The Instability of Globalization

Applying Evolutionary Game Theory to Global Trade Cooperation

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Abstract: A new wave of economic nationalism is threatening the open and cooperative international order, and the consequences for global trade liberalization are yet unclear. This paper applies evolutionary game theory to analyze the stability of international trade cooperation. Global trade liberalization is modeled as an iterated prisoner's dilemma between all possible pairs of WTO member states. Empirical data is used to model the size and competitiveness of the respective markets, which then determine the resulting gains and costs of trade cooperation. Because of the high number of WTO member states and repeated rounds of their interaction, we use computer simulations in order to calculate which strategies lead to the highest 'fitness' of the respective member states and consequently survive within an evolutionary selection process. The results of our simulations are ambivalent for the stability of international trade cooperation. Even large economies like that of the US suffer huge losses, if other countries play tit-for-tat and retaliate forcefully against protectionism. However, if other member states try to stabilize international cooperation with generosity, a protectionist strategy may be able to exploit their good-will. The danger of appeasement is that successful protectionism becomes an attractive strategy, that it is copied by other states, and that this leads to an overall decline of cooperation and welfare in the global economy.

1. Introduction

After thirty years of globalization, a new wave of economic nationalism is threatening the open and cooperative international order as we know it. Most notably, the world's largest economy – the United States of America – is turning towards protectionist trade policies since Donald Trump took office as American president.[1] By 2017, the Trump administration withdrew the US from the Transpacific Partnership (TPP), it put the negotiations of the Transatlantic Trade and Investment Partnership (TTIP) on ice, and started to re-negotiate the North American Free Trade Agreement (NAFTA). In 2018, the US imposed tariffs between 20% and 50% on solar panels and washing machines, and tariffs on aluminum and steel imports were raised to 10% and 25% respectively. Moreover, President Trump has repeatedly and openly announced an imminent increase of import tariffs on cars to 25%. In addition to these general measures, tariffs of 25% were specifically imposed on $34 billion of Chinese exports in July 2018, and another $16 billion of goods shall be addressed at a later date. Canada, China, the EU, and Mexico have imposed retaliatory tariffs on US exports with values similar to their own affected exports to the US. A global trade war seems to be unfolding, and the consequences for global wealth and security are likely to be severe.

The new economic nationalism is a puzzle for economists and international relations scholars alike. It is a standard wisdom of economic theory that international trade liberalization is welfare increasing,[2] and that protectionism is consequently an

[1] Ikenberry 2017, Irwin 2017, Norrlof 2018.

[2] Krugman 1987.

'irrational' policy. Trade wars cannot be won, and they only generate losses for every country involved.[3] International relations scholars have argued since the 1980s that countries can achieve international trade cooperation by playing tit-for-tat within iterated games,[4] and that international regimes are the institutionalized expression of this cooperation.[5] Much of the debate during the last thirty years has explored how formal international institutions[6] or even informal norms and identities[7] could create and stabilize international cooperation between states, but the possible collapse of global trade cooperation has hardly been discussed. The current developments contradict this optimism of the globalization era. The US and others adopt a protectionist trade policy, which seems to be economically 'irrational', and the international institutions of the global trade regime seem to be powerless in the face of this provocation.

In order to analyze the systemic reasons and consequences of the new economic nationalism, this article uses an evolutionary game theory approach. Since the 1980s, evolutionary game theory has become common use in evolutionary biology, where it is used to explain how cells, genes, or animals are able to develop cooperative behavior in order to develop organisms or societies.[8] Sacrificing an individual advantage in favor of common gains seems at odds with evolutionary

[3] Conybeare 1985, Ossa 2014

[4] Axelrod 1984,1997.

[5] Axelrod and Keohane 1985, Keohane 1984, Stein 1982.

[6] Koremenos et al 2001, Rosendorff and Milner 2001.

[7] Finnemore 1996, Wendt 1992.

[8] Maynard Smith 1982.

success, which is based on the 'survival of the fittest'.[9] However, evolutionary game theory demonstrates that cooperation leads to more fitness than defection if cooperative players encounter enough other cooperative players in the population. Under these circumstances, groups of cooperative players may be more successful in the evolutionary competition than short-sighted defectors. The success of cooperation and defection depends on the composition of the population.[10] Tit-for-tat strategies are able to enter a defecting population and to establish cooperation therein, but once the whole population cooperates, defection becomes an attractive strategy again in order to exploit the cooperative behavior of others. The result is an endless cycle in which the level of cooperation in a given population increases and declines.[11]

If international trade cooperation follows the same mathematical rules of evolutionary game theory as cells, genes, or animals, today's level of global trade cooperation may constitute the end of a cooperative upswing. The new economic nationalism might signal the beginning of a defectionist downswing. Such waves of cooperation and defection have occurred in the international system before. Under British hegemony, trade openness and globalization reached its first peak at the beginning of the 20th century.[12] It was the protectionist trade policy of the US – namely the Smoot-Hawley tariff act of 1930 – that marked the end of this era and led to a wave of protectionism around the world. We do not want to argue that history is

[9] Dawkins 1976.

[10] Friedman and Sinervo 2016.

[11] Imhof et al 2005, Nowak 2006, Nowak and Sigmund 2004.

[12] Harold 2001, King 2017.

doomed to repeat itself, but the parallels are striking. Thus, it is important to explore the possible success of protectionist trade strategies in an environment of global trade cooperation.

In order to explore the stability of global trade cooperation against protectionist attacks like those of the current US administration, this article proceeds in five steps. First, we discuss hegemonic stability and regime theory in order to lay the theoretical foundations for our own game theoretical analysis. Second, we build up our own evolutionary game theory model of global trade cooperation. This model includes a game of international trade cooperation and an evolutionary process, which determines the distribution of different strategies within the population of countries. Third, we run several simulations of global trade cooperation, present their findings, and discuss their implications. Fourth, we summarize the findings and discuss them critically. Finally, the appendix contains some robustness checks, which demonstrate that small changes in the assumptions of our model do not change the results of the simulations in an unpredictable way.

2. Hegemonic Stability, International Regimes and Game Theory

The question about the stability of the global trade order takes us back to an academic debate of the 1980s and 1990s. Therein, realists argued that the existence of a benevolent hegemon is a necessary and sufficient condition for the creation of an international liberal order.[13] Accordingly, this liberal order is a public good, and the supply of this good by a group of sovereign states is problematic due to the

[13] Gilpin 1981, Kindleberger 1973, Krasner 1976.

absence of a central authority in the international system. However, the existence of a benevolent hegemon transforms a group of states into a privileged group,[14] in which the hegemon has an interest to provide the public good on behalf of all others. Thus, it was British hegemony during the late 19th century and American hegemony after the Second World War that created and stabilized liberal orders. In contrast, the wave of protectionism during the first half of the 20th century was caused by the lack of hegemony and obscure leadership in the international system. Long cycles of technological leadership and the resulting hegemony of single countries allow hegemonic stability theory to explain the consequent waves of liberalism and protectionism, which distinguish the international economic system since the beginning of industrialization in Great Britain.[15]

Hegemonic stability theory has been repeatedly criticized on theoretical and empirical grounds. From a theoretical perspective, the theory seems to be insufficiently specified. It remains unclear which conditions need to be fulfilled in order to speak of hegemony. How big does the difference in economic and military power between the hegemon and other states in the system need to be?[16] And is it necessarily a single country that stabilizes the international order, or can a stable alliance of a small group of countries fulfill the same function?[17] From an empirical perspective, it is disputed whether it was really British hegemony that caused the relative openness of the international economic order during the second half of the

[14] Olson 1965.

[15] Thompson and Vescera 1992.

[16] Mansfield 1992.

[17] Snidal 1985, Yarbrough and Yarbrough 1987.

19th century.[18] If hegemonic stability theory fails to explain this historical episode, it is only a theory for one case of economic openness under American hegemony after the Second World War. More importantly, it is widely argued that American dominance in the global economy is declining since the early 1980s. As a result, hegemonic stability theory faces difficulties to account for thirty years of economic openness and globalization since the end of the Cold War.

John Conybeare's game theoretical analyses of international trade cooperation have started from the argument that international trade liberalization is not a public good, but that it should rather be understood as a prisoner's dilemma between two countries.[19] Trade liberalization does not share the characteristics of non-rivalry and non-excludability, which are constitutive for public goods. In fact, countries compete to some degree for market access and trade shares, and discriminatory trade policies allow to exclude single countries from consuming this good. Nevertheless, trade liberalization is a prisoner's dilemma, because every country prefers to get access to the other country's market while simultaneously protecting its own industry against imports.[20] The game is played bilaterally between pairs of countries, because each country can answer specifically to the trade policy of every other country. The direct reciprocity of trade liberalization between two countries has a crucial advantage for their cooperation. The prisoner's dilemma of trade liberalization

[18] Ashley Morrison 2012, McKeown 1983.

[19] Conybeare 1984, 1985.

[20] The reasons why international trade liberalization should be modelled as a prisoner's dilemma and not as a game of harmony are discussed in more detail in section 3.

is not a one-shot game: it is played continuously on a daily basis. As Robert Axelrod has shown, countries can play tit-for-tat against each other within such an iterated game, and mutual cooperation can emerge.[21] Thus, international trade liberalization is much easier to achieve than it is envisaged by the proponents of hegemonic stability theory.

Whereas Axelrod's and Conybeare's analyses have largely neglected international institutions, the rise of regime theory during the 1980s marked the beginning of an institutionalist turn in international relations theory.[22] The main idea behind regime theory is that countries face significant transaction costs when trying to cooperate with each other. Sets of international institutions – may they be substantive or procedural, formal or informal – can help countries to cooperate by reducing these transaction costs. For example, agenda-setting and decision-making rules reduce ex-ante coordination costs, whereas monitoring and dispute settlement mechanisms reduce ex-post implementation problems.[23] It is disputed whether it needs a hegemon in order to establish such international regimes, but a widespread consensus has emerged that regimes can at least stabilize international cooperation, even if the hegemonic power is in decline.[24] After turning away from the structuralist analyses of realism, much of the academic debate during the 1990s and 2000s has concentrated on the concrete form and influence of international institutions. Therein, rationalists – standing in the tradition of regime theory – have stressed the

[21] Axelrod 1984, 1997.

[22] Keohane 1982, 1984, Stein 1982.

[23] Abbott et al 2000, Fearon 1998, Pollack 1997.

[24] Krasner 1982.

instrumental character of international institutions to achieve and stabilize cooperation,[25] whereas constructivists have gone a step further and stressed the constitutive aspect of international institutions.[26]

The wave of globalization during the 1990s and 2000s seems to have confirmed the optimism of regime theory. The relative decline of American hegemony has not led to a collapse of the global trade regime and even the global financial crisis of 2008 has not led to a new wave of protectionism. On the contrary, the World Trade Organization (WTO) was established in 1995 and has further strengthened the General Agreement on Tariffs and Trade (GATT). In addition, a wave of regional and preferential trade agreements has created the so-called 'Spaghetti-Bowl' of trade agreements.[27] International trade has not collapsed, but it has increased to a formerly unknown extent. Whereas the first wave of globalization reached around 30% of international trade in relation to global GDP shortly before the First World War,[28] this share is around 60% today.[29] However, the new economic nationalism shows the boundaries of regime theory and the limited power of international institutions. The protectionist trade policies of the US violate WTO law, but there is not much what the WTO can do about it. International institutions can reduce the transaction costs of cooperation, but they cannot force countries to cooperate against their own will.

[25] Koremenos et al 2001, Rosendorff and Milner 2001.

[26] Finnemore 1996, Wendt 1992.

[27] Baldwin 2006, Mansfield and Milner 1999.

[28] Klasing and Milionis 2014.

[29] Based on data from the World Bank (data.worldbank.org).

Hegemonic stability theory and the game theoretical approaches would propose vastly different hypotheses in respect to the effects of the new economic nationalism on the stability of the liberal trade order. From the realist perspective of hegemonic stability theory, President Trump's protectionist trade policies can be interpreted as an answer to the 'hegemon's dilemma'.[30] Although it may be in the interest of the hegemon to provide a stable and liberal global order, smaller countries profit relatively more from international trade than the hegemon itself. Hegemonic stability necessarily strengthens the economic capacity of potential contenders in comparison to the hegemon. This dilemma becomes visible in the rise of China, which has profited enormously from its accession to the WTO, and which has become a real challenge for US hegemony. American protectionism reduces the trade deficit with China, and slows down the economic growth of a potential rival. Because hegemonic stability theory argues that US hegemony is the main fundament of the liberal trade order, a turn of the US towards protectionism is likely to have devastating effects for this order. The attempt to reconstitute American dominance with protectionist measures will not only damage China, but it will lead to a new wave of protectionism.

Axelrod's analysis of iterated prisoner's dilemmas suggest a more optimistic view on the stability of international trade cooperation. If the other member states of the global trade regime play tit-for-tat, protectionist trade policies can only produce higher payoffs in the very short-run. As long as countries cooperate on a reciprocal basis, trade barriers imposed by one country today will be answered by trade barriers against this country tomorrow. Thus, a protectionist country is only able to

[30] Stein 1984.

exploit the cooperation of others in one round of the game, and thereafter, its economy suffers from a loss of access to international markets. When the other countries go on to cooperate with each other and create a free market among themselves, the protectionist country loses out even more in relation to potential contenders.[31] Protectionism cannot be a successful strategy in the long run, and it is in the interest of all countries to return to a more cooperative strategy. Thus, reciprocal trade cooperation is self-reinforcing and the liberal trade regime should stabilize itself relatively soon.

We propose a modification of the game theoretical approach, which takes recent developments of evolutionary game theory into account, and which comes to more nuanced expectations with respect to the stability of international cooperation.[32] According to the evolutionary biologist Martin Nowak, there exists no stable equilibrium of cooperation or defection within a finite population of players that play iterated prisoner's dilemmas against each other.[33] Under realistic assumptions of incomplete information and uncertainty, tit-for-tat is not an optimal strategy, because misunderstandings or unintentional defection cause endless rounds of retaliation. This can only be avoided if countries are generous with each other and do not retaliate against every single defection. Once generous tit-for-tat has

[31] Snidal 1991.

[32] Since Axelrod's path breaking work of the 1980s and 1990s, evolutionary game theory has hardly been applied in the field of International Relations A recent and notable exception is the article from Little and Zeitzoff (2017), who build up an evolutionary model of bargaining and conflict.

[33] Imhof et al 2005, Nowak 2006, Nowak and Sigmund 2004.

established a lot of cooperation within the population, countries may start to cooperate unconditionally in order to save the surveillance cost of conditional strategies. However, generosity and unconditional cooperation can of course be exploited by the defection of ‘unfriendly’ countries, and this leads to a decline of cooperation within the whole population. As soon as defection is the dominant strategy, countries can yet again get a competitive advantage if they start to play tit-for-tat and profit from some cooperation. In this endless cycle of cooperation and defection, the strength or weakness of a particular strategy always depends on the dominant strategy within the population.

Translated to the area of international trade cooperation, the possible success of protectionist trade policies depends very much on the current strategies of all other countries. If other countries play tit-for-tat forcefully and retaliate against defection, protectionism may indeed become a very expensive and inefficient strategy. However, if a huge country like the US starts to defect, other countries may be tempted to appease this country. They may attempt to re-establish cooperation by playing very generous tit-for-tat or even unconditional cooperation. Such generosity is best exploited by a defectionist strategy, which increases the gains for the protectionist country. The danger is that a protectionist strategy may be copied by other countries if it turns out to be successful in a generous and cooperative environment. In this case, more and more countries would start to defect, and the liberal trade order would be at risk. Thus, the crucial task for the member states of the global trade regime is to find the right balance between generosity and retaliation. Too little generosity may lead to a trade war with endless rounds of

retaliation, whereas too much generosity makes protectionism a successful and attractive strategy.

3. An Evolutionary Game Theory Model of International Trade Liberalization

In contrast to classic game theory, evolutionary game theory does not assume that actors deliberately choose a certain strategy within a particular game in order to achieve the highest possible pay-off. Such a conceptualization of actors as rational utility maximizers would hardly be plausible to analyze the behavior of genes, biological cells or animals.[34] In evolutionary game theory, the crucial variable for the success of a particular player with a certain strategy is its fitness. This fitness resembles the accumulated payoffs, which the player receives in its interaction with every other player in each round of the game. The fitness of a player is decisive for the survival and success of its strategy within an evolutionary process. 'Weak' strategies produce less fitness for their players than 'strong' strategies, and, over the course of time, evolutionary competition favors player with a high fitness. Thus, the evolutionary process replaces individual rationality as a selection mechanism for strategies. Consequently, it does not matter, whether the US or any other country choose a particular strategy for normative reasons or for pure self-interest. What matters the extent to which the strategy contributes to the countries' fitness, and whether it can survive the selectivity of an evolutionary process.

Models of evolutionary game theory consist of two different parts: a game which is played repeatedly between all possible pairs of players within a certain

[34] Dawkins 1976, Maynard Smith 1982.

population, and a model of an evolutionary process in which successful strategies are reproduced and less successful strategies die.[35] Thus, firstly, we need to set up a game that countries play when they decide to open up their market or to protect domestic industries. Secondly, we need a model of an evolutionary process, in which more successful strategies of trade cooperation have a higher probability to diffuse in the population of countries than less successful ones.

3.1 The Prisoner's Dilemma of Trade Liberalization

Economists usually argue that open markets are beneficial for almost all countries under almost all circumstances.[36] International trade allows countries to utilize comparative cost advantages (which result from the different factor endowments of the participating economies) and economies of scale (which result from access to larger markets). A country would even benefit from unilateral trade liberalization if its counterpart closed its market, because open economies can produce more efficiently when importing goods at lower costs. From this point of view, international trade liberalization should be a game of harmony and there should not exist any cooperation problem between countries. However, despite these claims of economists, countries have adopted restrictive trade policies time and again in human history, and they usually drive a hard bargain about mutual trade concessions.

[35] Friedman and Sinervo 2016, Gintis 2009.

[36] Krugman 1987.

There are several reasons why even economically rational governments may establish restrictive trade policies, and why giving up these measures causes costs for them. Firstly, governments may establish tariffs in order to satisfy the demands of organized interests and to gain resources for the domestic political competition.[37] In this case, tariffs redistribute wealth domestically from less organized towards well organized groups. Secondly, even classic trade theory has acknowledged that big countries are able to improve their terms of trade, if they establish optimal tariffs.[38] And thirdly, tariffs can be part of strategic trade policies, which aim to support domestic industries in an oligopolistic competition or which protect infant industries at home.[39] In these cases, tariffs redistribute wealth from some external economies towards the domestic economy. As a result, political economists see trade liberalization between two countries as a prisoner's dilemma wherein market access is granted reciprocally.[40] Countries try to maximize their access to other markets in order to generate export possibilities for their competitive industries, while simultaneously minimizing foreign access to their domestic market in order to protect uncompetitive industries. As long as the costs of import competition are lower than the gains of trade liberalization, the respective countries play a prisoner's dilemma with each other. Cooperation would be beneficial, but countries are also tempted to defect and exploit the cooperation of their counterparts.

[37] Krueger 1974, Magee et al. 1989.

[38] Conybeare 1984, Johnson 1953.

[39] Brander 1986, Krueger and Tuncer 1982.

[40] Axelrod 1984, Conybeare 1984, 1985, Krugman 1992, Gawande and Hansen 1999, Milner and Yoffie 1989, Rhodes 1989.

Most models of evolutionary game theory assign simple numerical payoffs to the different outcomes of the prisoner's dilemma.[41] As long as all players get the same payoffs, such models do not need to distinguish between players and their strategies. It does not matter which player faces which opponent, but only which strategy is superior. However, we want to represent different market sizes in our model, because we expect that the strategies of larger countries have a bigger impact on the stability of the global trade order compared to smaller countries. Hence, we need to distinguish between actors with constant characteristics (like market size) and the variable strategies they play (like tit-for-tat). In contrast to Axelrod's version of the prisoner's dilemma, our model represents an asymmetric game wherein countries' payoffs result from their market size and that of their opponents. A small country like South Korea gains a lot when it exports to a large market like the USA, but it also gets hurt more when its cooperation is exploited by a large exporter. Conversely, a large country like the USA gains less by getting access to a small market like that of South Korea, but it also has less to lose by opening its market to a small exporter. In sum, small countries are much more sensitive to the outcome of the game then large countries.

[41] Axelrod 1984, Nowak 2006.

Figure 1: The Prisoner's Dilemma of Trade Liberalization

		Country B	
		S_b^{co}	S_b^{de}
Country A	S_a^{co}	$\frac{(ex_a - pr_a\, ex_b)\, Ma_b}{\sqrt{Di_{ab}}}$	$-\frac{pr_a\, ex_b\, Ma_b}{\sqrt{Di_{ab}}}$
		$\frac{(ex_b - pr_b\, ex_a)\, Ma_a}{\sqrt{Di_{ab}}}$	$\frac{ex_b\, Ma_a}{\sqrt{Di_{ab}}}$
	S_a^{de}	$\frac{ex_a\, Ma_b}{\sqrt{Di_{ab}}}$	*0*
		$-\frac{pr_b\, ex_a\, Ma_a}{\sqrt{Di_{ab}}}$	*0*

ex_a	Share of country a's export industry (total exports divided by GDP)
Di_{ab}	Distance (measured between the capitals of countries a and b)
Ma_a	Country a's market size (GDP)
pr_b	Rate of country b's protection against imports (trade weighted tariffs on imports)
S_a^{co}	Strategy of country a is cooperation
S_b^{de}	Strategy of country b is defection

We model the payoffs of the prisoner's dilemma of trade liberalization along the lines of the gravity model of international trade (see Figure 1).[42] Accordingly, the amount of potential trade between two countries is proportional to their market size *Ma* and inverse proportional to the distance *Di* between them. We discount more distant kilometers by using the square root of the absolute distance ($\sqrt{Di_{ab}}$) to accommodate the fact that transportation costs do not grow linearly. The larger and the closer the market of a trade partner is, the more a country gains by getting

[42] Bergstrand 1985.

access to that market. In addition to that, we also take the strength of countries' export industries *ex* and the rate of protectionism *pr* into account. It is only the export industry, but not the full economy of country A, which profits from access to the market of country B ($\frac{ex_a\, Ma_b}{\sqrt{Di_{ab}}}$). The costs of market liberalization hit the protected industry of country A and are the result of country B's export strength and market size ($\frac{pr_a\, ex_b\, Ma_b}{\sqrt{Di_{ab}}}$). Importantly, market size, location, export strength and rate of protectionism are characteristics of countries, but not of their strategies. Thus, these characteristics do not change immediately, if the respective countries change their strategies in the prisoner's dilemma of trade liberalization.[43]

3.2 Fitness, Selection and Evolution

In our model of international trade cooperation, the fitness of a particular country is equivalent to its accumulated market access over time. The more market access a country wins in the prisoner's dilemma of trade liberalization, the more its export industry grows and creates jobs because it is able to utilize comparative cost advantages and economies of scale by international trade. The costs of trade liberalization for the country's protected industry must be subtracted from this fitness. Thus, a successful strategy needs to maximize market access in all rounds of the

[43] In the course of time, a country's trade policy and its cooperation with other countries do of course have an effect on the country's market size and the strength of its export industry. However, for the time being, our model keeps the characteristics of countries stable and does not take such feedback effects into account.

iterated prisoner's dilemma while simultaneously minimizing the costs of trade liberalization. In addition to the gains and losses from international trade, countries' fitness also depends on the size of their own market ($\frac{Ma_a}{\sqrt{Di_a}}$).[44] The domestic economy always has the possibility to utilize comparative cost advantages and economies of scale on the domestic market. The larger the domestic market is, the more it contributes to the fitness of the country, and the more the respective country is independent from access to foreign markets. Thus, large countries start the iterated prisoner's dilemma of global trade liberalization with a competitive advantage, because their domestic market is enormous in comparison.

Countries' fitness depends on their own market size, their own strategies and – most importantly – the distribution of strategies in the rest of the population (see Figure 2). The only Nash-equilibrium in the prisoner's dilemma of trade liberalization is defection, and a single cooperative or tit-for-tat playing country would always be exploited by the defection of all other countries. However, if there are several tit-for-tat playing countries in the population, the situation changes completely, and tit-for-tat becomes the superior strategy (Axelrod 1984, Nowak and Sigmund 1992). Even

[44] In order to reflect the size of the domestic market in the fitness function of countries, we add that they get access to their own market in every round of the game ($\frac{Ma_a}{\sqrt{Di_a}}$). Because not only the export industry, but also the protected industry and the non-tradable sector operate on the domestic market, we do not discount the domestic market with the factor *ex*. Besides, we account for transportation costs on the domestic market with the square root of the countries' area ($Di_a = \sqrt{area_a}$), which resembles the average distance within that market.

when defecting countries exploit the cooperation of tit-for-tat playing countries in the first round of the game, this exploitation is short-lived, whereas tit-for-tat playing countries benefit in the long-run from trade liberalization between each other. Nevertheless, tit-for-tat is not an evolutionarily stable strategy, because it does not outperform unconditional cooperation in a population of tit-for-tat playing countries. The strategy of unconditional cooperation is of course also not an evolutionarily stable strategy, because it can be successfully exploited by defecting countries.

Figure 2: Fitness Functions of Selected Strategies

Strategy of country A	**Strategy of all other countries**	**Fitness of country A (in ascending order)**
Tit-for-Tat	Always defect	$f_a = \sum_{b=1}^{n-1} № \frac{Ma_a}{\sqrt{Di_a}} - \frac{pr_a\, ex_b\, Ma_b}{\sqrt{Di_{ab}}}$
Always defect	Always defect	$f_a = № \frac{Ma_a}{\sqrt{Di_a}}$
Always defect	Tit-for-tat	$f_a = \sum_{b=1}^{n-1} № \frac{Ma_a}{\sqrt{Di_a}} + \frac{ex_a\, Ma_b}{\sqrt{Di_{ab}}}$
Tit-for-tat	Tit-for-tat	$f_a = \sum_{b=1}^{n-1} № \left[\frac{Ma_a}{\sqrt{Di_a}} + \frac{(ex_a - pr_a\, ex_b)\, Ma_b}{\sqrt{Di_{ab}}}\right]$
Always defect	Always cooperate	$f_a = \sum_{b=1}^{n-1} № \left(\frac{Ma_a}{\sqrt{Di_a}} + \frac{ex_a\, Ma_b}{\sqrt{Di_{ab}}}\right)$

№ = number of games with each opponent

In evolutionary game theory, the evolution of finite populations is usually modeled by using a Moran process in which successful strategies are reproduced and weak strategies die.[45] Because the population of WTO member states is finite and does not grow indefinitely, we follow this approach as well. However, we need to modify it in order to distinguish between countries with stable characteristics and the

[45] Nowak et al 2004, Voelkl 2011.

variable strategies played by these countries. Countries are not born and do not die as a consequence of strong or weak trade policies, but they may change their strategies. In our model of the evolutionary process, a country is selected to reproduce its strategy with a probability equivalent to its relative fitness ($p_a^{co} = \frac{f_a}{\sum_{b=1}^{n} f_b}$). Another country is chosen randomly ($p_b^{de} = \frac{1}{n}$) and takes over the strategy of the successful country. In this way, both countries keep their stable characteristics, but one country adapts its trade strategy. It is important to keep in mind that the fitness of a particular country is not only the result of its performance in the prisoner's dilemma of trade liberalization: it also includes the domestic market of the respective country. Thus, the strategies of large countries are favored in this selection process, because their fitness is less dependent on the outcome of the game. Even supposedly inefficient strategies may reproduce within this selection process, if they are played by large countries.

The modified Moran process can be understood as a model of policy change and diffusion. Because we keep other economic variables stable, we assume that the economic success of a country correlates positively with its market access and negatively with its costs of market liberalization. A country with an inefficient strategy gains little market access for its export industry abroad, or it allows for too much imports that squeeze its uncompetitive industry out of the market. In any case, the country's domestic industry suffers, its economic growth declines, domestic wages shrink and unemployment increases. As a result, domestic opposition against the country's trade strategy rises, and policy change becomes necessary. How this policy change looks like depends on the internal constitution of that country. In democratic countries, governments either react to increasing domestic opposition

and change their policies, or they are voted out of government at the next elections. Authoritarian governments are probably able to resist the pressure for policy change sometime longer, but they as well cannot afford to enrage their population indefinitely without risking political turmoil or facing high costs for political suppression. Whenever a particular country needs to adapt its trade strategy, it is likely to observe the strategies of other countries and to follow the example of an economically successful one.[46] Thus, the strategies of countries with higher fitness are more likely to diffuse within the population than the strategies of countries with lower fitness. In other words, the strategies of fitter countries are more successful within the evolutionary competition of different trade strategies than the strategies of unfit countries.

In the next step, we introduce noise and generosity into our model. As a result of noise, countries act randomly with a probability of $\alpha = 0.1$. Thus, even if their main strategy requires cooperation, they may defect from time to time – for example, to accommodate domestic opposition to certain measures. Such erratic behavior of a particular country does not matter if its counterpart is playing an unconditional strategy – i.e. if it always defects or cooperates. However, such a deviation from the main strategy matters if the country's opponent plays a conditional strategy like tit-for-tat. If a particular country is an unconditional co-operator, an unintentional defection will be punished with only one defection by its tit-for-tat playing counterpart. If both countries play tit-for-tat, such an unintentional defection is the beginning of an endless circle of retaliation, which reduce the fitness of the two countries. Thus, tit-for-tat is not such a good strategy in a noisy environment, and it gets outplayed by

[46] Gilardi 2010, Simmons and Elkins 2004.

generous tit-for-tat.[47] Generous tit-for-tat is 'friendlier' than tit-for-tat, because it cooperates with a probability of $\beta = 0.3$, even if it should actually retaliate the previous defection of its opponent. Such 'unmotivated' cooperation of generous tit-for-tat allows the respective countries to break out of endless circles of retaliation and return to mutual trade liberalization.

Finally, we also introduce surveillance costs and mutations into the model. In order to play tit-for-tat or generous tit-for-tat, countries need to establish a bureaucracy, which monitors the global market and fights judicial disputes when needed.[48] In order to accommodate for such costs, we introduce discount factor $\gamma = 0.05$, which applies to all gains that result from a conditional strategy. Thus, when countries play (generous) tit-for-tat, they receive only 95% of the payoffs. As a result, unconditional cooperation becomes more appealing in a very friendly environment, and unconditional defection becomes more appealing in a very unfriendly environment. Mutations make it possible that such strategies like unconditional cooperation or defection can re-enter a population, even if they were already eliminated by the Moran process in previous rounds of the game. If we set the mutation rate $\delta = 0.1$, on average one out of ten selection processes produces a random result, in which a country chooses arbitrarily from a set of available strategies (in our case unconditional defection, tit-for-tat, generous tit-for-tat and unconditional cooperation). As a result, the Moran process does not have a natural end. In other words, even if all WTO member states are tit-for-tat players and cooperate with each other, mutation makes it possible that a new strategy is adopted

[47] Axelrod 1997, Nowak 2006, Nowak and Sigmund 2004.

[48] Bown and Hoekman 2005.

by one country. Whether this strategy can successfully enter the population depends on the fitness of this country – i.e. on its market size and the success of the strategy.

4. Results of the Simulations

In order to simulate the dynamics of international trade cooperation and defection, we implemented our evolutionary game theory model within a package based on the programming language Python.[49] Thereby, we were able to build up on the already existing Axelrod Python library.[50] However, the already existing Axelrod library is based on simple numerical values of zero, one, three and five as payoffs in the iterated prisoner's dilemma, and it cannot distinguish between variable strategies and players with stable characteristics. Our new program package modifies this and implements the payoffs of Figure 1 for the prisoner's dilemma. The population in our simulation consists of 126 countries. These are the WTO member states minus the EU member states (because the EU is one player in our simulation) and minus some small economies for which we have no data.[51] We use the World Bank's current US$ estimates of the GDP in order to determine the countries' market size *Ma*. The share of countries' export industries *ex* is calculated by dividing the countries' exports (obtained from the Observatory of Economic Complexity and UN Comtrade databases) with their GDP. The rate of protectionism *pr* is expressed by the countries' average tariffs, weighted by current imports (collected from WTO data).

[49] Isaac 2008.

[50] Knight 2015.

[51] We lack data for Afghanistan, Djibouti, DR Congo, Lesotho, Liechtenstein, Maldives, Papua New Guinea and Swaziland.

4.1 Absolute and Relative Losses due to Protectionism

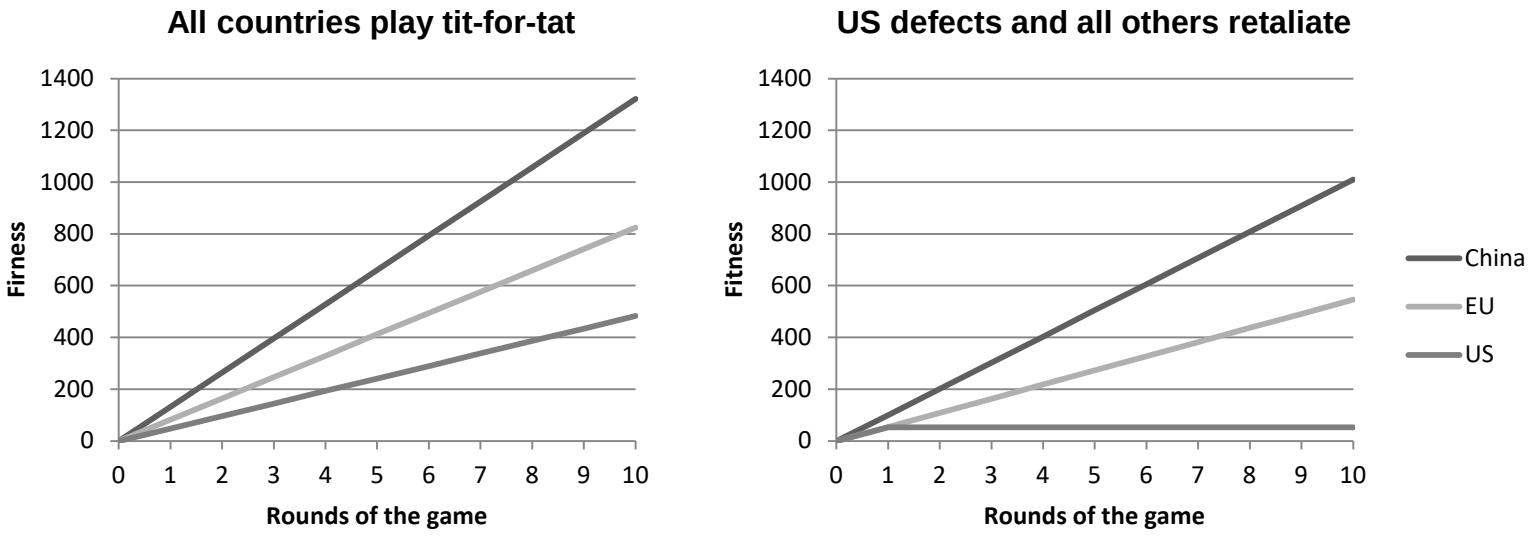
The hegemon's dilemma results from the fact that a liberal trade order is in the absolute interests of the hegemon, but that smaller economies profit relatively more from international trade than the huge economy of the hegemon.[52] As a result, hegemonic stability necessarily leads to relative gains for challenger countries and a relative decline of the hegemon. The left graph of Figure 3 shows, how much fitness China, the EU and the US gain through ten rounds of trade liberalisation, if the whole population is playing tit-for-tat. Of course, all three countries profit from trade liberalisation and enjoy absolute gains. However, the markets of China and the EU are slightly smaller than the US market, which implies that China and the EU gain relatively more fitness from access to the US market than vice versa. Thus, trade liberalisation reduces the gap between the fitness of the US and its two largest competitors.

The US can reduce the fitness gains for China and the EU considerably, if it defects unconditionally instead of playing tit-for-tat. The right graph of Figure 3 shows, how much fitness China, the EU and the US gain, if the US defects and all other countries play tit-for-tat. Despite the fact that only one country – the US – defects, the losses in fitness for China and the EU are large. However, the US needs to pay a high price for that. The defecting US can exploit the cooperation of all other countries only in round one, but thereafter the other countries retaliate and close their markets for US imports. As a result, the fitness of the US stagnates after round one, and the US loses even more fitness than China and the EU. In fact, the relative

[52] Stein 1984.

decline of the US in comparison to China and the EU is larger, if the US defects than if it plays tit-for-tat. This is due to the fact that tit-for-tat allows all other countries to cooperate with each other while isolating and punishing the US at the same time. As a result, even a large country and possible hegemon like the US cannot win by defecting unilaterally as long as all other countries forcefully retaliate against this.

Figure 3: The Relative Gains of Trade Liberalization[53]



Avoiding relative losses by defecting unilaterally may be a rational strategy in a bipolar setting, but it does not pay off in a multipolar setting.[54] A country like the US can prevent relative losses in comparison to another country by defecting against this opponent. If there exist only two significant players – like during the cold war –, this leaves the other player (in this case the USSR) without any gains from cooperation. However, if there exist more than two significant players – like in

[53] There is no noise, mutation or selection in this round-robin tournament of ten rounds. Here, countries' fitness does not include their domestic market.

[54] Snidal 1991.

today's global economy –, the US cannot prevent that other countries (like China and the EU) cooperate with each other. If the gains from such cooperation among other countries are significant, the US loses out in relative terms by not participating in such a cooperative agreement. Thus, a strategy which may avoid relative losses within a bilateral relationship can create exactly such relative losses within a multipolar setting.

4.2 The Strength and Weakness of Tit-for-Tat

The Achilles heel of the tit-for-tat strategy is its performance when it is confronted with noise.[55] Here, noise means that countries act out of line with their strategy from time to time. The problem with unintentional defection is that opponents with a conditional strategy like tit-for-tat start to retaliate, which then triggers another retaliation by the first country. As a result of endless rounds of retaliations, cooperation between these two countries collapses, even if none of them intended to exploit the cooperation of the other. Due to noise, there can be a high amount of defection in a population of tit-for-tat playing countries, and the fitness of the population declines. Consequently, unconditional defection can enter the population, because it saves the surveillance costs of a conditional strategy like tit-for-tat.

[55] Axelrod 1997, Nowak 2006a, Nowak and Sigmund 2004.

Figure 4: Defection against Tit-for-Tat[56]

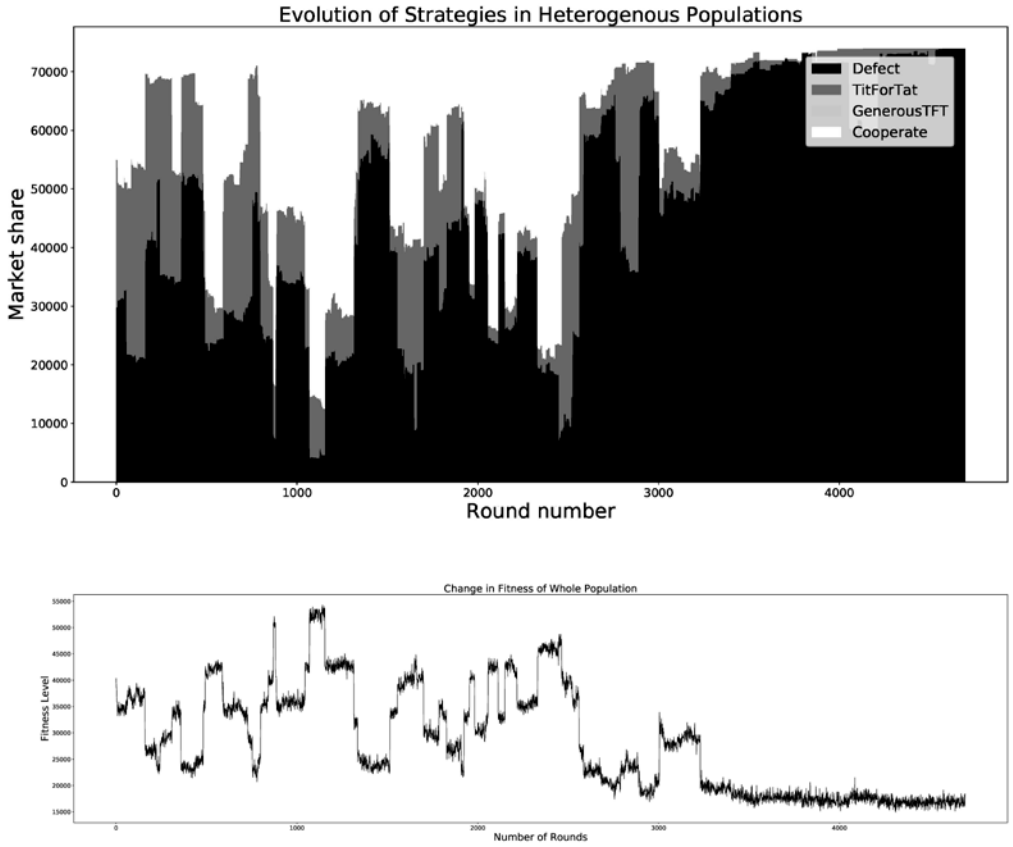


Figure 4 shows a simulation without mutation, but including noise ($\alpha = 0.1$) and surveillance costs ($\gamma = 0.05$). Mutation is not included in order that the modified

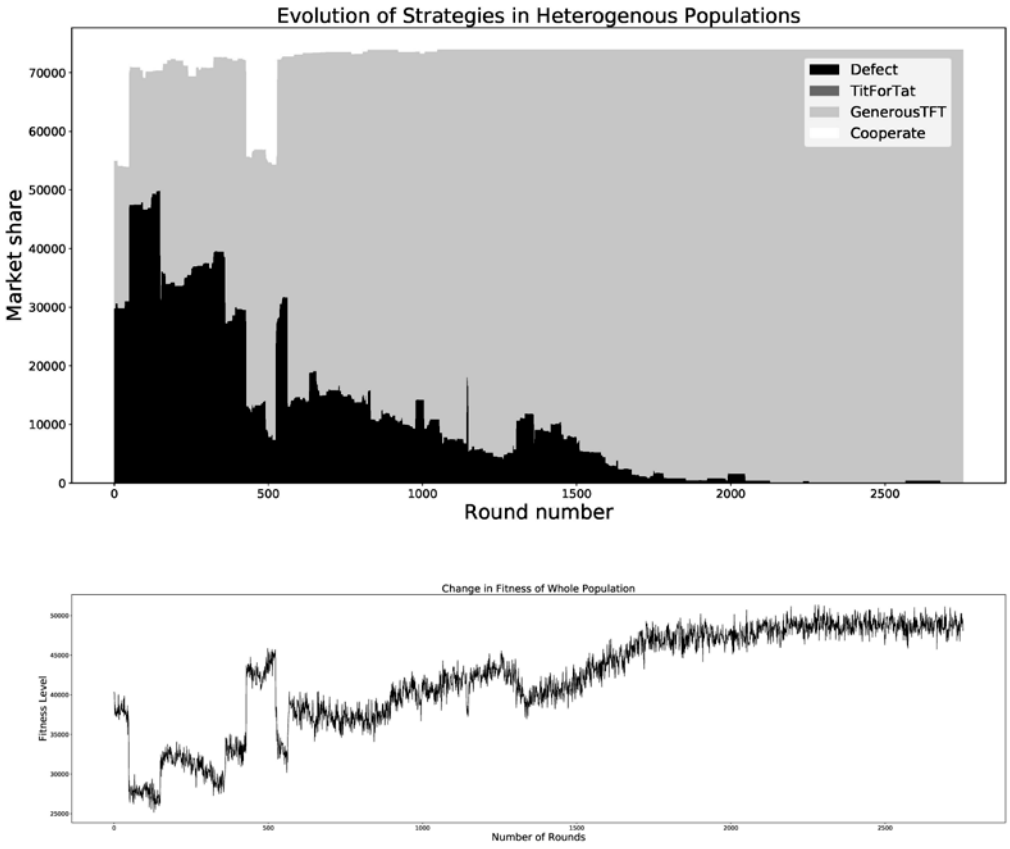
[56] The model is not deterministic, and the results of the simulations differ from each other to some degree. This is due to the fact that the modified Moran process includes selections based on probabilities. The country which reproduces its strategy is chosen with a probability of $p_a^{co} = \frac{f_a}{\sum_{b=1}^{n} f_b}$, and the country which adopts this strategy is selected with a probability of $p_b^{de} = \frac{1}{n}$. As a result, particular strategies need different numbers of rounds to win the Moran process without mutation. Besides, defection does not always win against tit-for-tat, but it always generates less fitness for the population than generous tit-for-tat.

Moran process selects a winning strategy, which is finally played by all countries in the population. We assume that China and the US are protectionists and enter the simulation by playing unconditional defection, whereas Canada, the EU and Mexico try to appease them and begin with unconditional cooperation. All other countries of the population play tit-for-tat. It is obvious that tit-for-tat (the dark grey strategy) does not perform very well, and most players play either unconditional defection (black) or cooperation (white) during the whole simulation. The graph at the bottom of Figure 4 shows, how much fitness the population gains in each round of the game. The population achieves a high growth of fitness, but only for short time periods when unconditional cooperation dominates the population. Thereafter, unconditional cooperation is exploited, unconditional defection takes over and the fitness growth in the population declines considerably. At the end, unconditional defection wins the Moran process after around 4.700 rounds.

Generous tit-for-tat performs much better in a noisy environment, because generosity allows countries to break out of the endless rounds of retaliation. Figure 5 shows the same simulation as Figure 4, but most countries (except Canada, China, the EU, Mexico and the US) play generous tit-for-tat instead of tit-for-tat. Thus, they cooperate with a probability of $\beta = 0.3$, even if their opponent has defected in the previous round. In Figure 5, generous tit-for-tat is much more successful than tit-for-tat is in Figure 4. Despite the fact that generous tit-for-tat is a conditional strategy and pays surveillance costs, it very quickly defeats unconditional cooperation, which becomes almost extinguished in round 550. Unconditional defection is able to resist generous tit-for-tat a little bit longer, but generous tit-for-tat finally wins the Moran process after around 2.800 rounds. It is especially striking that the growth of fitness

is on average much higher in Figure 5 than it is in Figure 4. Although the fitness growth of the population suffers from a wave of unconditional defection early on, it recovers quickly once generous tit-for-tat takes over. At the end of the Moran process, the population of Figure 5 wins more than three times as much fitness in each round of the game than the population in Figure 4.

Figure 5: Defection against Generous Tit-for-Tat



The success of generous tit-for-tat in the Moran process is good news for the stability of global trade cooperation. In fact, member states of the WTO play generous tit-for-tat against each other, because they do not retaliate against all possible trade restriction of their trade partners. The rules of the WTO's Sanitary and Phytosanitary (SPS) Measures and the Technical Barriers to Trade (TBT)

Agreement allow the member states to prohibit the import of goods, which endanger consumer health.[57] Although such trade restrictions can be challenged in front of the WTO's dispute settlement mechanism, the WTO's dispute panels and the appellate body decide circa 30% of all claims in favor of the defendant.[58] These 30% of 'legitimate' trade restrictions are equivalent to the optimum level of generosity as estimated by Nowak[59] and as being implemented in our model.

4.3 The Ups-and-Downs of Trade Liberalization and Protectionism

Tit-for-tat and generous tit-for-tat are strong strategies, which can establish cooperation under complete information and within a noisy environment respectively, but they are not evolutionary stable. In order to demonstrate this, we enter mutation ($\delta = 0.1$) in our model. On average in one out ten rounds, the Moran process does not replicate the strategy of a strong country, but a random country adopts indiscriminately one of the four available strategies. The Moran process does not produce a single surviving strategy anymore, but new strategy can enter the population at any time. If this new strategy is successful within the population, it becomes replicated and changes the composition of strategies in the population of countries. And once this composition has changed sufficiently, it may provide the opportunity for yet another strategy to enter the population with the help of mutation. As a result, only an evolutionary stable strategy would be able to dominate the population for a long time, because it could not be beaten by any other strategy. If

[57] Skogstad 2015.

[58] Hoekman et al. 2009.

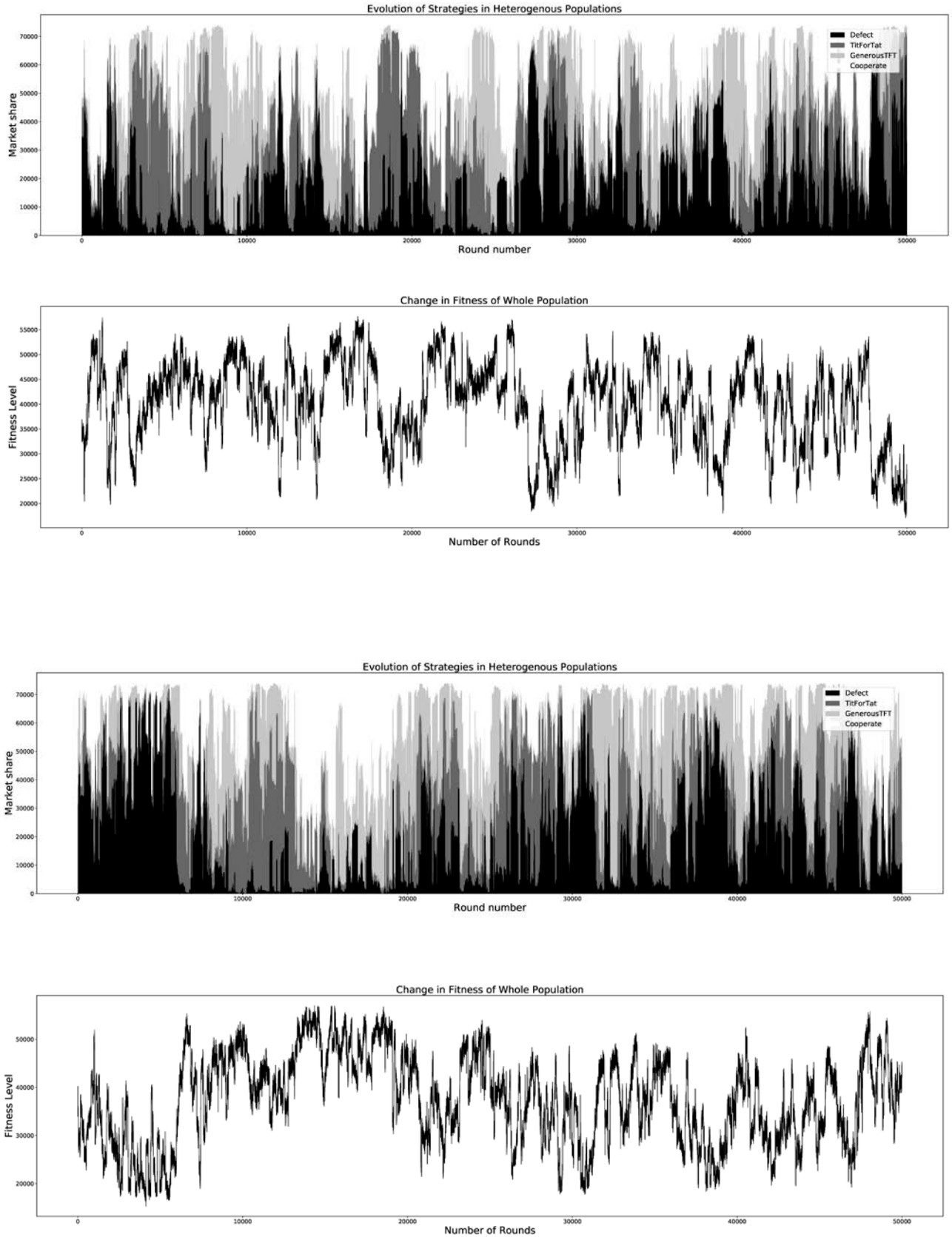
[59] Nowak 2006, Nowak and Sigmund 2004.

none of the available strategies is evolutionary stable, there always exists a strategy which outperforms the dominant strategy in the population. Thus, the composition of strategies within the population is in constant flux.

Figure 6 shows the results of two simulations with our evolutionary game theory model of international trade cooperation. In both simulations, the countries enter the game by playing randomly assigned strategies. The two simulations show clearly that whenever one strategy becomes strong, this opens room for another strategy to take over. When unconditional defection (black) dominates the population, tit-for-tat and generous tit-for-tat (grey) take over and establish cooperation. When tit-for-tat and generous tit-for-tat are the main strategies, unconditional cooperation (white) can enter the population and saves surveillance costs without being exploited by tit-for-tat or generous tit-for-tat players. However, once unconditional cooperation dominates the population, unconditional defection becomes strong again, because it can exploit cooperation. Thus, the cycle starts again, and no stable equilibrium emerges. The two fitness graphs illustrate, how the growth of fitness increases and declines in accordance with the level of cooperation within the population. Countries gain only their own domestic markets, when they do not cooperate. Their fitness growth increases, when tit-for-tit and generous tit-for-tat establish some cooperation within the population. The growth of fitness is the highest, when unconditional cooperation is strong within the population. However, it declines thereafter, when unconditional defection starts to exploit unconditional cooperation. This oscillation between low and high growth of fitness resembles very well Martin Nowak's endless cycles of cooperation and defection.[60]

[60] Nowak 2006, Nowak and Sigmund 2004.

Figure 6: Waves of Cooperation and Defection



The two simulations of Figure 6 show waves of cooperation and defection, but the concrete form of these waves differ considerably. For example, the upper simulation starts with much more cooperation than the lower simulation, which is dominated by unconditional defection up to round 6.000. The lengths of the waves differ as well, and the cooperative wave from round 8.000 to 20.000 in the lower graph is more than ten times as long as the small cooperative wave at the beginning of the upper graph. On average, the upper population achieves more cooperation than the lower population during the 50.000 rounds of the simulation. These differences between the simulations are due to the influence of probabilities within our stochastic model. The Moran process selects one strategy with a probability that is proportional to the fitness of the respective country, and a randomly chosen country takes over this strategy. Besides, the parameters for noise, generosity and mutation are also probabilities. Thus, no simulation produces exactly the same results as another one. This points to an important limit of our simulations. Our model cannot – and it does not aim to – calculate and foresee, how the global trade order is going to develop within the next weeks, months or years. However, what the model illustrates is the potential instability of international trade cooperation. Generous tit-for-tat and a high level of cooperation do not establish a stable equilibrium, but they instead prepare the ground for a wave of unconditional defection.

The cycles of global trade cooperation and protectionism indicate that globalisation is unlikely to be the 'end of history'.[61] The current level of economic exchange across borders became only possible with the rise of international

[61] Fukuyama 1992.

cooperation since the end of the Cold War. This cooperation of sovereign states led to the establishment of the WTO, to various amendments of the EU treaties, to the rise of the new regionalism around the world and to the 'Spaghetti bowl' of preferential trade agreements.[62] Nevertheless, the same sovereign states can ignore these international institutions and start to re-establish trade barriers, if defection and protectionism seem to be opportune to them. At the peak of a cooperative upswing, there exists a lot of generosity within the population of countries, and unilateral defection may successfully exploit this generosity. If such a protectionist strategy is successful, it is copied by other countries, and this leads to a defectionist downswing in the population. As a result, the level of cooperation and fitness in the whole population of countries declines. Thus, the success of trade liberalisation and globalisation is already sowing the seeds of its destruction.

The level of cooperation in the global trade order has been quite high in recent years, and we may have reached the 'Minsky-moment' of globalisation. The new wave of economic nationalism can be seen as an attempt to exploit the generosity and good-will within the population of countries. For example, the more concessions the EU offers in order to reduce its trade surplus with the US, the more successful becomes President Trump's strategy. The problem with appeasement is that it rewards unilateral protectionism – which increases the appeal of this policy for other countries. If other countries follow the US example, this would be the start of a defectionist downswing like after the Smoot-Hawley tariff act of 1930.[63] In order to avoid or slow down a full downswing, the WTO member states need to ensure that

[62] Baldwin 2006, Mansfield and Milner 1999.

[63] Harold 2001, King 2017.

unilateral protectionism does not become successful. They cannot allow that generosity is exploited, but they need to retaliate forcefully against protectionism. Trade wars against large economies like the US are expensive, and they lead to considerable losses of welfare. However, the losses for other countries like China and the EU can be reduced, if they manage to keep up cooperation and trade liberalisation among themselves. Global welfare will decline much more, if other countries find no answer to economic nationalism, and if unilateral protectionism becomes a winning strategy.

5. Conclusion

There exists indeed something like a hegemon's dilemma. The largest member states of a particular regime profit in absolute terms from international trade liberalization, but they profit less in relative terms than smaller member states. As a result, a stable and liberal trade order weakens the dominance of the largest economy and strengthens the capacities of contenders. Economic nationalism like that of the Trump administration is one possible reaction to this dilemma, but its success depends on the reaction of others. If other countries are able to uphold cooperation among each other while simultaneously punishing unilateral protectionism, the defecting country loses out even more in relative terms and reinforces its relative decline. However, if other countries try to stabilize cooperation by being generous and by appeasing defecting countries, economic nationalism may indeed become a successful strategy. Thus, the protectionist trade policies of the Trump administration may be risky, but they are not necessarily 'irrational'.

The problem for countries which are interested in an open and cooperative trade order is that they need to carefully balance retaliation and generosity with each other. Tit-for-tat is a strong strategy to punish unilateral protectionism, but it faces difficulties when confronted with noise. In an uncertain and unpredictable world, countries may sometimes be forced to defect ‘unintentionally’ for domestic reasons. If all countries play strictly tit-for-tat, such ‘unintentional’ defection leads to endless rounds of retaliation and the global trade regime collapses. In order to avoid this, countries need to be generous and not retaliate against every single defection. However, the problem of generosity and a high level of cooperation within the population is that it can be exploited by unilateral defection like the economic nationalism of the Trump administration. Countries need to distinguish between unintentional defection, on which they should react with some generosity, and exploitative defection, which requires forceful retaliation. In a noisy and uncertain environment, this distinction is crucial, but difficult.

Globalization is not the end of history, and our theoretical model demonstrates that there exists no stable equilibrium of one particular trade strategy. Instead, the population of countries goes through endless cycles of cooperation and defection. As long as the global trade order is very closed and protectionist, tit-for-tat and generous tit-for-tat playing countries are able to gain a competitive advantage in the evolutionary process, if they start to cooperate with each other. Once reciprocal trade liberalization has established an open and cooperative global trade order, single countries can gain a competitive advantage by exploiting the generosity of their environment. Thus, like hegemonic stability theory, our model offers an explanation for the long waves of openness and protectionism, which distinguish the

history of the global order since the beginning of industrialization in Great Britain. However, the reasons behind these waves of international cooperation and defection are different. Although our model takes the different market size and economic power of countries into account, it does not depend on the dominance of a single hegemon. It is the distribution of strategies within the population of countries, which determines the success of a particular strategy. And once a number of countries have adopted this strategy, the distribution of strategies within the population of countries changes, which them opens the door for yet another strategy. Large countries have obviously more leverage to change the distribution of strategies than small countries, but the same fluctuations could also be observed in a population of equally large and powerful players.

Of course, the findings of this paper are not based on empirical tests, but on computer simulations, which are based on assumptions. Nevertheless, we are confident that our simulations are able to capture important features of global trade cooperation. It is not possible to explore the stability of the existing global trade order empirically before it has broken down. Thus, such an assessment necessarily relies on a theoretical model. Our model is based on two sound theoretical fundaments' Firstly, it is widely accepted in the field of international political economy that international trade cooperation can be modelled as a prisoner's dilemma in which countries share the common interest in trade liberalisation, but still have an interest in protecting their own industries.[64] And secondly, because trade cooperation takes place on a daily basis and between all possible pairs of countries, we are able to

[64] Axelrod 1984, Conybeare 1984, 1985, Krugman 1992, Gawande and Hansen 1999, Milner and Yoffie 1989, Rhodes 1989.

apply an evolutionary game theory model, which is inspired by the work of evolutionary biologists.[65] We argue that the strategic interactions within populations of players are general phenomena that are not restricted to the biological realm, but which also take place in different economic, political and social circumstances. In fact, models of evolutionary game theory seem to be especially well-suited for the analysis of international politics, because they are not based on a central authority and hierarchy, but on the interdependent actions of autonomous players. We modified the usual models of biologists and distinguished between variable strategies and players with constant characteristics. This allows us to accommodate the fact that sovereign states in the international system differ in respect to their economic capacities, and market size.

[65] Friedman and Sinervo 2016, Imhof et al 2005, Nowak 2006, Nowak and Sigmund 2004.

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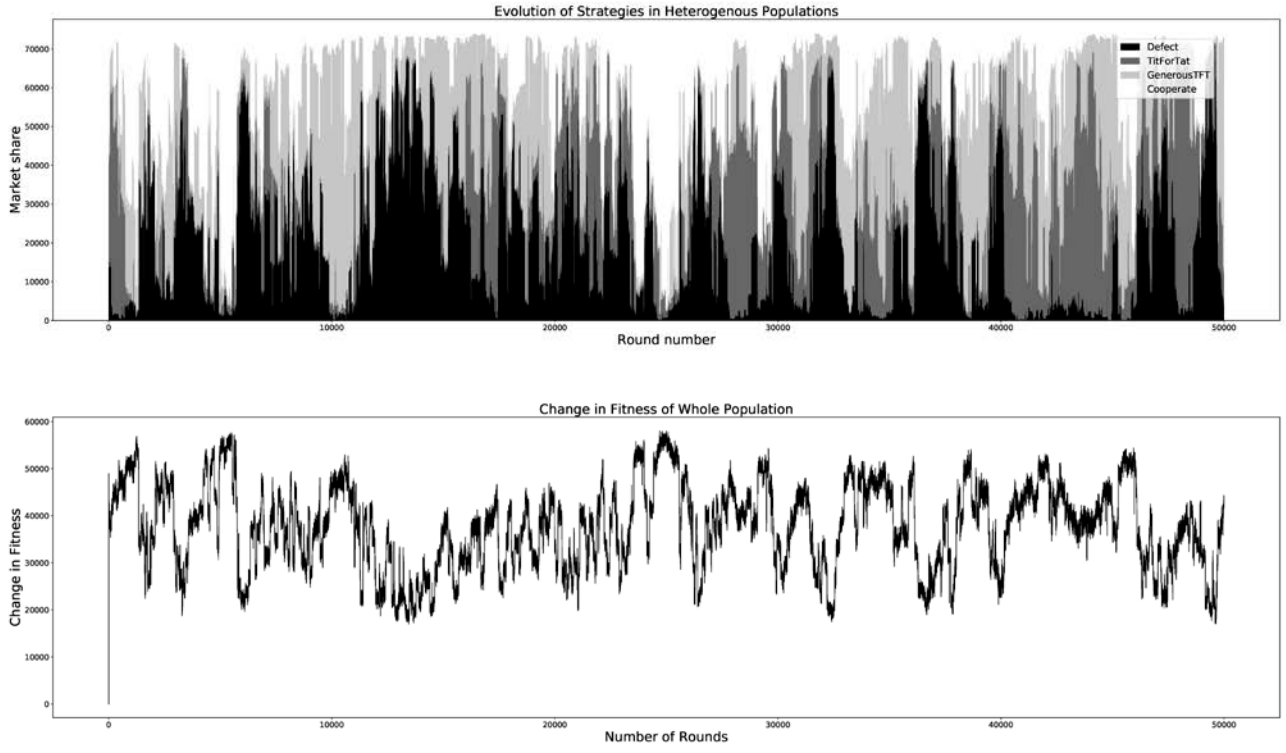
Appendix: The Robustness of the Evolutionary Game Theory Model

The purpose of the following robustness check is to demonstrate that the results of our simulations are not arbitrary or insignificant. Therefore, we discuss some modifications of core parameters in comparison to Figure 7, which shows a simulation of 50.000 rounds with our regular model. The initial distribution of strategies is randomly assigned – i.e. each country plays one of the four strategy with a probability of 0.25 in the first round of the game.

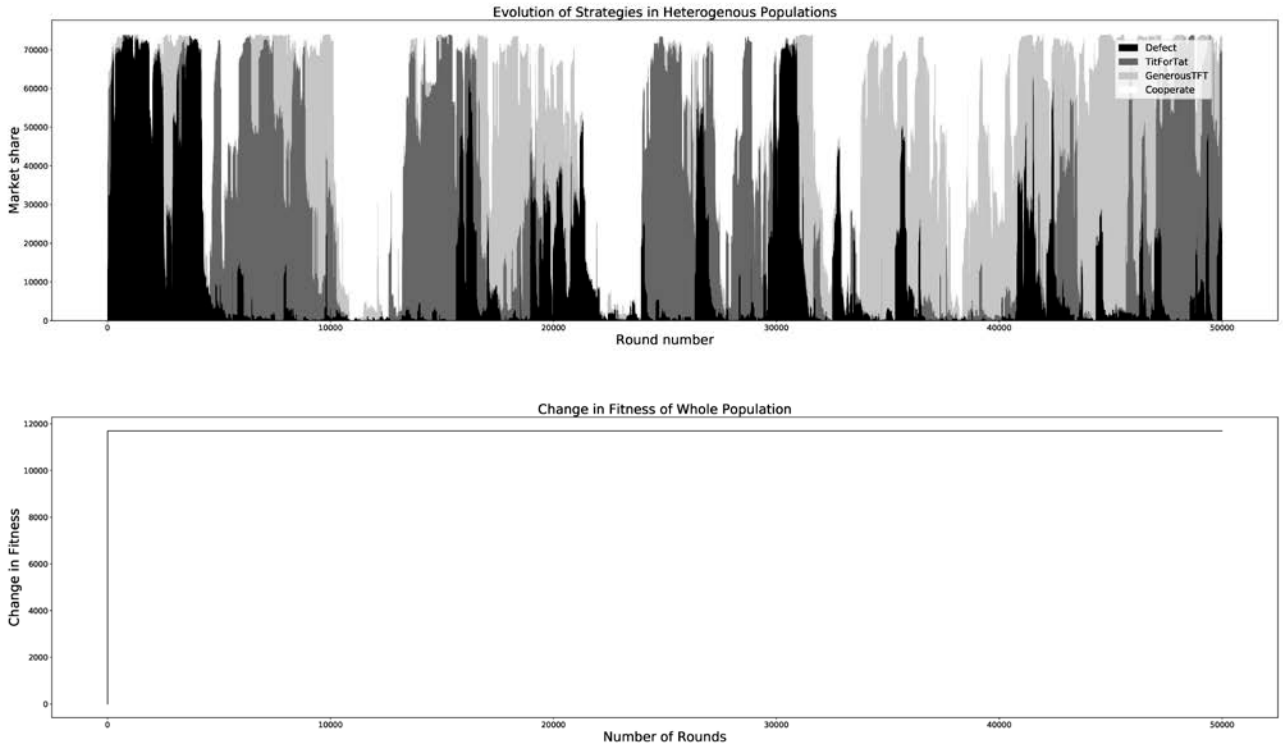
Figure 7: The Regular Model ($\alpha = 0.1, \beta = 0.3, \gamma = 0.05, \delta = 0,1$)



A.1 Comparison with no Strategic Interdependence

The fitness of countries and their performance in the evolutionary process of our regular model is determined by the countries' market size and by their strategies in the prisoner's dilemma of trade cooperation. In comparison, Figure 8 shows a simulation wherein countries do not play against each other, but only gain access to their domestic market in each round of the game. The Moran process works as usual, but countries' fitness is only determined by their own market size and not by their strategic interaction. Thus, the simulation favors large players like China, the EU and the US. If the pattern of Figure 8 would resemble the pattern of Figure 7, we could not posit that the waves of cooperation and defection are a function of the international trade game, but they would only be caused by the strategies of large markets that diffuse within the population.

Figure 8: Fitness only Determined by Domestic Market



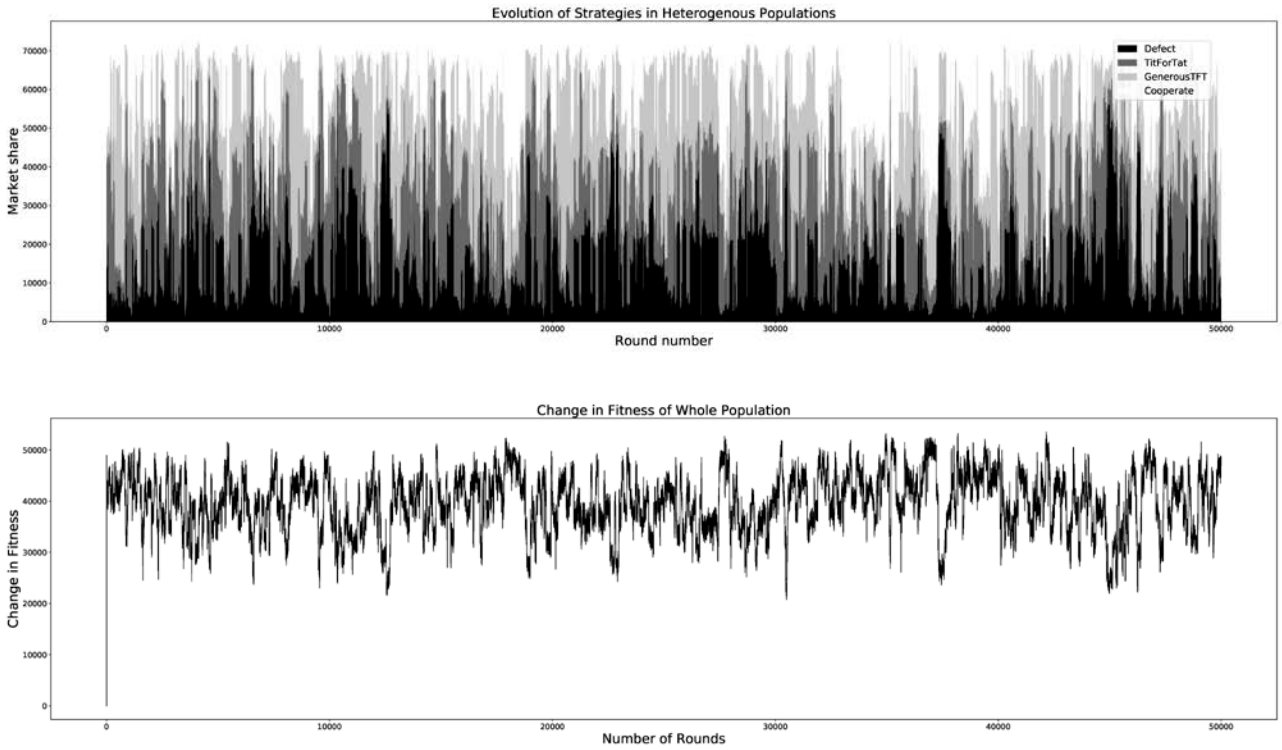
The major difference between the regular model and the model without strategic interaction is that a single strategy can take over nearly the entire population for considerable amounts of time in the latter. Figure 8 shows that the strategies of the largest markets are quickly copied by all other players. For example, if China, the EU and the US are randomly assigned to defect, defection spreads very quickly through the population. If the strategy of either of them mutates, this opens up the possibility that a different strategy becomes dominant. There exist no meaningful pattern in the sequence of dominant strategies in Figure 8. During the first 10.000 rounds, a defecting population is shortly invaded by generous tit-for-tat, but quickly becomes defecting again. Thereafter, the population is taken over by cooperators, which are then invaded by tit-for-tat and generous tit-for-tat players. In contrast to Figure 7, these waves in Figure 8 are incompatible with the theoretical framework and the logic of evolutionary game theory. There is no reasonable explanation why a population of defectors should be invaded by cooperators, or why cooperators should be invaded by tit-for-tat players.

A.2 Comparison with Random Selection of Strategies

The results of our simulations are stochastic, but they are not arbitrary. To demonstrate the difference between these two, we present a simulation with a completely random change of strategies in Figure 9. The only parameter we changed in comparison to Figure 7 is the mutation rate, which is set to $\delta = 1$. This means that strategies are not changed according to the modified Moran process, but that a randomly chosen country adopts one of the four strategies with a probability of 0.25 in each round of the game. However, countries are still playing the game in

accordance to their respective strategy, which implies that the fitness growth of the population fluctuates.

Figure 9: Random Change of Strategies (δ = 1)



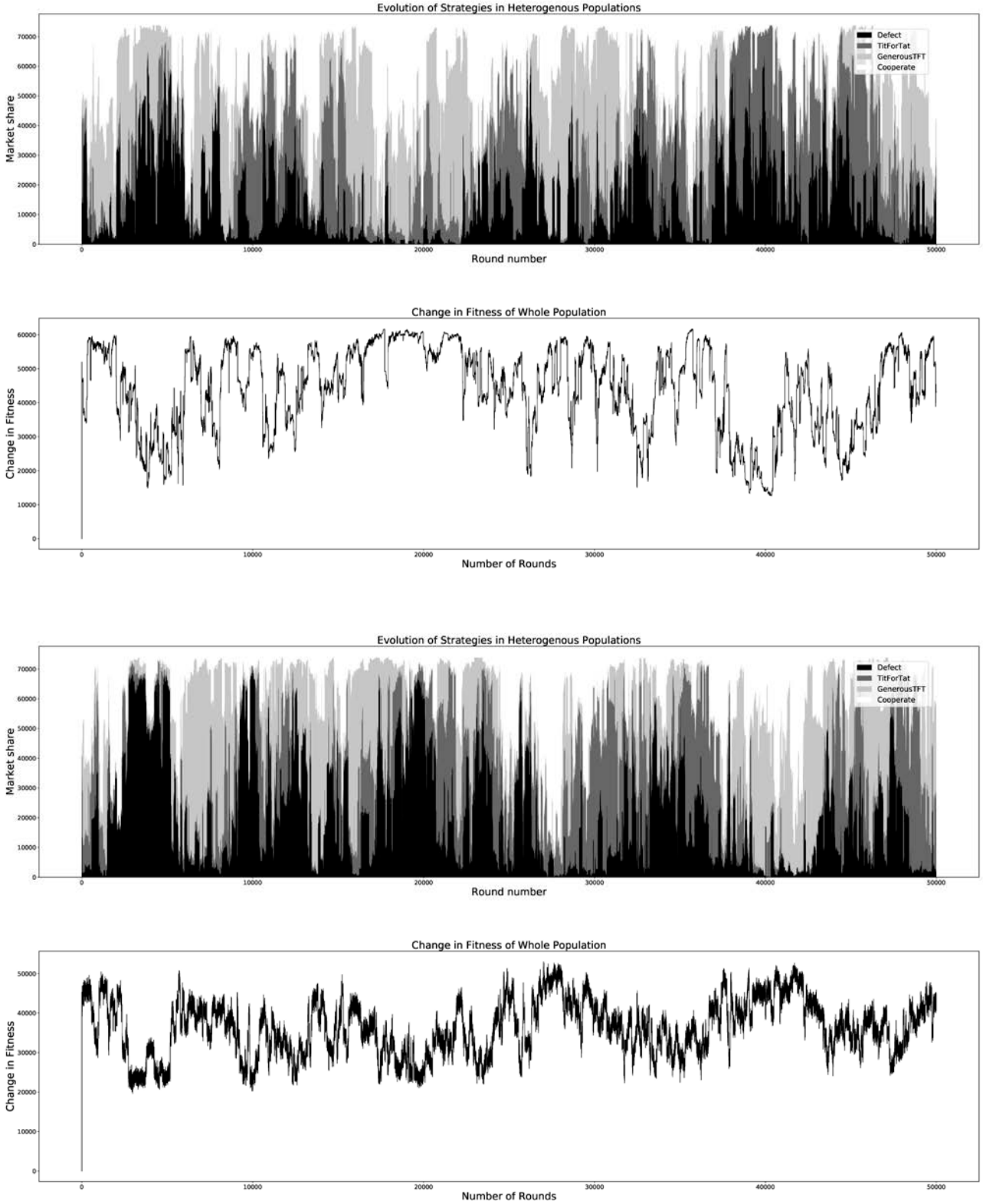
In contrast to the regular model, the random model with a mutation rate of δ = 1 does not show any interpretable patterns. The difference between Figure 7 and Figure 9 illustrates the strength of the Moran process, which determines selection and reproduction based on fitness rather than chance. Accounting for fitness introduces the continuous cycles of successful invasions by the various strategies. For example, a generous population is subject to invasions by defectors and when defectors have invaded the population successfully, they themselves become subject to invasion by tit-for-tat players. Figure 9 displays no such pattern, and no strategy ever becomes dominant in the population. Whereas Figure 7 shows long

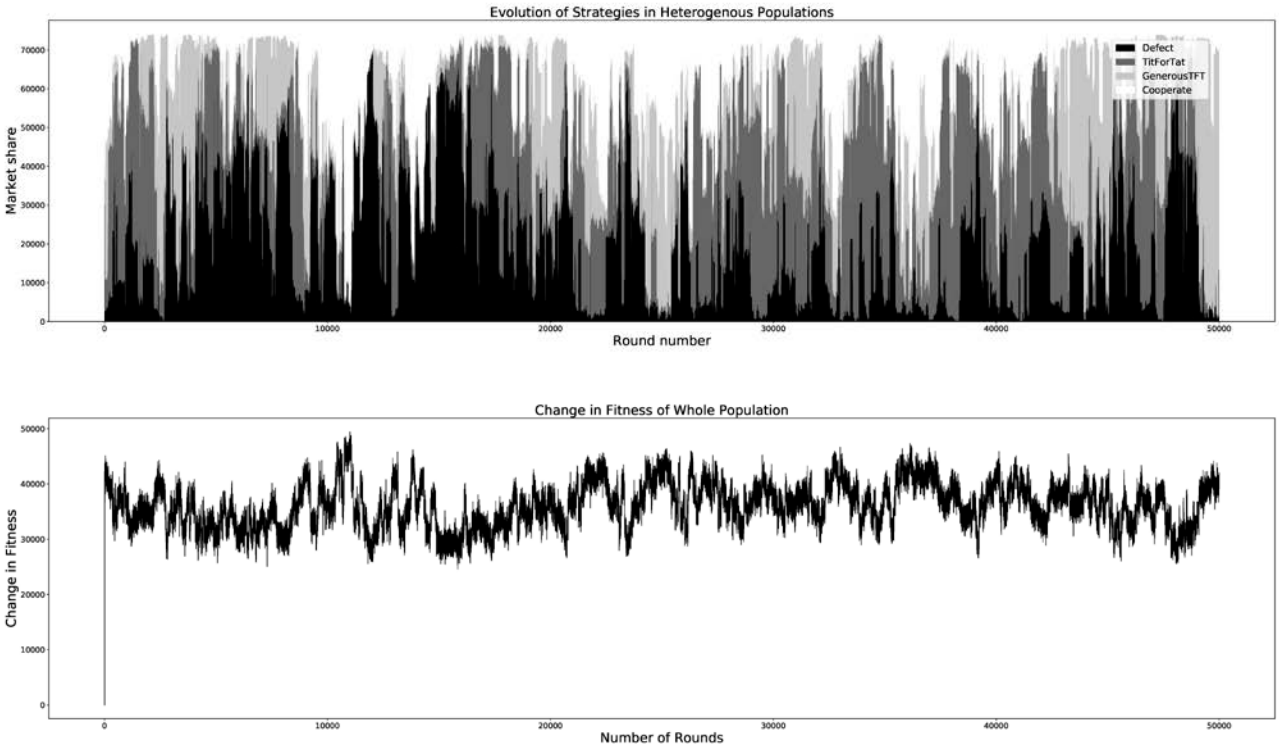
waves of cooperation and defection with the dominance of certain strategies in the population, the changes in Figure 9 are much shorter and appear in no systematic order. As we can see in the fitness graph, the random selection of strategies causes the fitness of the population to swing up and down instantly. Besides, the average level of fitness is lower than in the regular model of Figure 7.

A.3 Comparisons with Different Levels of Noise

Tit-for-tat loses much of its strength in our model when we include noise with a level of α = 0.1. Thus, on average in one out of ten rounds, a country makes the opposite move than prescribed by its strategy. For example, a defector cooperates, or a tit-for-tat players defects without being provoked by its opponent. Here, we explore how our model reacts to different levels of noise. Figure 10 shows simulations with α = 0.0, α = 0.2 and α = 0.3. Increasing the level of noise much further does not make any sense. With a noise level of $\alpha = 0.5$, countries would play their strategies in half of their interactions, and they would make the opposite moves in the other half of their interactions. Thus, the behavior of players becomes completely random.

Figure 10: The Effects of Increasing Noise ($\alpha = 0.0$, $\alpha = 0.2$ and $\alpha = 0.3$)





Two major developments can be detected when the level of noise increases. Firstly, the waves of cooperation and defection become shorter. For example, the first simulation of Figure 10, shows a long wave of cooperation from round 15.000 to 25.000. Such a clearly identifiable wave does not exist in the third simulation of Figure 10, where the level of noise is $\alpha = 0.3$. And secondly, the average growth of fitness declines with increasing noise. Without any noise ($\alpha = 0.0$), the population achieves a fitness growth of 60.000 when the level of cooperation is high. In our standard model ($\alpha = 0.1$, Figure 7), the maximum growth of fitness is already reduced to around 55.000. When noise is further increased ($\alpha = 0.2$ and $\alpha = 0.3$), the population can hardly achieve a fitness growth of 50.000, even in periods when the level of cooperation is relatively high. In sum, increasing noise reduces the possibility of countries to react on each other's actions in a meaningful way, and this leads to more randomness and declining fitness of the population.