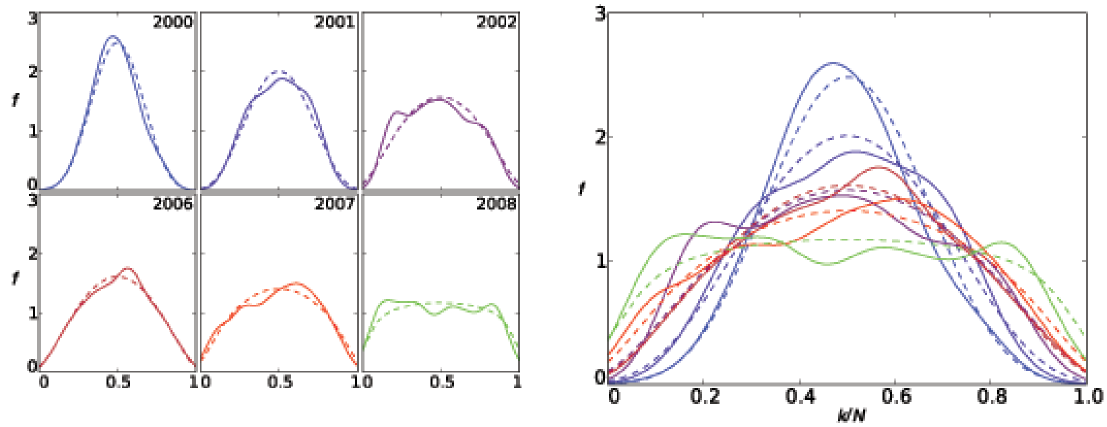

FIG. 3: The co-movement of stocks. Plotted is the fraction of trading days during the year (f, vertical axis) in which a certain fraction of stocks (k/N, horizontal axis) moved up. Empirical data are shown (solid lines) along with one-parameter theoretical fits (dashed lines) for the years indicated. Three years are omitted that do not differ much from the year immediately preceding and following them. Right panel combines all of the years shown. Stocks included are from the Russell 3000 that trade on the NYSE or Nasdaq. Curves are kernel density estimates with Gaussian kernels. Fits pass the X^2 goodness-of-fit test (the deviation of the data from the theoretical distribution is not statistically significant at the 25% level).

cal transition for which early warnings are being sought. The "collective flight" aspect of such a transition should be revealed in measures of mimicry that is considered central to panic. We used co-movement data to evaluate whether the recent market crisis and earlier one-day crashes are internally generated or externally triggered. Based upon a hypothesis about mimicry, we constructed a model that includes both mimicry and external factors and tested it empirically against the daily extent of co-movement. Our objective was to determine the relative importance of internal and external causes, and, where internal causes are important, to find a signature of self-induced panic which can be used to predict panic.

The literature generally uses volatility and the correlation between stock prices to characterize risk. These measures are sensitive to the magnitude of price movement and therefore increase dramatically when there is a market crash. Studies find that, on average, volatility increases following price declines, but do not show higher volatility is followed by price declines. We are interested in the extent to which stocks move together. The extent of such co-movement may be large even when price movements are small. Indeed, even when price changes are small, we expect that co-movement itself is the collective behavior that is characteristic of panic or panicky behavior that precedes a panic. Thus, rather than measuring volatility or correlation, we measured the fraction of stocks that move in the same direction.

We found that this increases well before the market crash, and there is significant advance warning to provide a clear indicator of an impending crash. The existence of the indicator shows that market crashes are preceded by nervousness that gives rise to following behavior — increased collective behavior prior to a panic.

We consider the "co-movement" of stocks over time by plotting the number of days in a year that a particular fraction of the market moves up (the complement moving down). Intuitively, if substantially more or less than 50% of the market moves in the same direction, this represents co-movement. As shown in Fig. 3, the results indicate that in 2000, the curve is peaked near 1/2, so that approximately 50% of stocks are moving up or down on any given day. Over the decade of the 2000s, however, the curve became progressively flatter — in 2008 the likelihood of any fraction is almost the same for any value. The probability that a large fraction of the market moves in the same direction, either up or down, on any given day, increased dramatically. Such high levels of co-movement may manifest the collective behavior we are searching for.

To quantitatively describe co-movement, we start from a behavioral economics model of a single stock that describes trend-following "bandwagons." It has been shown that investors can benefit from trend-following. Moreover, there is no need for the change to be based upon fundamental value for it to provide benefit to the investors. When individuals observe that a stock increases (decreases) in value, and choose to buy (sell) in anticipation of future increases (decreases), this self-consistently generates the desired direction of change. Such a "bandwagon" effect can undermine the assumptions of market equilibrium. We hypothesized that this trend-following mimicry across multiple stocks can cause a marketwide panic, and we built a model to capture its signature. We assume that investors in a stock observe three things, the direction of their stock, external indicators of the economy and the direction of other stocks. The last of these is the potential origin of self-induced, market-wide panic.

To model the co-movement fraction, we represent only whether a stock value rises or falls. This enables us to directly characterize the degree to which stocks move together and not how far they move at any particular time. Stocks are represented by nodes of a network and influences between stocks by links between nodes, an appropriate representation for market analysis. We consider both fully and partly connected networks. Every day, each of the N nodes is labeled by a sign (+/−) indicating the daily return of the stock. Market dynamics are simulated by randomly selecting nodes which maintain their current sign or randomly copy the sign of one of their connected neighbors. To represent external influences, we add nodes that influence others, but are not themselves influenced, i.e. "fixed" nodes. The number of fixed nodes influencing in a positive direction is U and the number influencing in a negative direction is D. The effective strength of the positive and negative external influences is given by the number of these nodes. External influences of opposite types do not cancel; instead larger U and D reflect increasing probability that external influences determine the returns of a stock independent of the changes in other stocks. This is the conventional view that news is responsible for the market behavior. Good news would be represented by U greater than D, bad news by D greater than U.

We have previously proposed this model as a widely applicable theory of collective behavior of complex systems. Successful matching to data will be a confirmation of this theory. It has also been previously identified as a model of conformity and non-conformity in social systems, and it has been studied in application to evolutionary dynamics.

If we consider a more complete model of influences, in which investors of one stock only consider specific other stocks as guides, we have a partly connected network. We have studied the dynamics of such networks analytically and through simulations, and the primary modification from fully-connected networks is to amplify the effect of the external influences. As the links within the network are fewer, the network can be approximated by a more weakly coupled, fully connected network, with a weakening factor given by the average number of links compared to the number of possible links. Similarly, if only a subset of the external influences are considered relevant for the return of a specific stock, the relative strength of the external influences can be replaced by weaker, uniform external influences. Otherwise, for many cases, the shape of the distribution is not significantly affected. The model thus measures the relative strengths of the internal and external influences rather than the absolute strength of either. The models robustness indicates a universality across a wide range of network topologies, suggesting applicability to real world systems.

Compared with recent empirical market data in Fig. 3, the model fits remarkably well. A Gaussian model fits the early years, less well in the final years, and does not fit 2008. The good agreement of our model is obtained with equal up and down influences, $U = D$, which is the only adjustable parameter. When U=1, as was the case in 2008, a transition to crisis can be expected. Fig. 4 shows the one-day crashes leading up to crisis.

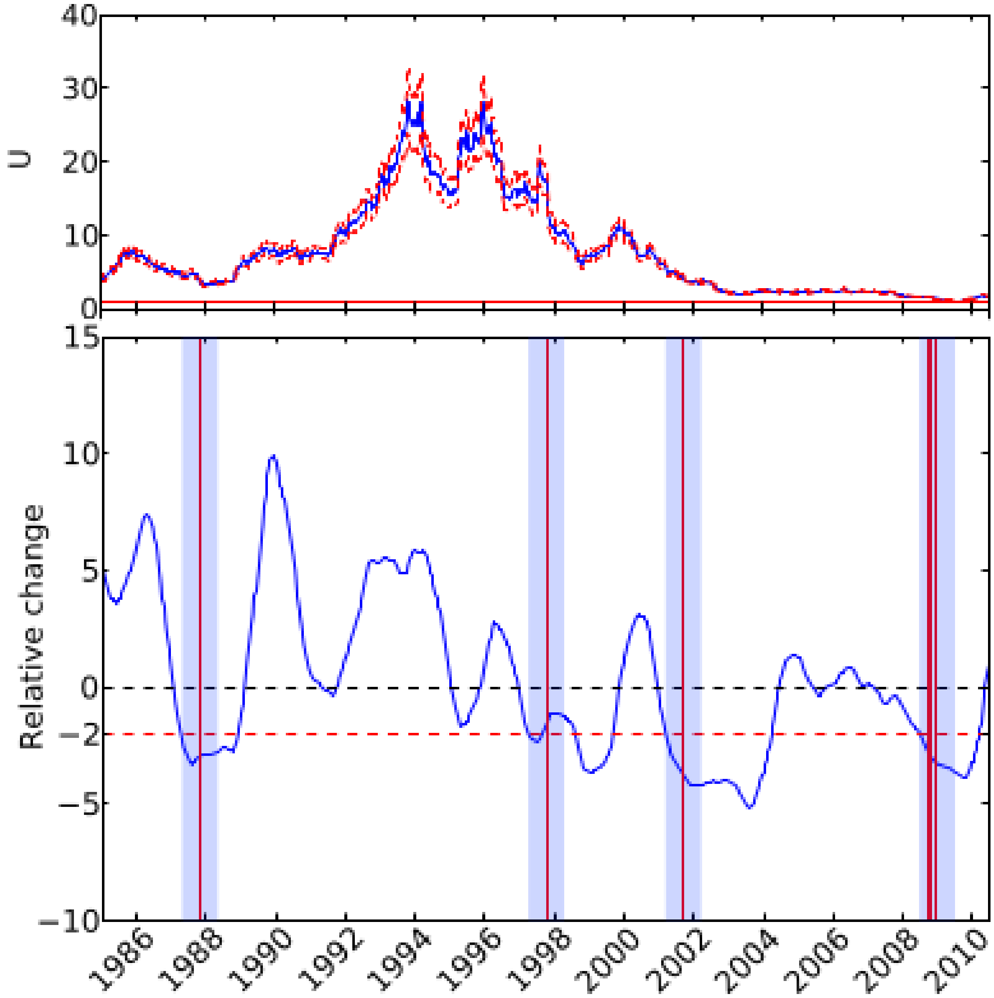

FIG. 4: Model parameter (top panel) for the period 2000-2010. Estimates of the model parameter are shown at the end of the year-long period for which U was estimated. Sampling error estimates are drawn at +/−1 standard deviations. Positive-return distributions are computed from the daily returns of stocks of the Russell 3000. Bottom panel is the annual change of U as a fraction of its standard deviation from one year earlier averaged over the previous year. Of the twenty largest percentage drops of the Dow Jones Industrial Average, eight are in the displayed time period: 10/19/1987, 10/26/1987, 10/27/1997, 9/17/2001, 9/29/2008, 10/9/2008, 10/15/2008, 12/1/2008 (vertical red lines). Four year-long windows (shading) follow two standard deviation drops in the the model parameter after periods of increase. Positive-return distributions are computed from the daily returns of stocks of the Russell 3000 for dates after July 1, 1999. Before July 1, 1999, returns were obtained for the Russell 3000 membership lists from 2001, 2004 and 2007. Each positive return fraction was computed with more than 140 stocks.

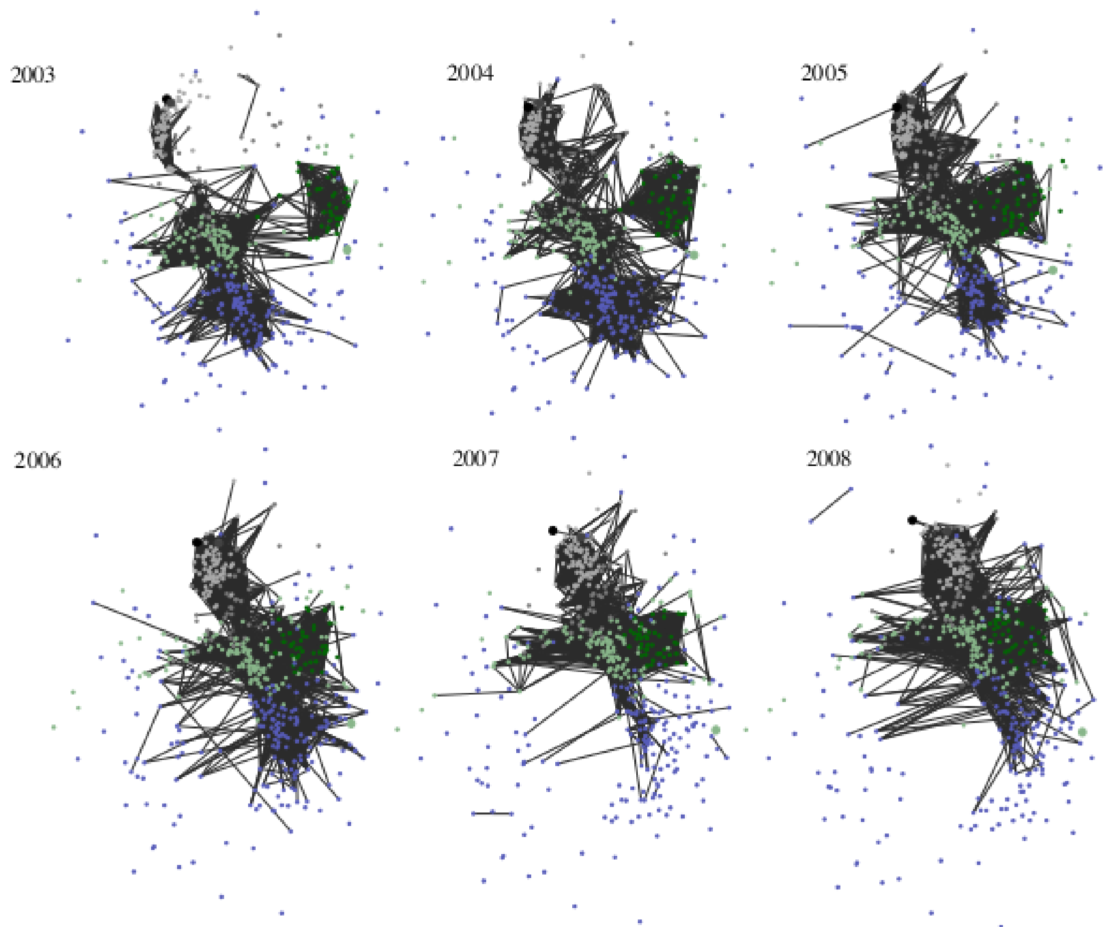

FIG. 5: Network of correlations of market daily returns for years as indicated. Dots represent individual corporations colored according to economic sector: technology (blue), basic materials including oil companies (light grey) and others (dark grey), and finance including real-estate (dark green) and other (light green). Links shown are the highest 6.25% of Pearson correlations of $\log(p(t)/p(t-1))$ time series, where $p(t)$ are adjusted daily closing prices of firms, in each year. Larger dots are spot oil prices at Brent, UK and Cushing, OK (black) and the price of ten year treasury bonds (green).

V. NETWORKS OF ECONOMIC MARKET INTERDEPENDENCE AND SYSTEMIC RISK [15]

The global economy is a highly complex system whose dynamics reflect the connections among its multiple components, as found in other networked systems. A common property of complex systems is the risk of cascading failures, where a failure of one node causes similar failures in linked nodes that propagate throughout the system, creating large scale collective failures. Economic risks associated with cascading financial losses are manifest in the recent economic crisis and the earlier Asian economic crisis, but are not considered in conventional measures of investment risk.

A central question is the role that complex systems science can play in informing regulatory policy that preserves the ability of markets to promote economic growth through freedom of investment, while protecting the public interest by preventing financial meltdowns due to systemic risk.

Characterizing the network of economic dependencies and its relationship to risk is key. The dependencies among organizations involve large numbers of factors, including competition for capital and labor, supply and demand relationships among organizations that deliver common end products or rely upon common inputs, natural disasters and climate conditions, acts of war and peace, changes of government or its policies including economic policy such as interest rates, and geographic association. Quantifying such dependencies, e.g., through Leontief models, is difficult because many of the dependencies are non-linear and driven by socio-economic events not included in these models. Also, behavioral economics suggests that under some conditions collective investor behavior, e.g., from perceptions of value, may have significant effects. Reflecting both fundamental and behavioral interactions, correlations in market value of firms can serve as a measure of the perceived aggregate financial dependence and quantify "herding" behavior in collective fluctuations. Moreover, price correlations are directly relevant to measures of risk.

We constructed a network of dependencies among 500 corporations having the largest stock trading volume, augmented with several economic indices (oil prices and bond prices reflecting interest rates). We formed a network where links are present for the highest correlations in daily returns in each year from 2003 to 2008. In order to display the effect of changes over time, we constructed a single network over all years, with each corporation in a particular year represented by a node linked to itself in the previous and next year. Each year is separately shown in Fig. 5. We included only economic sectors that are significantly self-correlated, as the larger network constructed from the entire market obscures key insights. Previous correlational analyses have described how correlations may arise from external forces across the market (arbitrage pricing theory [16, 17]) or used correlations to characterize sectors and market crashes (econophysics [18, 19]). This work lacks an understanding of the economic origins of changes in dependencies and their policy implications. We examine variations of within- and between-sector correlations, arising from non-linear effects, for information about changes in economic conditions prior to and during the economic crisis.

The study of network community properties often requires careful analysis. In our case, the observations we describe are manifest visually and were also tested statistically. In particular, apparent trends were tested using the t-statistic of differences in link densities within and between sectors (merging), or the minimum of this statistic between one sector and each of the others (self-clustering). Sectors are statistically linked (unlinked) to an index if the t-statistic comparing links to the index relative to the link density of the graph is above 4 (below 2).

Limiting investments (i.e., limiting capital-to-asset ratios) in order to moderate risk directly influences opportunities for growth. However, our results also point to a different strategy, which recognizes that financial institutions cross-link otherwise weakly correlated economic sectors. The key is that economic couplings among companies propagate the effect of failures. If economic entity G fails in a financial obligation to entity H, the impact on H may affect other entities J and K, that are linked to H, even if their activity has nothing to do with G. Conversely, while a small capital-to-asset ratio may be risky for a particular institution, if the investments are within a particular economic sector the failure of that institution is unlikely to cause economy-wide repercussions. Thus, segregating financial relationships, particularly among activities that are not otherwise related, or are weakly related, reduces systemic risk.

The idea that separations between components of the financial sector contribute to economic stability was a key aspect of legislation to stabilize the American banking system after the market crash of 1929. The Glass-Steagall Act of 1933 separated investment banking from consumer (retail) banking to prevent the fluctuations from other parts of the economy affecting consumer banking. This Act was progressively eroded until its repeal in 1999. Other historical forms of separation imposed by law or by practice included the separation of savings and loan associations and insurance providers from commercial and investment banking, as well as geographic separation by state. While many effects contribute to correlations in economic activity, nonlinearities associated with investment during market declines support the historical intuition that regulating these dependencies is more critical than regulating those arising from, e.g., supply chains. One of the arguments in favor of deregulation was that banks, by investing in diverse sectors, would have greater stability. Our analysis implies that the investment across economic sectors itself creates increased cross-linking of otherwise much more weakly coupled parts of the economy, causing dependencies that increase, rather than decrease, risk. Quite generally, separation prevents failure propagation and connections increase risks of global crises. Subdivision is a universal property of complex systems. An increase in separation of financial services is likely to entail costs, and the cost-benefit tradeoffs of imposing particular types of separation are yet to be determined.

In summary, complex systems science focuses on the role of interdependence, a key aspect of the dynamical behavior of economic crises as well as the evaluation of risks in both "normal" and rare conditions. We have analyzed the dynamics of correlational dependencies in rising and falling markets. The impact on the economic system of repeals of Depression-era government policies is becoming increasingly manifest through scientific analysis of the current economic crisis. This study suggests that erosion of the Glass-Steagall Act, the consolidation of banking functions and cross sector investments eliminated "firewalls" that could have prevented the housing sector decline from triggering a wider financial and economic crisis.

VI. GOOD FENCES: THE IMPORTANCE OF SETTING BOUNDARIES FOR PEACEFUL COEXISTENCE [20]

Efforts to resolve conflicts and achieve sustained peace are guided by perspectives about how conflict and peace are based in interpersonal and intergroup relationships, as well as historical, social, economic and political contexts. We have introduced a complex systems theory of ethnic conflict that describes conflicts in areas of the former Yugoslavia and India with high accuracy. In this theory, details of history and social and economic conditions are not the primary determinants of peace or conflict. Instead, the geographic arrangement of populations is key. Significantly, our theory points to two distinct conditions that are conducive to peace — well mixed and well separated populations. The first corresponds to the most commonly striven for peaceful framework: a well integrated society. The second corresponds to spatial separation, partition and self determination — a historically used but often reviled approach. Here we consider a more subtle third approach, that of within-state boundaries in which intergroup cooperation and autonomy are both present. The success of this approach is of particular importance as the world becomes more connected through international cooperation. As illustrated by the European Union, the role of borders as

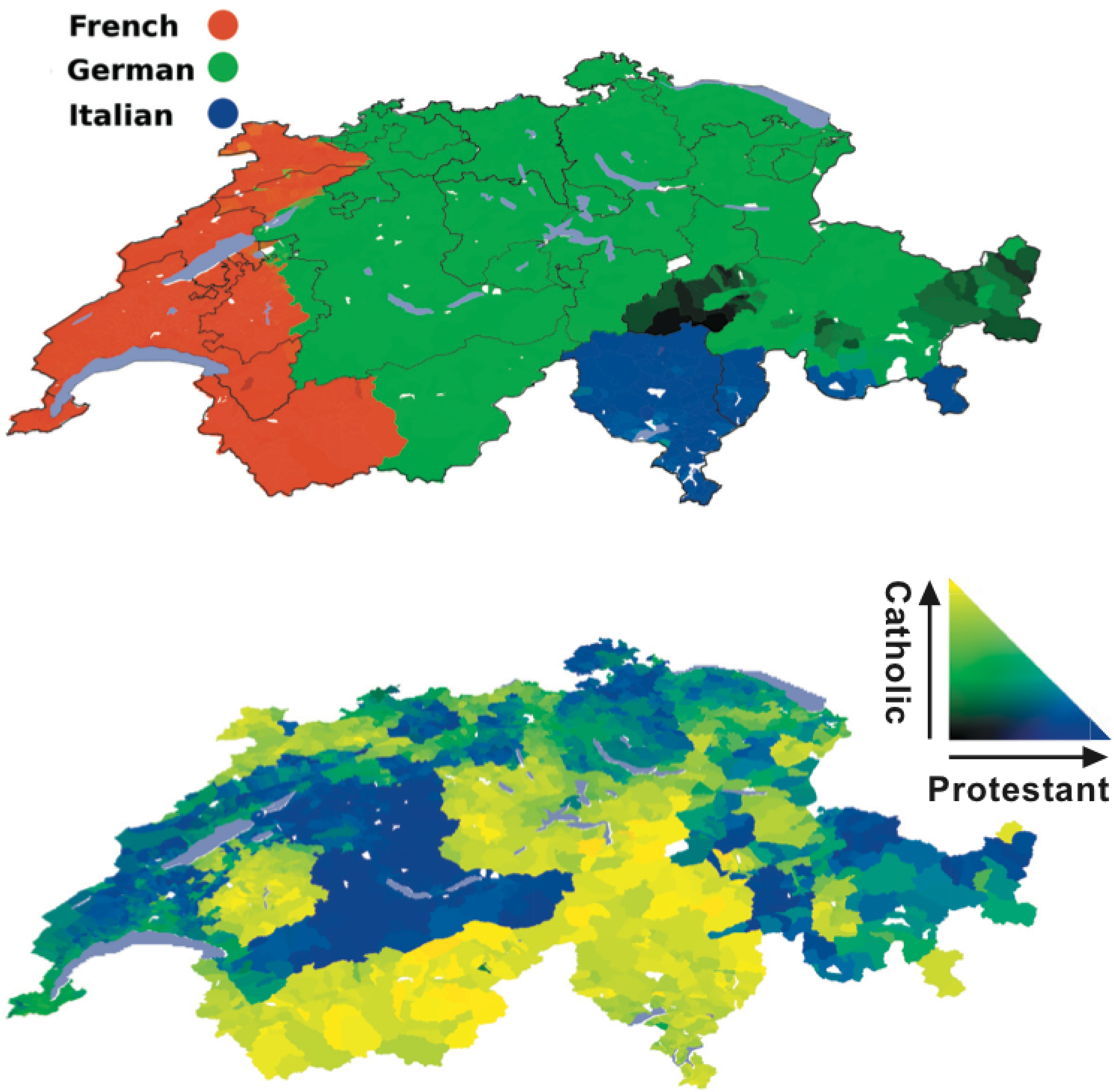

FIG. 6: Maps of Switzerland showing the 2000 census proportion of linguistic groups and Catholics and Protestants (Mercator projection).

boundaries is changing.

In order to evaluate the role of within-state boundaries in peace, we considered the coexistence of groups in Switzerland. Switzerland is known as a country of great stability, without major internal conflict despite being home to multiple languages and religions. Switzerland is not a well-mixed society, it is heterogeneous geographically in both language and religion (Fig. 6). The alpine topography and the federal system of strong cantons have been noted as relevant to coexistence; their importance can be seen in Napoleons statement, after the failure of his centralized Helvetic Republic, that nature had made Switzerland a federation.

But the existence of both alpine and non-alpine boundaries between groups and the presence of multiple languages and religions within individual cantons suggest partition is not essential for peaceful coexistence in Switzerland. In identifying the causes of peace, the literature has focused on socio-economic and political conditions. These include: a long tradition of mediation and accommodation; social cleavages that cross-cut the population rather than coincide with each other; unwritten and written rights of proportionality (fairness) and cultural protectionism; a federal system with strong sub-national units; a civil society that fosters unity; direct democracy through frequent referenda; small size; historical time difference between cleavages in language and religion; neutrality in international warfare; and economic prosperity [21–28]. Geography plays an unclear, presumably supporting, role in these frameworks. The analysis of coexistence in Switzerland is also part of a broader debate about whether social and geographical aspects of federalism promote peace or conflict [29].

We analyzed the geographical distribution of groups in Switzerland based solely upon the hypothesis that spatial patterns formed by ethnic groups are predictive of unrest and violence among the groups. The model also allows that topographic or political boundaries may serve as separations to promote peace. We test the ability of the theory to predict peaceful coexistence in the context of internal country boundaries in Switzerland. Where explicit boundaries do not exist, such as in mixed cantons where alpine boundaries are absent, violence might be expected, and the results of the model in these areas serve as a particularly stringent test of the theory. In most such cases, violence is not predicted, consistent with what is found. In one area, a significant level of violence is predicted, and in fact violence is actually observed. The analysis sheds light on the example of Switzerland as a model for peaceful coexistence. The precision of the results provides some assurance of the usefulness of the theory in planning interventions that might promote peace in many areas of the world.

We briefly summarize five categories of distinct successful comparisons between model predictions and the observed data that are contained in the results.

Our examination of linguistic and religious groups in Switzerland included cases where violence is predicted without the presence of boundaries, but is mitigated by the consideration of topographical and political boundaries appropriate to linguistic and religious groups, respectively.

1. Topographical boundaries reduced violence between linguistic groups. This occurred along (a) Alpine boundaries of the Swiss Alps between German-speaking and Italian-speaking populations, (b) Alpine boundaries between German-speaking and French-speaking populations, and (c) Jura range boundaries between German-speaking and French-speaking populations.

2. Political boundaries reduced violence between religious groups. This is the case both for (a) canton boundaries and for (b) circle boundaries in the canton of Graubunden. Our analysis also identified locations in which our model does not predict violence despite linguistic or religious heterogeneity and no explicit boundaries.

3. The straightness of the boundary prevents violence between linguistic groups in Fribourg/Freiburg.

4. Isolation of a Protestant population on an appendage from the Catholic majority prevents violence in Fribourg/Freiburg. We also identified one area at the highest level of calculated residual propensity to violence and it corresponds to an area of unresolved historical conflict.

5. The northeastern part of the canton of Bern is the location of both the highest prediction of propensity to violence, and a real-world history of intergroup tension. The unique condition of the conflict in this part of Switzerland and its correspondence to the prediction by the model provides additional confirmation of the model.

Our research has consistently identified improperly aligned boundaries as a key underlying cause of localized ethnic violence. Using policy to establish clear borders and regional autonomy offers an avenue to ending sectarian conflict.

VII. LONG-RANGE INTERACTION AND EVOLUTIONARY STABILITY IN A PREDATOR-PREY SYSTEM [30]

We have modeled the behavior of predators and pathogens in spatially extended evolutionary models. Our results suggest that such models are relevant to studies of systems with long-range interactions. There is a transition that occurs from coexistence to global extinction. This transition can be sudden and can occur even in systems that already have a

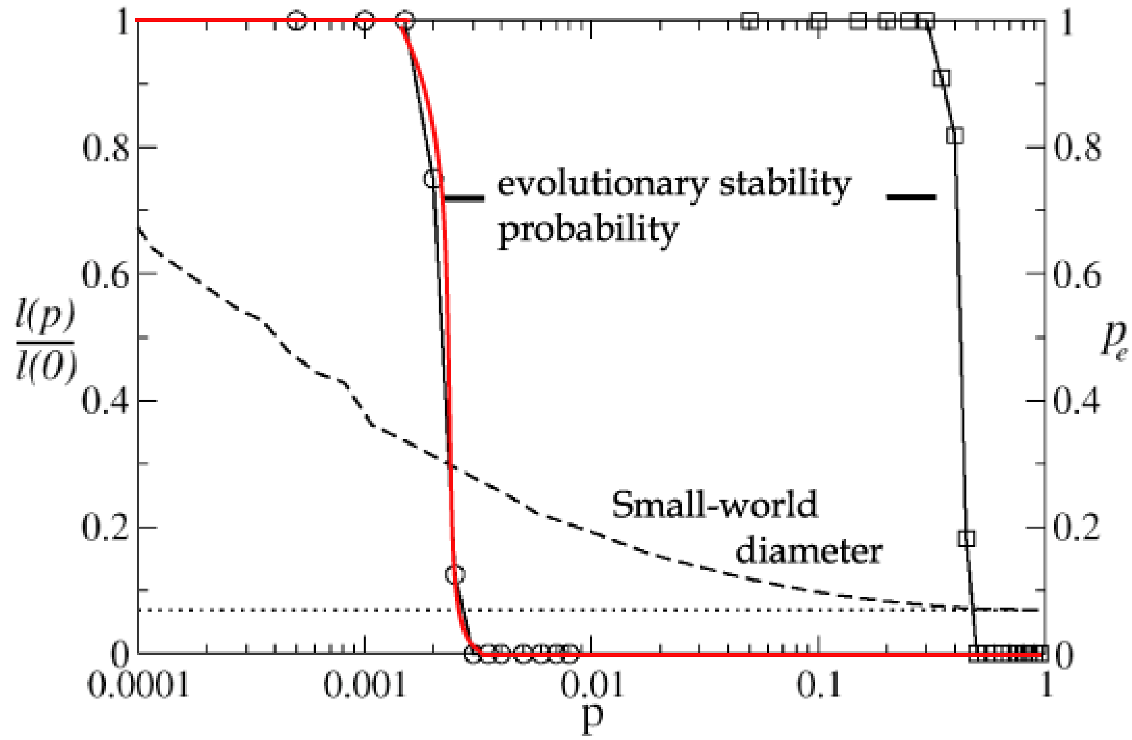

FIG. 7: Evolutionary stability on a two-dimensional Small-World network. The probability p_e that predator and prey coexist for 100 000 generations, as a function of p, averaged over 11 runs, for $g = 0.05$ (circles) and $g = 0.2$ (squares) (depletion rate $v = 0.2$, lattice size $L = 250$). Note the logarithmic scale of p. We identify the point of transition to instability p_c as the density such that for all $p > p_c$, $p_e < 1 / 2$. For comparison, the average path length $l(p)$ between nodes is plotted as a fraction of $l(0)$ (dashed line, same scale). For comparison, the dotted line shows $l(1) / l(0)$, that is, the value for a random network.

significant density of long-range interactions. Thus, one should not conclude that a system that already has long-range mixing will be stable to additional mixing.

According to our simulations, when global mixing increases beyond the critical density, overexploiting predator or pathogen strains escape local extinction and replace sustainable strains globally, leading to their own extinction and decimation of the prey population. Our results apply directly to simple evolutionary models, but similar considerations apply to the phenomena of emergent diseases (such as Ebola, SARS and Avian Flu), most of which evolve on short time scales, and may also apply to invasive species, which have been of widespread ecological concern. While the demonstration that some long-range connections do not always destabilize evolving systems provides some reassurance, the danger from additional connections suggests that a system may cross the transition and become unstable with little warning as global mixing increases in frequency (see Fig. 7).

Our results predicted the outbreak of Ebola in West Africa and suggest the need for concerted response, including medical developments and, perhaps, societal changes. Due to increasing global transportation, human beings appear to have crossed the transition to large pandemics. Preventive actions should be taken that either limit global transportation or its impact.

VIII. CONCLUSION

We have demonstrated that policy decisions made by governments and regulatory bodies can have far-reaching consequences in the modern world. An understanding of complex systems methods and concepts, especially multiscale analysis, network structures and non-linear dynamics, enables analysis that can inform effective real world decision making. One nation's energy subsidies can cause global food prices to spike, setting off political unrest halfway around the world. Financial markets that become too interdependent have a high risk of cascades, and collective panics cause global crises. Ethnic violence can be largely predicted from ethnic spatial geography and alleviated by policies that allow for local autonomy. Global connectedness promotes the existence of virulent diseases that can cause devastating global pandemics. Complex systems science has a proven record of predicting and explaining the causes of global phenomena. Policy makers and regulators who seek to achieve specific objectives or to more generally improve economic and social systems can benefit from the insights of targeted studies.

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