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CREE Working Paper 10/2014

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.
ISBN: 978-82-7988-180-3
ISSN: 1892-9680
http://www.cree.uio.no

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March 2014

Abstract

Trade with differentiated goods normally provides a form of insurance against disasters, such as floods and fires, through an increasing relative price of goods from the afflicted country. With open access renewable resources this is reversed. A country hit by a negative shock recovers faster if trading with fewer countries and, if trading with many, shocks affecting also the trading partners are preferred over idiosyncratic shocks. Trade thus increases economic vulnerability to disasters and local disasters will be worse than global. Furthermore, world markets transmit shocks so a natural disaster in one country can cause man-made disasters in competitor countries. These results are particularly relevant for developing countries due to high renewable resource reliance, more problems of open access and more economic vulnerability to disasters. A calibration suggests these concerns may apply to around 60 percent of world fisheries and that around 20 percent risk collapsing following small idiosyncratic shocks.

JEL Codes: D62, F18, Q27, Q28

Keywords: Open Access, Renewable Resource, Trade, Disaster, Variety

*We like to thank Brian Copeland, Anne-Sophie Crepin, Florian Diekert, John Hassler, Larry Karp, Martin Quaas, Andries Richter, Nick Sheard, Sjak Smulders, Scott Taylor, seminar participants at the The Beijer Institute of Ecological Economics, Stockholm University, NTNU, Oslo University, CREE, Syracuse University, UC Berkeley and the EAERE and SURED conferences for valuable comments.

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1 Introduction

In recent years a large number of scientific reports have shown that several renewable resources are in a poor state, most notably fish. This is a particularly large problem in developing countries, being the most reliant on fish and other renewable resources both for their consumption and in their production and exports.[1]

International trade with renewable resources in general and fish in particular has increased significantly during a number of decades.[2] This has been coupled with over-fishing and outright collapses of fish stocks.[3] Overharvesting is not confined only to fisheries. In response to falling fishery yield rates, hunt for bushmeat has increased significantly in West and Central Africa (Brashares et al. 2004, Damania et al. 2005, Waite 2007). Furthermore, trade with wild animals shot by poachers has led to near extinction of, for instance, rhinos. Other examples of collapses and mismanagement directly or indirectly attributed to trade are those of buffaloes in North America (Taylor, 2011) and hardwood in the Philippines and the Ivory Coast (Bee, 1987; Kummer, 1992; Brown, 1995).

What a large part of these industries and cases have in common is that they are characterized by open access to harvesting the resource – either legally (like in many fishing areas) or in practice (like with poaching and illegal logging) – leading to the familiar "tragedy of the commons" (Hardin, 1968; Loayaza, 1992). The problem of open access essentially boils down to individual harvesters not having incentives to maintain the resource stock. But, as has been shown by Quaas et al. (2013) open access-like dynamics can appear more generally also if harvesters use

[1] Fish alone provides one sixth of all animal protein intake globally, and more than one half in developing countries such as Bangladesh, Cambodia, Ghana, the Gambia, Indonesia, Sierra Leone, Sri Lanka and some island states (FAO, 2012). Fishery related products make up for a large share of net exports in developing countries. The share out of total export is as large as one half in some countries and more than half of all exported fish come from developing countries (FAO 2012).

[2] In the period 1976–2008, world trade in fish and fishery products rose from US$8 billion to US$102 billion, with annual growth rates of 4 percent in real terms (FAO 2012). In volume terms, the share of fish going to exports has been increasing steadily and corresponded, in 2009, to around 40% of all fish. This represents 1% of all merchandise exports and involves 197 exporting countries (ibid).

[3] Hillborn (2003) find that many fish populations are being harvested at only half of their historical maximum and that the stocks of Newfoundland cod and several whale species has collapsed. A study by Mullon et al, (2005) suggests that one out of four fisheries has collapsed in the last 50 years. It is estimated that around more than half of all marine fish stocks are overexploited (Froese et al., 2012). Facing diminishing returns of traditional fish stocks, the catch increase has come mainly from fishing of new species and at more inaccessible locations such as at the high seas (Cullis-Suzuki & Pauly, 2010).

high discount rates.[4] This implies that other ubiquitous market imperfections (such as political considerations and corruption discussed later in the paper) will create the same problems as open access. Following the Rio+20 meeting, many have recognized the importance of governance (i.e. proper management) in dealing with food security in the developing world (FAO, 2012). Implementing proper management practices is typically more difficult in developing countries since they are often unable to control their land and waters from both domestic and foreign illegal harvesting (ibid) and since corruption and political instability is more prevalent. The specific problem of overfishing has even led to a recent UN general assembly resolution (UNGA Resolution 65/38).

In a recent paper, Quaas & Requate (2013) show that consumer preferences for variety when eating fish can exacerbate overfishing when there is open access. These results naturally hold for other renewable resources too. Using a similar setup we extend their analysis to evaluate welfare gains from international trade and, in particular, the effect of natural disasters and how trade may lead to uninsurance – i.e. an enhancement of the negative economic effects of a disaster.

Our analysis of the welfare effect of increased trade openness, with regard to open access renewable resources, decomposes the net effect into two opposing effects. Firstly, the variety effect improves welfare since trade enables consumption of a more varied basket of goods. The value of increased variety may wear off but remains positive also when the number of trading partners becomes large. Indeed, earlier research has shown increased variety to be an important component of the welfare gains of trade.[5] Secondly, a negative stock effect comes about as the increased demand for the resource from other countries makes harvesters willing to exert more effort implying the stock becomes more overharvested. We show that the relative weight of the stock effect increases as more trading partners are added. This leads to welfare being hump-shaped in the number of trade partners – opening up for trade increases welfare up to a certain point after which additional increases in the number of trade partners decreases welfare. If the harvesting function has sufficiently low stock elasticity, this may even lead to the resource collapsing.[6]

[4] Quaas et al (2012) show the implicit discount rate in many fisheries is much higher (10-200 percent) than the market interest rate.

[5] For variety gains to arise, trade must give access to goods which are imperfect substitutes to currently consumed goods. Different types of renewable resources are clearly imperfect substitutes. It has also been found empirically that different fish species are imperfect substitutes to each other (e.g. Barten & Bettendorf, 1989; Bose & McIlgrom, 1996). More generally it has been estimated that the welfare gains from variety through trade from 1972-2001 in the US counts for an equivalent of 2.6% of GDP (Broda & Weinstein, 2006).

[6] A low stock elasticity essentially implies that it is possible to "catch" parts of the resource also

The main contribution of the paper is the consideration of the effects of trade when natural disasters occur. The disaster may strike in the form of a storm, a flood, a fire or disease that kills part of the resource stock. Typically developing countries are more economically vulnerable to natural disasters.[7] Under normal circumstances, this vulnerability is a motivation for trade. If one country has, say, half its factories devastated by a flood then, assuming that countries produce differentiated goods, the price of their good goes up which cushions the blow. Importantly, the increased price also allows them to rebuild their factories faster than if they were not trading. International trade thus provides a form of insurance against idiosyncratic shocks. This is reversed when there is open access to a renewable resource. The reason is that a negative shock to a country's resource stock, for example by having half their fish population die from a disease, leads to an increase in the relative price of their resource as supply falls. The price increase will then lead to even more extensive overharvesting in that country which implies a longer time for recovery and that the risk of collapse increases. Had the shock been common to all countries, this price effect would not have occurred and hence collapse would have been less likely and recovery would have been faster.[8] Likewise, the more countries that are trading the more likely it is that a shock will lead to collapse. This means that the economic impacts of natural disasters will be aggravated by trade. It also means recovery will be slower following a local disaster compared to a global one – i.e., trade works as a negative insurance against idiosyncratic shocks. It may in itself also explain why developing countries, being very reliant on resources, are so economically vulnerable to natural disasters. Now, the price effect also has its benefits. It increases the income for any given harvest in the affected country. The question then arises whether the short run price effect overshadows the long run effect of slower recovery or collapse. We show that if a country is beyond the optimal degree of trade openness (in the hypothetical world without shocks), then from the point of view of a country hit by a shock, global shocks are preferred to idiosyncratic shocks.

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when the stock is low. This follows, for instance, if, as the stock becomes smaller, it concentrates to a smaller area or if there are "waterholes" or breeding grounds which are always visited by the fish or animals and which the harvester can target. Assuming a low stock elasticity is also reasonable when it comes to clear-felling, prevalent in illegal logging, since trees are immobile.

[7] It is important to distinguish between the probability of a disaster and its size on one hand and the social and economic impacts a disaster of a certain size will have on the other hand. By vulnerability we mean the latter which is in line with the definition of Wisner (2004): "The characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of natural hazards". Typically, developing countries are considered more vulnerable (e.g. Briguglio, 1995; Wisner, 2004).

[8] To be more precise, holding all else equal, the size of the negative shock needed to create collapse is smaller if the shock is idiosyncratic.

In an extension to the model we consider a case where groups of countries each have the same resource. That is, within a group all countries compete in selling the same resource. We show that a natural disaster hitting one country can cascade into a man-made collapse of the stock in countries having the same resource (but who were not themselves hit by the natural disaster). The transmission mechanism is the price increase caused by the decrease of total supply if one country within a group is hit by a disaster which lowers its stock. Following the price increase, the competitor countries will increase their supply and they may, hence, collapse their own stock. This effect becomes more pronounced the more trading partners a country has. This way trade and the world market works as a mechanism of contagion of natural disasters.

Finally, we analyze positive TFP shocks to one's trade partners. This has a similar effect as a natural disaster in the own country. The increased TFP of the trade partners increases the price of one's own resource which leads to more overharvesting and potential collapse. This holds true not only if the TFP increase is permanent. Also a temporary increase in partners' TFP may lead the country to a state of collapse.

A calibration of the model parameters to those estimated in the empirical research on fisheries firstly suggests that most if not all fisheries could, given extensive enough trade, be susceptible to the main dynamics described in the paper. Secondly, when looking at stock levels of individual fisheries, roughly 60 percent of the major fisheries in the world are overharvested to the extent that trade reduces welfare and where, if a disaster should occur, for a single fishery it would be preferred if all were hit simultaneously. Furthermore, about 20 percent of fisheries are in a state where a small idiosyncratic shock would induce collapse.

The result that extensive trade is not necessarily the optimum when market imperfections are present was shown early by, for instance, Lipsey & Lancaster (1956) and Viner (1983). These insights were first applied to trade with open access renewable resources by Chichilnisky (1993) and in a series of papers by Brander & Taylor (1997a, 1997b, 1998). Brander & Taylor (1998) set up a two country, two sector, trade model where one of the sectors relies on a renewable resource to which there is open access. In this setting trade induces specialization so that the resource abundant country harvests more. The conclusion is that, comparing the outcome with trade to the autarky outcome, welfare increases in the labor abundant country and decreases in the resource abundant country. A few papers have since then elaborated upon these results. Regarding specific trade structures Lopez (2000) shows that the type of openness affects whether there are gains or losses from trade. In regard to forms of property rights Nielsen (2009) shows that there may be gains or losses from trade depending on the management scheme; Engel et al. (2006) show that third party involvement in mediations for control over the resource may incur losses; Emani & Johnston (2000) show that unequal property rights between trading countries may in itself be a problem. In regard to the biological effects Smulders et al. (2004) analyze the effect of trade on habitat destruction and welfare. Regarding industry and country assumptions, Hannesson (2000) shows that diminishing returns in the non-resource sector can lead to gains from trade in situations where there would be losses without the diminishing returns. Finally, Copeland & Taylor (2009) endogenize the institutional settings and show how the very presence of an open access regime is affected by trade and world prices. The main contribution of our paper in comparison to the previous literature is to analyze the effect of natural disasters on harvest, collapse and welfare.

There is also a broad empirical and theoretical literature showing that resource rich countries often do worse than resource poor countries (see van der Ploeg, 2011 for a survey). One of the mechanisms proposed is that increased prices of a country's commodities may lead to increased corruption and conflict (see e.g. Dal Bo & Dal Bo, 2011, for a general equilibrium model). In effect we show in this paper that both TFP shocks and natural disasters provide an alternative channel for the resource curse highlighting the importance of economic institutions such as property rights. Our model stresses not the conflict or corruption generated by price increases but rather the overharvesting and worsening of the tragedy of the commons. It also stresses that resource reliant and institutionally weak countries that trade extensively, will be more economically vulnerable to natural disasters and to collapsing of fisheries, wildlife and ecosystems.

The rest of the paper is structured as follows. In the next section we set up the model and derive results for the effects of increased trade openness on steady-state variables. Following that, in section 3, we consider natural disasters that manifest themselves as shocks to the resource stocks in a single country or a group of countries. We then, in section 4 analyze a case of more than one country having a certain resource and the case of cascading collapses. In section 5 we generalize the analysis by no longer assuming that one's trade partners are exporting renewable resources. Section 6 calibrates the model to empirical estimates from the fishery literature and discusses how various model extensions would affect the results. Finally, section 7 concludes. The main body of the paper contains only analytical results necessary for describing and understanding the central results in the paper. Most proofs, derivations and supplementary analytical results are to be found in the appendix.

2 Model setup and steady-state analysis

We start by analyzing a case where there is a continuum of countries.[9] Each country has a unique type of a renewable resource provided by an ecosystem. This resource can be thought of as a fish species or any wildlife, forest or plant which can be sold on a market. The model may represent the case where, for example, one country has a fish stock, another country has a forest and a third country has a game population. Or it may represent a case where countries have different type of fish. We further assume that there is a continuum of mass one of agents in each country, who all work with harvesting from the renewable resource, to which there is open access.[10] Open access will imply that individual harvesters will not take into account the effect their harvesting has on the future resource stock since refraining from harvesting only induces others to harvest more. Hence , each agent will behave as if being completely myopic. This is comparable to the effect of political shortsightedness or other problems leading to myopic behavior. For short we will from now on refer to all these problems as open access. In the exposition of the model and results we will use specific functional forms. The results are, however, generalizable. The functional forms we choose are simply more effective in highlighting the results and driving mechanisms.

To keep the notation simple throughout the paper we suppress the time index of variables where possible. Flow utility of the representative agent in country i is given by

$$U_i = \left(\int_0^J (c_i(j))^q \, dj \right)^{\frac{1}{q}} - AN_i^{\theta} \tag{1}$$

where $c_i(j)$ is the consumption of the good from country j by an agent in country i and N_i is the harvesting effort of an agent in country i. The parameter θ determines the shape of the effort cost function while A is the weight of work disutility. The disutility of harvesting effort can also be interpreted as an alternative cost in terms of reduced production of non-traded goods. We will assume that $\theta > 1$ so that the marginal cost is increasing in effort. J denotes the mass of countries that country

[9] We make this assumption to enable differentiation with respect to the number of trading partners, J. If J is an integer, the results are the same as what they would be if there were J discrete countries. This means that $J = 1$ represents the case of autarky.

[10] For tractability, we assume that the resource sector is also the only sector in the economy. We therefore restrict the interpretation of our analysis to correspond to gains from trade with these types of goods. A richer model could of course include also other sectors but, intuitively, we do not think this will have an effect on the results since the general mechanism will still be present. I.e. when opening up for trade the price of the resource good goes up which will either attract more workers into this sector or increase the efforts of the present workers.

i trades with. Unless otherwise stated, increased trade openness and trade liberalization will be used synonymously for an increase in J. When considering resources such as fish, wildlife and plants it seems reasonable to assume that the different varieties of goods are fairly good, but not perfect, substitutes. That is, we assume that $q \in (0, 1)$.

Generally, a harvest function $H(N, x)$, where x is the resource stock, should have the property that it is increasing in both its arguments. Here we will use a generalized version of Schaefer's (1957) standard harvest function (see Clark, 1990 for details).

$$H(N, x) = Nx^{\beta}, \ \beta \in (0, 1) \tag{2}$$

Thus, for a given stock x, harvest is linear in effort N.[11] This means that there will be no (within-period) externalities between the harvesting efforts of different agents. Furthermore, the assumption $\beta \in (0, 1)$ implies that, for a given effort, harvesting is higher the larger is the stock. The restriction $\beta < 1$ implies that the effect of an increased stock on harvest wears off as the stock becomes large. Likewise, even for a very small stock it is possible to get some harvest. Thus, it is always possible to locate the last individuals of a species, for instance, due to existence of breading grounds or water holes. In forestry it more or less follows from trees being immobile. This restriction is based on a solid body of empirical estimates (e.g. Grafton et al., 2007; Kronbak, 2005; Bjørndal & Conrad, 1987; and Richter et al., 2011, all estimate β to be well below 1). In Section 6 we will discuss the results when relaxing this and other assumptions.

An agent in country i faces the budget constraint

$$\int_0^J p(j)c_i(j)dj = p(i)N_i x_i^{\beta}, \tag{3}$$

where $p(j)$ is the world market price of the good from country j and x_i is the stock of the resource in country i. Total world consumption of the good from country j must be equal to the harvest in that country, so

$$\int_0^J c_i(j)di = N_j x_j^{\beta}. \tag{4}$$

Given the assumption of open access, and an infinite number of agents, the harvesting decisions will be static and not take the effect on the stock into account. This

[11]The assumption of linearity is made to reduce the number of model parameters. It would be more realistic to assume decreasing returns to effort – i.e., H is a concave function of N. Such an assumption would strengthen the results presented in the paper. We discuss such an extension in Section 6.

means that the harvesting rule for the agents can be written as a function of only the current resource stocks $\{x_i\}$ and the parameters of the problem. The representative agent thus wants to maximize (1) subject to (3). The solution must also satisfy (4). The detailed steps of solving this problem appear in appendix A.1. We then get the following. Let the price index $\tilde{p}$ be defined as

$$\tilde{p} \equiv \left(\int_0^J p(j)^{\frac{q}{q-1}} dj \right)^{\frac{q-1}{q}} .$$

The price of good i normalized by the price index is in equilibrium

$$\frac{p(i)}{\tilde{p}} = \left(\frac{\int_0^J x_{i'}^{\beta \frac{q\theta}{\theta - q}} di'}{x_i^{\beta \frac{q\theta}{\theta - q}}} \right)^{\frac{1-q}{q}} . \tag{5}$$

Furthermore, the equilibrium flow utility and harvesting effort are given by

$$U_i = (\theta - 1) A \left(N_i^* \right)^{\theta} \tag{6}$$

$$\begin{aligned} N_i^* &= (\theta A)^{\frac{1}{1-\theta}} \left(\frac{p(i)}{\tilde{p}} \right)^{\frac{1}{\theta - 1}} x_i^{\beta \frac{1}{\theta - 1}} \\ &= (\theta A)^{\frac{1}{1-\theta}} \left[\frac{\int_0^J x_{i'}^{\beta \frac{q\theta}{\theta - q}} di'}{x_i^{\beta \frac{q\theta}{\theta - q}}} \right]^{\frac{1-q}{q} \frac{1}{\theta - 1}} x_i^{\beta \frac{1}{\theta - 1}} . \end{aligned} \tag{7}$$

Equation (6) immediately implies the following lemma.

Lemma 1 *Flow utility U_i is strictly increasing in individually optimal harvesting effort N_i^*.*

Although a high effort N entails a cost, the lemma implies that it can be used as a proxy for flow utility. The intuition for this is roughly that a higher effort is indicative of a higher utility from consumption. Note that this does not mean that agents do best in exerting a high effort. Rather, N_i is a choice variable for the individual agent, and hence what the lemma says is that when we observe agents exerting a high effort then that is a sign of high utility. Below we will use this result to determine signs of changes in flow utility.

The previous equations describe what the agents do given the resource stocks $\{x_i\}$, i.e. a partial equilibrium reflecting the economic forces of the model but missing the biological dynamics. To get the steady-state of the bio-economic general equilibrium we need to specify what determines the stock size. The resource stock in country i evolves according to

$$\dot{x}_i = f_i(x_i) - N_i^* x_i^{\beta} \tag{8}$$

where f_i is a biological function denoting the growth of the resource in the absence of human interference. We will assume the same biological growth function in all countries. For expositional purposes we will use the logistic growth function

$$f(x) = kx(1-x). \tag{9}$$

This is a very standard assumption in renewable resource economics and in particular when combined with trade (e.g. Brander & Taylor 1997a, 1997b, 1998, Quaas & Requate 2013).[12] Had we considered a growth function including depensation our results would have been strengthened (see Section 6 for more details). This function $f(x)$ is such that, absent any harvesting, there are two steady-states. One unstable at $x = 0$ and one stable at $x = 1$. That is, over time the stock would go to its maximum size $x = 1$ if there was no harvest. The parameter k represents the intrinsic growth rate. The growth function has a single peak at $x = 1/2$. Furthermore, the function is concave.

Initially we restrict our attention to symmetric countries in symmetric steady-states. This allows consideration of the mechanisms determining the welfare effects of increased trade openness (later, shocks resulting in heterogeneous stocks will be considered). Symmetry implies that $x_i = x$ for all i which in itself has the further consequence that $N_i = N$ for all i and that $c_i(j) = c$ for all i, j. Imposing these symmetries in (6) and (7) and using (2) gives harvest and flow utility as functions of the current stock.

$$H^* = (\theta A)^{\frac{1}{1-\theta}} J^{\frac{1}{\theta-1}\frac{1-q}{q}} x^{\beta\frac{\theta}{\theta-1}} \tag{10}$$

$$U = (\theta-1)A\left(N^*\right)^{\theta} = (\theta-1)\theta^{\frac{\theta}{1-\theta}} A^{\frac{1}{1-\theta}} J^{\frac{\theta}{\theta-1}\frac{1-q}{q}} x^{\beta\frac{\theta}{\theta-1}} \tag{11}$$

The bio-economic dynamics with symmetric countries can be illustrated in a phase diagram for a representative country (see Figure 1). The dashed line represents harvest as a function of the current stock as stated by equation (10). The solid curve represents the biological growth function in (9). In the specific case in the figure there exists one stable steady-state where the curves cross. If the stock is above this

[12] Often, the specification is $f(x) = kx(1 - \frac{x}{r})$. However, since the parameter r only determines the size of the stock, it can be normalized to one and other parameters can be adjusted accordingly. For reference see Clark (1990).

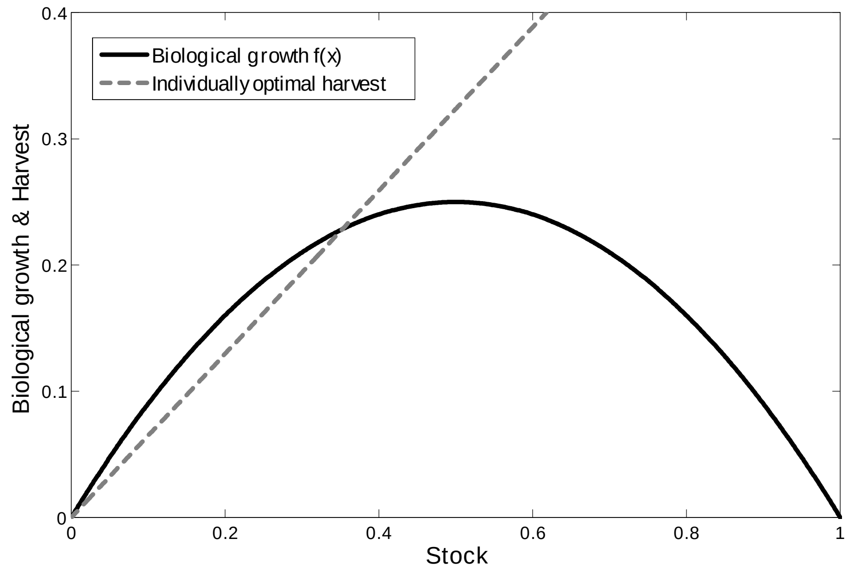

Figure 1: Phase diagram of contributions and withdrawals from the resource stock.

level, harvest will be higher than the biological growth leading to a falling stock. If, instead, the stock is below the steady-state level, harvest is lower than the biological growth and the stock increases. There exists another unstable steady-state where the stock is zero.

It is straightforward to show existence of a stable steady-state, provided that J is sufficiently low. In equation (10) we can see that as J approaches zero, H goes to zero for any x. Graphically, in Figure 1, this implies that the harvest curve becomes one with the x-axis implying, in turn, an intersection with $f(x)$. From this figure it is also immediate that an increase in J will lead to a decrease of the stock (since this tilts the harvesting curve upwards). Similarly, increasing J first increases steady state harvest but for sufficiently large J steady state harvest will decrease. Finally, under certain conditions we will analyze later, a sufficient increase in J will imply the harvest function in Figure 1 is steeper than the biological growth function when $x = 0$ and hence the harvesting function is above the biological growth for small x. Such a case would imply $x = 0$ is a stable steady-state. In that case there is a risk of what we will call (bio-economic) collapse, that is, the harvesting decisions can drive the resource stock to zero.

One way to analyze the welfare effects of increasing J is to decompose the welfare change into a variety and a stock effect. Whereas the variety effect captures the welfare gains from increased consumption variety, the stock effect captures the negative consequences of a decrease in the steady-state stock. Starting from equation (11) and taking the full derivative of the flow utility with respect to J yields

$$\frac{dU_{ss}}{dJ} = \frac{\partial U_{ss}}{\partial J} + \frac{\partial U_{ss}}{\partial x_{ss}} \frac{dx_{ss}}{dJ} \tag{12}$$

where $\frac{dx_{ss}}{dJ}$ is the change in the steady-state stock that is induced by a change in J. The first term represents the variety effect and the second term represents the stock effect. Since $\theta > 1$ and $q < 1$ from (11) it can be seen that $\frac{\partial U_{ss}}{\partial J} > 0$ and $\frac{\partial U_{ss}}{\partial x} > 0$. Furthermore, since the steady-state stock always decreases with J, $\frac{dx_{ss}}{dJ} < 0$.[13] The variety effect is thus always positive while the stock effect is always negative.[14] Through explicit computation of the involved derivatives it can be shown that the variety effect will dominate when $\frac{f(x)}{x^\beta}$ is decreasing in x while the stock effect will dominate when $\frac{f(x)}{x^\beta}$ is increasing in x. This can also be understood in terms of Lemma 1 since equation (8) implies that steady-state harvesting effort N must be equal to $\frac{f(x)}{x^\beta}$. Standard functional forms for $f(x)$ typically have a unique cutoff stock above which welfare is increasing in trade and below which welfare is decreasing. For the logistic case used here, this cutoff is $x_{ss} = \frac{1-\beta}{2-\beta}$. I.e., for $x_{ss} > \frac{1-\beta}{2-\beta}$ welfare is increasing in trade and for $x_{ss} < \frac{1-\beta}{2-\beta}$ it is decreasing. The main symmetric results are summarized in the following proposition.

Proposition 1 *In symmetric steady states:*

1. *The stock $x_{ss}(J)$ always decreases with J, and harvest increases with J until $x_{ss}(J) = \frac{1}{2}$.*

2. *Utility increases with J until $x_{ss}(J) = \frac{1-\beta}{2-\beta} < \frac{1}{2}$, after which further increases in J reduce utility.*

3. *Furthermore, if and only if $\beta \leq \frac{\theta-1}{\theta}$ (the low elasticity case) then increasing J beyond the value that gives $x_{ss}(J) = \frac{(\theta-1)-\beta\theta}{2(\theta-1)-\beta\theta} < \frac{1-\beta}{2-\beta}$ in steady-state will drive the stock to collapse at $x_{ss} = 0$.*

   Proof. *See appendix.* ■

[13] Graphically this can be seen in Figure 1 – an increase in J tilts the harvesting function upwards which implies a lower x. Analytically this is shown in the appendix section A.2.

[14] Note that the steady-state stock may be lower with more trading partners also in the optimal outcome. So, a negative stock effect does not necessarily only capture overharvesting.

This proposition highlights a few noteworthy results. Firstly, there is a maximum number of trade partners beyond which welfare is falling. Secondly, when $\beta \leq \frac{\theta-1}{\theta}$, there is a risk of collapse. This is not simply a biological collapse, since absent of harvesting the resource will recover, but a bio-economic collapse which is driven by the interaction of economic incentives and biological properties – agents have incentives to harvest also when the stock is small which refrains it from recovering. Later, when we consider shocks leading to stock asymmetries, we will see that the range of parameter values where there can be collapse is in fact larger than this.

The low elasticity case can be illustrated using Figure 1. In that figure we have an induced harvest function which is linear (a linear function occurs when $\beta = \frac{\theta-1}{\theta}$). As we lower the elasticity so that $\beta < \frac{\theta-1}{\theta}$ this function becomes concave and is above the biological growth function for small x. This implies $x = 0$ becomes a stable steady state. This, though, by itself is not sufficient for collapse. For low J the harvest function intersects f twice implying there are two steady-states. One larger that is stable and one smaller that is unstable. If starting from some arbitrary stock, the unstable steady-state gives the threshold below which the stock will go to zero. This may be the effect of a negative shock to the stock, which we analyze in the next section. If J is increased this shifts the harvest function upwards which also implies the two intersections converge. Once J is increased beyond the point which gives $x_{ss} = \frac{\theta-1-\beta\theta}{2(\theta-1)-\beta\theta}$, there is no longer any steady-state with positive stock and the stock will go to zero regardless of where it starts from.

Figure 2 summarizes the main results with regard to steady state utility (for a case without collapse). Note that the x-axis is in reverse – going from high to low levels of x_{ss} – to represent increases in J. Leftmost in the graph is the steady state stock in autarky ($J = 1$). As we move rightwards, x_{ss} falls (following an increase in J) which initially leads to a higher flow utility since the variety effect dominates. At the point where $x_{ss} = \frac{1-\beta}{2-\beta}$ the maximum steady state utility is attained. After that, further increases in J lower utility (the stock effect dominates). This also means that when $x_{ss}(J) < \frac{1-\beta}{2-\beta}$ small reductions in J will improve welfare. However, it does not necessarily mean that going all the way back to autarky is preferred as there are levels of J where $U_{ss}(J) > U_{ss}(1)$. So very large reductions in J may overshoot the maximum point to an extent which actually reduces welfare. But once J becomes very large (at the right end of the figure) any reduction in J, large or small, will improve welfare.

3 Natural disasters

We will now analyze the effects of shocks to the stocks $\{x_i\}$. In practice they may emanate from any type of natural disaster such as a flood, a storm, a wildfire or

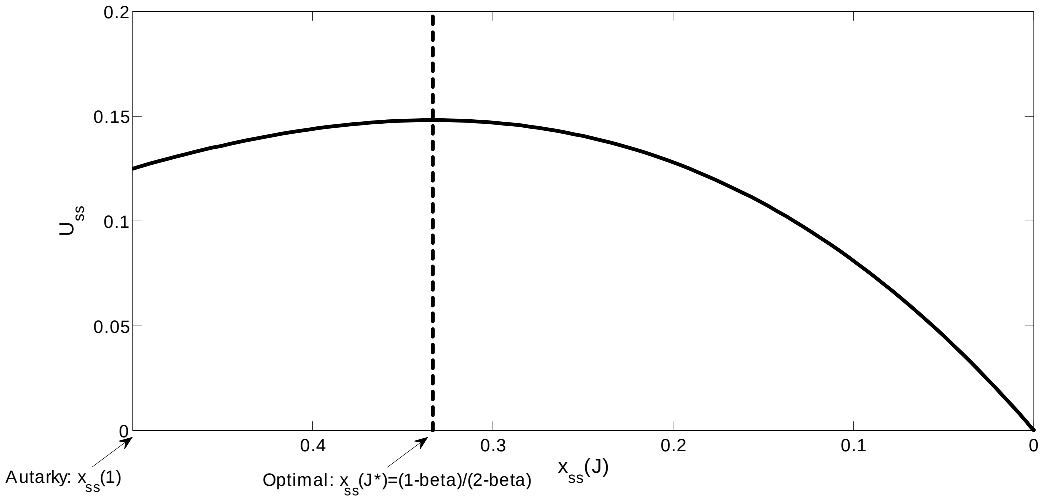

Figure 2: Solid line: U_{ss} as a function of x_{ss} which in itself is a function of J. Dotted line: the endogenous stock which in steady yields the highest utility. Parameters: $\beta = 0.5$, $q = 0.5$, $A = 1$, $\theta = 2$, $k = 1$.

a disease that exterminates part of the stock. Firstly, we analyze the observable reactions of the economy to a shock. That is, the dynamic effect on harvest and prices in countries hit by the shock as well as countries not directly affected. Then we evaluate welfare.

To analyze the shocks, stock asymmetries will be considered. Denote by x_i the stock in the single country i and by x_j the stock in another country. Combining (2) and (7) we get the harvest in country i as a function of its own stock and the stock of its trading partners.

$$\begin{aligned} H_i^* &= \frac{1}{\theta A}\left(\frac{p(i)}{\tilde{p}}\right)^{\frac{1}{\theta-1}} x_i^{\beta\frac{\theta}{\theta-1}} \\ &= (\theta A)^{\frac{1}{1-\theta}}\left[\frac{\int_0^J x_j^{\beta\frac{\theta q}{\theta-q}} dj}{x_i^{\beta\frac{\theta q}{\theta-q}}}\right]^{\frac{1}{\theta-1}\frac{1-q}{q}} x_i^{\beta\frac{\theta}{\theta-1}} \end{aligned} \tag{13}$$

An idiosyncratic shock to country i, when starting from the symmetric steady-state with $x_i = x_j = x_{ss}$, is represented by setting $x_i < x_{ss}$ while $x_j = x_{ss}$ for all countries $j \neq i$. A symmetric shock on the other hand would mean that $x_i = x_j < x_{ss}$ for all countries i and j.

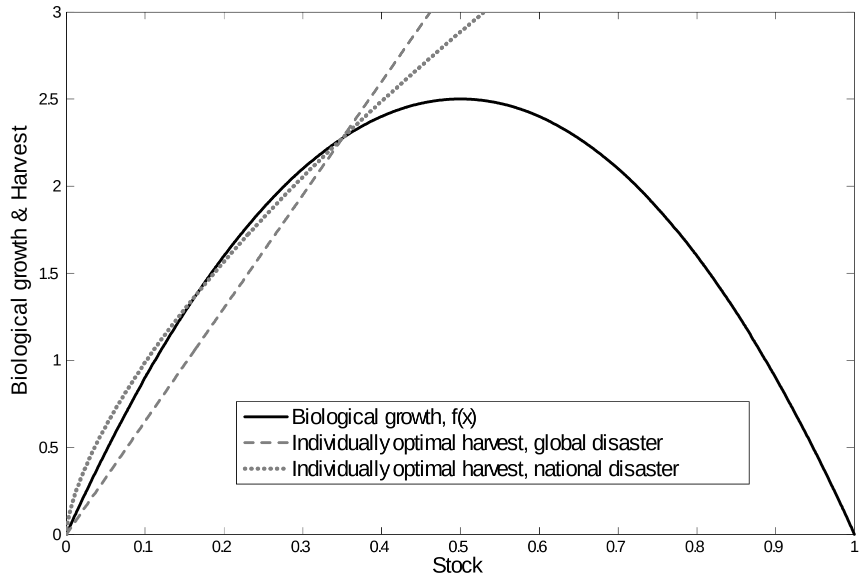

Figure 3: Phase diagram with symmetric and idiosyncratic shocks. Parameters: $\beta = 0.5$, $A = 1$, $K = 10$, $q = 0.5$, $r = 1$, $\theta = 2$, $J = 13$.

The dynamics following a symmetric shock hitting all countries (which we will refer to as a global shock) can be analyzed using a phase diagram of the symmetric equilibrium in the previous section (see Figure 1). Depending on the number of trade partners and on β and θ, we get either convergence back to the steady-state or collapse.

Now, suppose that an idiosyncratic shock hits only country i. Since each country is negligible in size, this will not affect the harvesting decisions of the other countries.[15] Hence, starting from a steady-state, the integral in the numerator of the square bracket in (13) can be treated as a constant. The harvesting function in country i will then be proportional to $x_i^{\beta\frac{\theta}{\theta-q}}$. In Figure 3 the ensuing harvesting decision of country i is depicted along with the harvesting decision if the shock would have been global. As can be seen in this figure, if the shock is negative the harvest in country i will be strictly higher following the idiosyncratic shock compared to the global shock.

To see this analytically, equation (13) can be compared for the two alternative shocks. Since each country gives a negligible contribution to the integral, the integral

[15] We show later what the effect would be if each country is not negligible in size.

will be determined by the value of $x_{\sim i}$ which denotes the stock in countries other than i. Let subindex *glob* denote a variable under a global shock and subindex *id* denote a variable under an idiosyncratic shock. To be able to compare, suppose x_i is the same under both shock types and that under the global shock $x_{\sim i,glob} = x_i$ (which means the global shock is entirely symmetric) while under the idiosyncratic shock $x_{\sim i,id} \neq x_i$. Harvest in country i (H_i^*) can then be compared between the two shock types as follows.

$$\nabla H_i \equiv \frac{H_i^*\left(x_{\sim i,id}\right)}{H_i^*\left(x_{\sim i,glob}\right)} = \frac{\left(\frac{p_{id}(i)}{\tilde{p}_{id}}\right)^{\frac{1}{\theta-1}}}{\left(\frac{p_{glob}(i)}{\tilde{p}_{glob}}\right)^{\frac{1}{\theta-1}}}$$

$$= \left[\frac{Jx_{\sim i,id}^{\frac{q\theta}{\theta-q}\beta}}{Jx_{\sim i,glob}^{\frac{q\theta}{\theta-q}\beta}}\right]^{\frac{1}{q}\frac{1-q}{\theta-1}} = \left(\frac{x_{\sim i,id}}{x_{\sim i,glob}}\right)^{\frac{(1-q)\theta}{(\theta-q)(\theta-1)}\beta}$$

Here $\nabla H_i > 1$ if and only if $x_{\sim i,glob} < x_{\sim i,id}$ (i.e., which is the case under negative shocks).[16] We here compare harvest in country i for the same stock x_i but where the stock in the other countries differ. The difference in harvest comes entirely from the difference in the normalized price of the good produced in country i. Over time the stocks will change dynamically under both shocks according to the phase diagram in Figure 3. We then arrive at the following proposition.

Proposition 2 *Under negative shocks to the stock:*

1. *The normalized price of the good from country i is higher for any $x_i(t)$ if the shock is idiosyncratic than if the shock is global.*

2. *Thus, for any given $x(t) < x_{ss}$, harvest is higher under an idiosyncratic shock compared to a global shock.*

3. *Thus, convergence back to steady-state is slower if the shock is idiosyncratic.*

4. *Suppose, furthermore, $\beta < \frac{\theta-q}{\theta}$, then there is a risk of bio-economic collapse and the shock size necessary to induce collapse is strictly smaller if the shock is idiosyncratic compared to if the shock is global. Moreover, there exists a J such that the steady-state is unstable for any negative idiosyncratic shock but stable for a global shock of limited size.*

[16] This follows directly from $q < 1$ and $\theta > 1$.

Proof. *See appendix.* ■

The first result of the proposition highlights the upside of trade when one country is hit by a negative shock while the others are not. The lower supply of one's own product raises its world price which is a form of immediate insurance or cushioning of the shock. This effect is, however, also a curse in disguise when looking at the dynamic aspects. Under open access, the higher price induces higher harvesting effort and thus a slower convergence back to the steady-state. So while agents are better off for any given size of the stock following an idiosyncratic shock when trading, the combination of an idiosyncratic shock and trade ensures that they are left in a bad situation with a low stock for longer – recovery is slower.

Considering the risk of collapse, idiosyncratic shocks are more problematic than global shocks in at least two ways. Firstly, the possibility of collapse arises for a larger range of β-values when the shock is idiosyncratic. There is a risk of collapse when $x = 0$ constitutes a stable steady-state. In the case of global shocks, this happens when $\beta < \frac{\theta-1}{\theta}$ while for idiosyncratic shocks, this happens when $\beta < \frac{\theta-q}{\theta}$, where $\frac{\theta-q}{\theta} > \frac{\theta-1}{\theta}$. Secondly, the higher harvesting effort under an idiosyncratic shock also implies that smaller shocks are needed for the bio-economic system to collapse (the range of x-values leading to collapse is larger). As the number of trading partners is increased a situation emerges where any idiosyncratic shock, no matter how small, will lead to collapse. This happens when trade induces an endogenous steady-state stock $x_{ss} = \frac{(\theta-q)-\beta\theta}{2(\theta-q)-\beta\theta}$. At the same point countries can be resilient to large global shocks. This can be seen in Figure 3. A global shock cannot induce collapse but an idiosyncratic shock that brings x_i below the intersection of the idiosyncratic harvest function (dotted curve) and the biological growth function (solid curve) will lead to collapse. More generally the harvest function following a global shock (dashed curve) will intersect the growth function (solid curve) for a smaller x compared to the harvest function following an idiosyncratic shock (dotted curve). Furthermore, the fact that the country is trading, increases the risk of collapse. Had it not been trading, a shock to its stock would not have led to any shifts in the relative price and its stock level would not have been as low in the first place.

These results are very much in contrast to classic results from trade theory. Trade, between individuals or between countries, is normally a way of indirectly insuring against bad states. When the production of a country is hit negatively by a shock its price goes up as long as goods are differentiated. This means that recovery will be faster when there is trade since for every unit produced the country is getting a higher income which it can invest in building up its production capacity. In a case of trade with open access renewable resources this is reversed since the higher price leads to more extensive overharvesting (and thus to slower recovery) and it increases the risk that a shock of a certain size will lead to collapse. This is a form of the resource curse. A country reliant on resources with open access (or other market imperfections leading to myopic behavior) will find it hard to recover from disasters when it is trading.

The results of Proposition 2 also highlight the two forces determining total welfare. Idiosyncratic shocks imply a slower convergence back to steady-state (and a higher risk of collapse) but the price effect ensures that flow utility is higher at any given stock level. Hence, whether one country hit by a disaster is better off if it is global than if it is idiosyncratic is ambiguous.

Using linearization around the steady-state the relative importance of the two effects when shocks are small can be considered. We thus consider small deviations from a symmetric steady-state. Earlier, when considering an infinitessimal country, there were no effects on the harvesting efforts in the other countries. In the upcoming analysis we will also include dynamic reactions of other countries. We will therefore consider shocks hitting a group of a non-zero measure of countries and refer to such a disaster as *partially global*. In order to make the analysis more transparent, suppose all countries are divided into two groups and that the stock level is the same for all countries within each group. Each country is atomistic but a mass $\check{J}$ of all countries are hit negatively by a shock and thus have a stock $\check{x}$ and another mass $\hat{J}$ of all countries are not hit and have stock $\hat{x}$. Together, these two groups make up for all countries, i.e. $\check{J} + \hat{J} = J$.[17] We linearize around a steady-state where all countries have stock x_{ss}. Using (13), the harvests in the two groups are given by

$$\check{H} = (\theta A)^{\frac{1}{1-\theta}} \left[\frac{\check{J}\check{x}^{\beta \frac{\theta q}{\theta - q}} + \hat{J}\hat{x}^{\beta \frac{\theta q}{\theta - q}}}{\check{x}^{\beta \frac{\theta q}{\theta - q}}} \right]^{\frac{1}{\theta - 1} \frac{1-q}{q}} \check{x}^{\beta \frac{\theta}{\theta - 1}} \tag{14}$$

$$\hat{H} = (\theta A)^{\frac{1}{1-\theta}} \left[\frac{\check{J}\check{x}^{\beta \frac{\theta q}{\theta - q}} + \hat{J}\hat{x}^{\beta \frac{\theta q}{\theta - q}}}{\hat{x}^{\beta \frac{\theta q}{\theta - q}}} \right]^{\frac{1}{\theta - 1} \frac{1-q}{q}} \hat{x}^{\beta \frac{\theta}{\theta - 1}}. \tag{15}$$

From these expressions it can be seen that harvesting effort in each group is increasing in the stock of both groups. This has the important implication that the dynamic reaction in the countries not hit will increase the risk of collapse in those who *are* hit. Compared to Proposition 2 where the shocked country was so small that the others did not react, now the risk of collapse increases since the other countries react by lowering their harvest which also implies their stock will grow. This reaction is

[17] Note that the analysis would be the same if we had discrete countries and one or a few were hit by a shock.

due to changes in prices. The normalized prizes of goods from the two groups of countries are

$$\frac{\check{p}}{\tilde{p}} = \left(\frac{\check{J}\check{x}^{\beta \frac{\theta q}{\theta - q}} + \hat{J}\hat{x}^{\beta \frac{\theta q}{\theta - q}}}{\check{x}^{\beta \frac{\theta q}{\theta - q}}} \right)^{\frac{1-q}{q}} \text{ and } \frac{\hat{p}}{\tilde{p}} = \left(\frac{\check{J}\check{x}^{\beta \frac{\theta q}{\theta - q}} + \hat{J}\hat{x}^{\beta \frac{\theta q}{\theta - q}}}{\hat{x}^{\beta \frac{\theta q}{\theta - q}}} \right)^{\frac{1-q}{q}}$$

for the shocked and non-shocked group respectively. The price of the good from a country in one of the groups thus depends positively on the stocks in the other group of countries. The increase in the stocks of the initially unaffected countries increases the price in the shocked group further, amplifying the increase of harvest there and hence increasing the risk of collapse.

From now on we will analyze the welfare effects of shocks small enough as to not cause collapse. We know that for $\check{x} = \hat{x} = x_{ss}$ we have that $\check{H} = \hat{H} = f(x_{ss})$. Linearizing the dynamics of the state variables around the steady-state and then linearizing the flow utility yields an approximation of the total discounted utility, integrated along the convergence back to steady-state, following a partially global shock (for derivations see appendix A.4). In our linearization we use the deviations of the stocks from their steady-state values as our state variables. We thus define

$$\Delta\check{x}(t) \equiv \check{x}(t) - x_{ss} \text{ and } \Delta\hat{x}(t) \equiv \hat{x}(t) - x_{ss}.$$

The discounted utility for a country hit by a small negative shock is represented by the following expression

$$\check{V}\left(\Delta\check{x}_0, \Delta\hat{x}_0\right) = \int_{t=0}^{\infty} \check{U}(t) e^{-\rho t} dt. \tag{16}$$

The integral is computed over the time paths generated by equations (14) and (15) when starting from initial conditions $\Delta\check{x}(0) = \Delta\check{x}_0$ and $\Delta\hat{x}(0) = \Delta\hat{x}_0$. Using the linearized dynamics and the linearized utility function (see appendix A.4) this integral can be computed explicitly. We will now consider the effects of a shock hitting one of the groups on discounted welfare of countries in that same group. Setting $\Delta\hat{x}_0 = 0$ we have that

$$\begin{aligned} \check{V}(\Delta\check{x}_0, 0) \approx V_{disaster} \equiv \frac{1}{\rho}U_{ss} + & \frac{U_{ss}}{x_{ss}} \frac{\check{J}}{J} \beta \left(\frac{\theta}{\theta - 1} \frac{1}{\rho - \lambda_1} - \frac{q\theta}{\theta - q} \frac{1}{\rho - \lambda_2} \right) \Delta\check{x}_0 \\ & + \frac{U_{ss}}{x_{ss}} \beta \frac{q\theta}{\theta - q} \frac{1}{\rho - \lambda_2} \Delta\check{x}_0. \end{aligned}$$

where λ_1 and λ_2 are the eigenvalues of the linearized state dynamics. In the case where the steady-state is locally stable, both eigenvalues are negative. $V_{disaster}$ can be evaluated as a function of $\check{J}$. This tells us whether a country hit by a negative shock to its stock is better off when more countries are hit too ($dV_{disaster}/d\check{J} > 0$). That is, whether global shocks are better than partial. Since U_{ss} and x_{ss} are independent of $\check{J}$, the sign of $dV_{disaster}/d\check{J}$ is determined by the factor

$$\frac{\theta}{\theta-1}\frac{1}{\rho-\lambda_1}-\frac{q\theta}{\theta-q}\frac{1}{\rho-\lambda_2}=\frac{\theta^2(1-q)\left(\rho-\left[\frac{1-\beta}{2-\beta}-x_{ss}\right]k/\left(2-\beta\right)\right)}{(\theta-1)(\theta-q)(\rho-\lambda_1)(\rho-\lambda_2)}.$$

The sign of this expression is the same as the sign of

$$\rho-\left[\frac{1-\beta}{2-\beta}-x_{ss}\right]k/\left(2-\beta\right). \tag{17}$$

Since $\Delta\check{x}_0 < 0$ we get the following proposition.

Proposition 3 *$V_{disaster}$ is increasing in $\check{J}$ if and only if expression* (17) *is negative.*

This proposition expresses when a single country is better off being part of a global disaster rather than a national disaster. The upside of the global disaster comes from the feedback that enables a faster recovery back to the steady-state. This is why low discounting is needed for the country to prefer global shocks (a large ρ lowers the threshold x_{ss}). Otherwise agents primarily care about welfare right after the shock occurs which is higher the fewer countries are hit, due to the relative price effect. Likewise, note that $x_{ss} = \frac{1-\beta}{2-\beta}$ corresponds to the welfare maximizing number of trade partners in steady-state from Proposition 1 which is also depicted in Figure 2. So Proposition 3 shows that this same number of trade partners gives the cutoff for when a single country prefers to be part of a global disaster (if there is little discounting).

These results also extend to a case where a country (call it i) is *not* hit by the disaster but its trade partners are. So more generally it can be said that small disasters hitting other countries are good from the point of view of country i once its stock is smaller than $\frac{1-\beta}{2-\beta}$ (at least if we use a low discount factor). When considering larger shocks two additional effects (which are hard to evaluate analytically) need to be taken into account. First of all, if stocks collapse in some countries the welfare calculations need to take into account that the new resulting steady-state differs from the initial steady-state. The dependency of welfare on the number of remaining trade partners is shown in Figure 2. For instance, if we start slightly to the right of the maximum point in Figure 2 (such that $x_{ss} < \frac{1-\beta}{2-\beta}$) and then envision a disaster making many other countries collapse, then this would clearly be worse from the point of view of country i than if there was no disaster. This means that very extensive shocks to a few trading partners may result in a higher steady state utility but if many trade partners are hit then this may lead to lower steady state utility. Second of all, the dynamic path towards the new steady state will imply a lower flow utility initially since the price of the own resource falls when supply of others' resources fall.

4 Extension 1 – Cascading collapses among competitor countries

So far all countries have had a unique resource. Here this assumption will be relaxed. What we have in mind is a country i which has a renewable resource. This country is, however, not alone in producing this resource – there are other, "competitor", countries with the same resource. Suppose there is a discrete set J of different resources and a discrete set of countries I. Adapting the utility function (1), budget constraint (3) and the market clearing conditions (4) to a discrete set of goods and countries, we solve for the intratemporal equilibrium in appendix A.5. Letting I_j denote the set of discrete countries having a resource $j \in J$ we define

$$X_j \equiv \left(\sum_{k \in I_j} x_k^{\frac{\theta}{\theta-1}\beta} \right)^{\frac{\theta-1}{\theta-q}}$$

which is a measure of the global stock of j (since the expression is increasing in each x_k).

Now, suppose country i has a resource of type j_i. We are interested in analyzing the effects on the stock in country i (i.e., on x_i) when a natural disaster happens in other countries having the same resource j_i. In appendix A.5 we derive the harvest in country i.

$$H_i^* = (\theta A)^{\frac{1}{1-\theta}} \left[\frac{X_{j_i}^q + \sum_{j \neq j_i} X_j^q}{X_{j_i}^q} \right]^{\frac{1}{q}\frac{1-q}{\theta-1}} x_i^{\frac{\theta}{\theta-1}\beta} \tag{18}$$

What this equation shows is that the harvest in country i is increasing in its own stock (x_i),[18] increasing in the measure of the stock (or productivity) of countries having a complement good ($X_{j \neq j_i}$) and decreasing in the measure of the stock of

[18]Note that x_i appears both outside of the brackets and as a non-negligible part X_{j_i}. However, it can be shown that the term outside has a stronger effect on H_i.

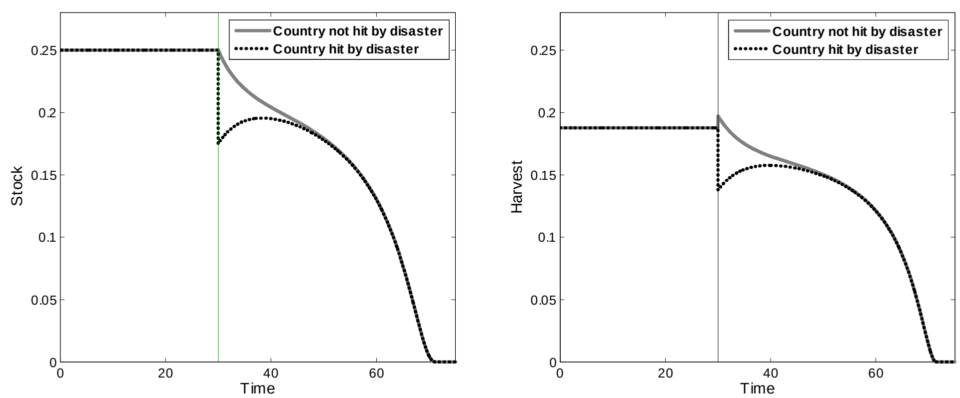

Figure 4: Example of cascading collapse. $J = 15$, $I_j = 2$, $\beta = 0.5$, $\theta = 2$, $q = 0.5$, $A = 10$, $k = 1$. Stock in symmetric steady state is 0.25. All countries are in steady state for 30 periods. At $t = 30$ one country is hit by a disaster reducing its stock by 30%. The graphs depict the evolution of the stock and harvest in that country and in a competitor country having the same type of resource.

countries having the same resource X_{j_i}. Our focus here is however on how a change in the global stock of j_i (that is, in the measure X_{j_i}) affects H_i^* which in turn affects x_i and which again affects H_i^*.

Suppose, for instance, j_i represents white cod-like fish. A decrease in X_{j_i} could then follow from a disaster hitting Alaskan Pollock. The question is then what effect this will have on Haddock fisheries. Alternatively, the analysis represents how a natural disaster to one whale fishery affects whaling in another part of the world. From equation (18) it is immediate that harvest will increase in country i following a decrease in its competitors' stocks. The simple reason for this is that a decreasing stock in competitor countries lowers total supply of j_i which increases the price of resource j_i (because of the love of variety). As we have seen in earlier sections, a price increase leads to increased harvest which lowers the stock. At the same time harvest will decrease in countries having complementary resources to j_i, leading to an increase in $X_{j \neq j_i}$. This, by (18), will increase H_i^* even more.

One detrimental such case is depicted in Figure 4. There we have two countries with the same resource j. There are also other countries who have other resources than j but for brevity we will not describe the dynamics there. We start in a steady state but then one of the countries having j is hit by a natural disaster which reduces its stock in a way that eventually leads to collapse. We denote this country i. Then the price of good j goes up, which temporarily increases harvest also in the other country producing j. We denote this other country by i'. As $x_{i'}$ falls also $H^*_{i'}$ falls and eventually collapses to zero. Hence, a natural disaster in one part of the world can trigger a chain event of collapses in countries in other parts of the world who are exporting the same resource. It may be interesting to note that the increased harvesting in i' helps the stock in country i temporarily recover. However, once the stock in i' falls sufficiently they lower their harvest as well which increases world prices and hence drives stocks in both i and i' to collapse. This way trade creates a channel transforming natural disasters in one country into man-made disasters in competing countries creating contagion of collapse.[19]

5 Extension 2 – TFP increases in other countries

Next let us make the model slightly more abstract. From the harvesting function (2) it follows that, at any point in time, x_i^{β} is equivalent to a TFP factor in a production function that is linear in the amount of labor used. In the analysis here we again, for analytical convenience, assume a continuum of countries. Each country is a negligible part of the total trade system and the actions of a single country will not affecountrct the production and harvesting decisions in other countries. Both of these assumptions imply that the paths of $\{x_{j\neq i}\}$ can be treated as independent of what happens in country i. The integral in (13) can then be treated as an exogenous factor. Defining

$$B \equiv (\theta A)^{\frac{1}{1-\theta}} \left[\int_0^J x_j^{\frac{\theta q}{\theta - q}\beta} dj \right]^{\frac{1}{\theta-1}\frac{1-q}{q}}$$

the harvesting function in country i is

$$H_i^* = B x_i^{\frac{\theta}{\theta-q}\beta}. \tag{19}$$

An increase in B can thus be interpreted as an increase in the number of trading partners or an increase in productivity of existing trade partners. The other goods may be renewable as well, but they may also be any other type of manufacturing

[19] The model by Quaas & Requate (2013) also exhibits cascading collapse. In their as well as our settings the potential for collapse in the first place comes from the love of variety maintaining relatively high demand even as decreased stocks drive up the prices of a particular type of fish. The mechanism of contagion of collapse is, however, different. In our setting, as a resource in one country decreases, this increases demand for resources of the same type elsewhere triggering collapse of the resources there as well. In the setting of Quaas & Requate (2013), as availability of one type of fish decreases, this increases demand for other types of fish since the substitutability between different fish species is higher than the substitutability between fish and other types of goods. Hence, in their paper it is not the love of variety that drives contagion but rather that the marginal utility of fish is infinite when consumption is low.

good or commodity. We are interested in seeing how country i reacts (in terms of harvest, collapse and welfare) when production possibilities in the other countries change, as captured by changes in B. Our interpretation here is that an increase in B represents an increase in total factor productivity (TFP) in the other countries following, for instance, an increase in capital or technology for manufacturing. We will first analyze utility in steady-state and then discounted dynamic utility when going from one steady-state to the next.

In a steady-state, H_i^* from equation (19) equals f_i in equation (9). The steady-state stock is decreasing in B since an increase in B shifts the harvest function upwards as can be seen in (19). From Lemma 1 we know that steady-state flow utility is increasing in the steady-state value of N^*. The effects of changes in B on the steady-state harvest and flow utility will thus, as before, only depend on the biological growth function and the steady-state stock x_{ss}. An increase in B will result in an increase in steady-state harvest if and only if $x_{ss} > 1/2$ and result in an increase in steady-state flow utility if and only if $x_{ss} > \frac{1-\beta}{2-\beta}$. This is similar to the dynamics in Proposition 1 and can therefore be graphically depicted using Figure 1. Following a permanent shift in B, a new steady-state is reached. This new steady-state may have $x_i = 0$ if the change in B induces collapse. Note also that, if the TFP increase comes in the form of a temporary shock, the stock may collapse as well. For a given level of TFP there is a region of the stock which will yield collapse. This region can be reached either by a natural disaster to the own country or by a temporary and positive TFP shock in other countries. The latter increases harvest and may lower the stock in country i to the region where it cannot recover even if TFP goes back to the initial values in the other countries. In this sense a natural disaster and a positive TFP shock in other countries (if permanent or temporary) will have similar effects of increasing harvest and enhancing the risk of collapse.

What is the effect on discounted dynamic utility following a change in TFP in other countries? The harvesting effort is

$$N^* = Bx^{\frac{q}{\theta-q}\beta}$$

and since flow utility is increasing in induced effort (see Lemma 1), flow utility is increasing in both B and x. An increase in B will thus always have an immediate positive effect on flow utility. Over time the stock will decrease and the net effect on flow utility may be ambiguous. If an increase in B also leads to an increase in steady-state flow utility, the total effect is of course unambiguously positive. However, if instead the steady-state flow utility decreases, there will be a trade-off between the short run gain and long run loss. Considering small changes in B we can, again, compute the total discounted welfare effect using linearization (see appendix A.6 for details). This will represent the discounted flow utility when going from one steady-state to the next. Denote the initial level of B by B_0, let the implied steady-state be $x_i = x_{ss,0}$ and let the associated flow utility be $U_{ss,0}$. The value of B then changes to $B_0 + \Delta B$. Based on the harvest function (19) the linearized dynamics can be derived. One important difference here compared to before is that following the permanent change in B the resource stock x_i will go to a new steady-state value $x_{ss,1}$. Linearizing the flow utility around $x_{ss,0}$ an (approximate) expression for the discounted flow utility can be derived

$$\begin{aligned} V &= \int_{t=0}^{\infty} U(t) e^{-\rho t} dt \\ &\approx V_{TFP} \equiv \frac{1}{\rho} U_{ss,0} + \frac{\theta}{\rho} U_{ss,0} \frac{\rho - \left[\frac{1-\beta}{2-\beta} - x_{ss,0}\right] k / (2-\beta)}{\rho - \left(f'(x_{ss,0}) - \frac{\theta}{\theta - q} \beta \frac{f(x_{ss,0})}{x_{ss,0}}\right)} \frac{\Delta B}{B_0}. \end{aligned}$$

The first term is equal to the flow utility that would result from remaining in the initial steady-state forever. The second term represents the total discounted welfare effects of the change in B. The denominator is positive whenever the initial steady-state is stable. The sign of the welfare effect of increasing B therefore is the same as the sign of

$$\rho - \left[\frac{1-\beta}{2-\beta} - x_{ss,0}\right] k / (2-\beta) \tag{20}$$

which immediately leads to the following proposition.

Proposition 4 *V_{TFP} is increasing in ΔB if and only if the expression in (20) is positive.*

A larger ρ gives more weight to the short-run relative to long-run effects. This means that positive TFP shocks to one's trade partners increases one's own welfare in a larger range of cases. This simply reflects that the higher TFP increases welfare in the short run through the increased price of one's resource while the negative effects on the stocks happen gradually. However, if $\rho \to 0$, the sign of the welfare effect is the same as $x_{ss} - \frac{1-\beta}{2-\beta}$. This captures that, when discounting goes to zero, the total effect is completely determined by the resulting change in steady-state flow utility. The cutoff for when TFP shocks to one's partners are good for oneself is hence the same as when global natural disasters are preferred over idiosyncratic ones (in Proposition 3) and the same as when trade reduces steady-state welfare (in Proposition 1) and as is depicted by the vertical line in Figure 2.

As before, we need to qualify these results – they hold only under sufficiently small TFP shocks. Roughly speaking, in terms of Figure 2, if $x_{ss,0}$ is just below $\frac{1-\beta}{2-\beta}$, a very large permanent reduction to the trade partners' TFP would imply a new $x_{ss,1}$ which yields a lower U_{ss}. However, if $x_{ss,0}$ is sufficiently small (i.e. when trade is very extensive) then also very large reductions in the trade partners' TFP would be good as $U_{ss}(x_{ss,0}) < U_{ss}(x_{ss,1})$ for any $x_{ss,1} > x_{ss,0}$.

6 Empirical relevance and theoretical robustness

This section will first calibrate the model parameters to existing fisheries to empirically evaluate the relevance of the theoretical predictions of the model. Then, it will briefly describe how relaxing various model assumptions would affect the results. The predictions of the model relate to how the extent of trade openness (in conjunction with other parameters) affects welfare in steady state and following various disasters. However, what the model shows is that the results can be expressed in terms of stocks (which are induced by trade openness). This is convenient, since stock and harvest data are readily available and enable us to evaluate the predictions of our model with less requirements on other parameters.[20] Note also that, like any calibration of a theoretical model, this will not be a causal test of the model itself. Rather, it will evaluate the applicability of various model results given that one believes the main assumptions (of variety gains and open-access-like conditions) are a relevant description of reality. We spend part of this section in providing further evidence of the prevalence of open-access-like conditions.

6.1 Welfare effects of trade and disasters

The welfare consequences of trade and disasters in our model depend on parameter values. Firstly, the parameter β – which represents the elasticity of the harvest with respect to the stock level – was assumed to be below 1. This is what makes welfare humpshaped in trade openness. Secondly, β also determines the stock level below which more extensive trade reduces welfare, and below which global shocks are preferred over local and below which positive TFP shocks to one's trade partners reduce the own welfare.[21] From Propositions 1, 3 and 4 we have that the critical

[20] We will use the observed stocks and assume they are in steady state. This is conservative as long as stocks are either decreasing or constant. Froese et al. (2012) show that few, if any, stocks are increasing.

[21] In the analysis here we assume that the discount rate is small enough not to matter. Since we only use the discount rate for welfare analysis, we should not necessarily calibrate the discount rate based on, e.g., market interest rates. Arguments similar to those put forward in the Stern review (Stern 2007) would instead advocate a discount rate close to zero.

cutoff value in terms of the resource stock is

$$x_{cutoff} \equiv \frac{1-\beta}{2-\beta}.$$

Below this stock level trade creates the adverse effects in our model. Note that x is normalized to represent the share of the maximum stock. We will now evaluate the relevance of these results by using data from fisheries around the world.

Table 1: Harvest elasticities and threshold stocks

Species	Reference	β estimate	x_{cutoff}
Yellowfin Tuna	Grafton et al (2007)	0.23	44%
Big-eye Tuna	Grafton et al (2007)	0.6	29%
Orange Roughy	Grafton et al (2007)	0.4	38%
Baltic Cod	Kronbak (2005)	0.64	26%
North Sea Herring	Bjørndal & Conrad (1987)	0.56	31%
North East Atlantic Cod	Eide et al (2003)	0.42	37%

Table 1 presents the estimated β for a number of fisheries and the implied x_{cutoff}. As can be seen, β ranges from 0.23 to 0.64 which yields support to our initial assumption of $\beta < 1$.[22] These levels of β imply an x_{cutoff} of between 44 and 26 percent. That is, if the stock is below 44 percent of its maximum for Yellow fin Tuna or below 26 percent of its maximum for Baltic Cod, then they would be small enough for trade to constitute a problem and small enough so that national disasters are more problematic than global. This strongly suggests that many fisheries *could* in principle be susceptible to the described problems if trade is extensive enough. But is this really the case? Are actual stocks low enough for x_{cutoff} to be relevant?

As a back of the envelope exercise we can compare these values of x_{cutoff} to the stock levels in actual fisheries. To be conservative (following Table 1) we use $x_{cutoff} = 25\%$. With a logistic growth function (see later in this section for a relaxation of this assumption) we get the stock at maximum sustainable yield to be

$$x_{MSY} \equiv \arg\max f(x) = 50\%.$$

[22] Additional estimates for North East Atlantic Cod are $\beta = 0.22$ for longline fisheries and $\beta = 0.58$ for trawlers (Richter et al, 2011) and β has been estimated to have been between 0.74 and 0.9 for the period 1950-1978 (Hannesson, 1983).

Hence, our conservative value of x_{cutoff} can be expressed as

$$x_{cutoff} = 0.5 * x_{MSY}.$$

This happens to coincide with the standard category used in marine research for when a fishery is overexploited. I.e. a fishery is overexploited if the current stock is below 50 percent of x_{MSY} (e.g. Froese et al., 2012; Hilborn et al., 2003). If, furthermore, the stock is below 10 percent of x_{MSY} then it is categorized as collapsed. Now, Froese et al. (2012, Figure 7) find that 58 percent of the major fisheries are in such a state.[23] Hence, a large share of global fisheries seem to be in a state at which trade reduces welfare and where idiosyncratic shocks are particularly problematic and where increased TFP among trade one's partners reduces welfare. Note that a higher (and probably more realistic) value of x_{cutoff} would have implied a larger share being in this bad state.

6.2 The risk of collapse

The possibility of collapse under idiosyncratic disasters depends on two things. Firstly, the values of β, θ and q together determine whether collapse is possible. Secondly, the level of the stock determines whether one is close to the region leading to collapse. We evaluate these two prerequisites one at a time. From Proposition 2 we get that if

$$\beta < \beta_{\text{col}} \equiv \frac{\theta - q}{\theta}$$

then idiosyncratic shocks could induce collapse. Now, it is hard to pin down θ without more detailed micromodeling of how the harvesting costs depend on effort and on how flexible labor is in moving from other sectors into harvesting of renewable resources. However, for the purpose here, we can suppose it equals 1 so costs are linear in work hours. While this is a bit unrealistic (typically one would think costs would be a convex function of effort) it is the most conservative value we can use since it implies the least risk of bio-economic collapse. From Quaas & Requate (2013) we get an estimate of q to be around 0.4 for fish.[24] With our conservative value of θ this implies

$$\beta_{\text{col}} \simeq 0.6.$$

[23] Similar numbers can derived from Hilborn et al (2003, Figure 6) who report the ratio between current fishery yields and their historical maxima for the 495 major fisheries of the world. From Quaas et al (2012, Table A1) one can also see that Eastern Baltic Sea Cod, North Sea Cod and Central Baltic Herring are specific fish stocks below $x_{cutoff} = 25\%$ (all these fish stocks are classified as de-facto open access). They report also some other stocks which are above but close to x_{cutoff}.

[24] More precisely, they estimate the elasticity of substitution (σ) between salmon and crustaceans to be 1.66. In our setting this corresponds to $q = (\sigma - 1)/\sigma \simeq 0.4$.

From Table 1 this seems to be the case for many fisheries since they have a β at or below this level. Hence, it seems likely that many fisheries have the characteristics enabling collapse.

As mentioned in the introduction, many fisheries (and other renewable resources) have collapsed historically. But are today's fisheries at such low stock levels to imply any idiosyncratic disaster will lead to collapse? The cutoff of this is (from Section 3)

$$x_{\text{col}} \equiv \frac{(\theta - q) - \beta\theta}{2(\theta - q) - \beta\theta}.$$

Using a reasonable value of $\beta = 0.5$ (see Table 1), $q = 0.4$ from Quaas & Requate (2013) and the conservative $\theta = 1$ (this is conservative here too since x_{col} is increasing in θ) we get the cutoff level of the stock to be

$$x_{\text{col}} \simeq 14\%.$$

With a logistic function this implies harvest to be at 48 percent of maximum sustainable yield.[25] From Hilborn et al. (2003, Figure 6) we then get that around 22 percent of the world's major fisheries are under this level implying small idiosyncratic shocks can lead to collapse.[26] It may be interesting to note that with the conservative value of $\theta = 1$ there would be no collapse under a global disaster. For a global disaster to cause collapse it is necessary that $\theta > 1$. While this seems reasonable, we cannot say something quantitative without having an actual estimate.

6.3 Prevalence of open-access-like conditions

Now, it is hard to say which of the fisheries included here are subject to open access-like conditions and which have more first-best-like management. To the best of our knowledge, there is no over-arching description summarizing which stocks belong to which category. As Hilborn et al. (2003) describe, most fisheries were accessible to fishermen from many countries with no clear coordination up until the 1970:s. After this coastal zones were established implying that individual countries could in principle regulate the harvest. However, many fish species swim across these borders (e.g.

[25] I.e. $f(0.14) \simeq 0.48 * f(0.5)$.

[26] To get this result we note from Froese et al. (2012, Table 2) that if current harvest is at 48 percent of the maximum sustainable yield then this corresponds to current harvest being roughly 30 percent of maximum historical catch. We get this by noting that 48 percent of MSY is in the middle of the interval between a stock being collapsed and overexploited. Assuming a linear relationship we then get that the middle of the interval between collapse and overexploitation of $c/c_{\max}$ is 30 percent. $c/c_{\max}$ is the measure used in Figure 6 of Hilborn et al. (2003). From that figure one can see that around 22 percent of the major fisheries are at or below this level.

in the Baltic sea and Lake Victoria) which, through competition between countries, implies open-access-like conditions (FAO, 2010). It is estimated that around a third of the global ocean capture fishery harvests come from such conditions (Munro et al., 2004). Apart from this problem, in most cases countries created de-facto open access for fishermen within the country leaving the problem unresolved (Hilborn et al., 2003). Over time formal regulation improved but still today enforcement is a large problem.

However, even without knowing which fisheries do display open access, it seems implausible that a stock level well below that of maximum sustainable yield, as reported for 60% of the stocks, could ever be the result of anything close to first best. The results presented above are clearly indicative of open access conditions *or* other market failures. What is important for the applicability of our model is not open access as such but rather whether the low stock levels are driven by a market imperfection inducing myopic behavior among harvesters. Note also that fully myopic behavior is not necessary for the results – high discount rates are sufficient (Quaas et al., 2013). Quaas et al. (2012) show that the returns of letting fish stocks recover would be comparable to getting a market interest rate of 10-200%. Hence, de-facto discount rates are very high in many cases.

So what other market failures may lead to myopic behavior? One possibility is that corrupt officials look the other way when it comes to overfishing or illegal vessels. This may induce agents and firms to harvest rapidly in order to avoid the risk of a new official being more strict. In practice corruption is perceived as a significant problem in fisheries in the Pacific Islands region (Hanich & Tsamenyi, 2009). There are proven cases of corruption in issuing of fishing licenses, access agreements and monitoring and inspection of vessel logbooks (ibid).[27]

Alternatively, politicians deciding on quotas may simply maximize current employment, revenues or the share of revenues they get as bribes in the resource sector (either because they want to improve re-election probabilities or because they want to use the opportunity of attaining private rents while in office). Or, when politicians cannot commit to future agreements, they may sell the extraction rights temporarily. Not knowing whether the deal will hold in the future, harvesters may then simply maximize current yield.[28] A much debated case is that of the fishing agreement

[27] The use of other renewable resources are also affected by corruption and lack of compliance to regulation. According to the World Bank (2006) a large share of logging is estimated to be illegal. Most notably, the shares in Cambodia, Bolivia, Indonesia and Papua New Guinea are 90%, 80%, 70-80% and 70% respectively (ibid, Table 2.1). The share of illegal logging is highly correlated with measures of corruption (ibid, Figure 2.1).

[28] One can of course also imagine behavioral constraints whereby agents do not understand fully the dynamic nature of the resource.

between the EU and Morocco, giving European fishing fleets access to the fishing waters outside Western Sahara. This is controversial since the UN does not recognise Morocco as having sovereignty over Western Sahara.[29] If Moroccan politicians fear losing control over Western Sahara in the future, they may as well sell the rights, with few constraints, already today. EU fishermen, may then, fearing not having the right to harvest these waters in the future, simply take up as much as possible. There is also a debate whether other African countries (e.g Mauretania) selling fishing rights has led to overfishing.[30] Note that too generous quotas can lead to collapse results as in our model. In steady state the stock growth will equal the quota. If then, the quota is not stock-contingent in the short run, a disaster will lead to the quota not binding (since individually optimal harvest is below the quota anyway) and hence to slow recovery.

It is hard to verify, yet seems plausible, that the lion share of market imperfections in fisheries come from either open access, political shortsightedness, corruption or too generous quotas. Perhaps the main market imperfection which is not well represented by our model is if the low stocks are due to environmental externalities rather than irresponsible harvesting.

6.4 Robustness to functional forms

There are many realistic extensions one could add to the model. We will discuss a few here. One way of extending the model would be to assume a different biological growth function than the logistic by allowing for the resource to have depensation characteristics. Depensation essentially means that biological recovery is slower for low stock levels. In terms of Figure 1 that would imply $f(x)$ is convex near $x = 0$. We have fully solved the model with a more general growth function which allows for depensation and the results presented about the negative effects of trade are enhanced by such an addition. The reason is that when $f(x)$ is convex for small x then the biological growth function lies below the harvesting function for a wider range of stocks which enables collapse for larger x, for smaller J and for larger β. In a survey article Liermann & Hilborn (2001) find evidence for depensation for various mammals (antelopes and monkeys), fish (e.g. Lake Malawi chichilds, Salmon and Bass), insects, plants and trees (and even humans). Now, apart from depensation there can also be critical depensation or so called Allee-effects (due to Allee, 1938). In such cases there is a lower threshold of the population below which the growth is negative – the stock can collapse without interference of man.

[29] See EU (2013a and 2013b) for a description of the agreement and BBC (2011) and The New York Times (2012) for a description of some of the controversy surrounding the agreement.

[30] See e.g. Wall Street Journal July 23rd, 2007 "Global Fishing Trade Depletes African Waters".

Having growth functions exhibiting critical depensation would of course aggravate any negative effects we find even more. Using data for a large number of fish species Keith & Hutchings (2012) estimate the number of recruits per spawner (essentially $f(x)/x$) for different levels of the population. They find that in at least 20 percent of the fish species, many of them important commercially, there is depensation (for instance, various species of Tuna and Sardines) and that, for instance, cod exhibits critical depensation. To overthrow the results that trade can decrease welfare one essentially has to assume $\beta = 1$ and, at the same time, that there is no depensation. This seems like a rather unrealistic combination of harvesting and biological growth function.

Another realistic extension would be to assume that harvest is a concave function of effort – e.g., use $H = x^{\beta} N^{\alpha}$ where $\alpha < 1$. This would be more in line with a standard economic production function and also has empirical support (e.g., Diekert, 2013). Under such a specification, on one hand, harvesting is attenuated when effort is high. On the other hand harvesting can be kept rather high even with a low effort N. Since the negative effects described in his paper mainly occur when the stock is low, the latter effect is more important. While it does not change x_{cutoff} it *does* imply that collapse can occur for a broader range of β values.[31]

7 Concluding remarks

This paper has explored a mechanism through which trade may be harmful to countries with open access renewable resources. Essentially, when property rights are not defined properly (or when other market failures, such as corruption or political shortsightedness lead to myopic behavior), the individual harvester does not take the future into account when harvesting. By introducing trade, the individual gets access to a broader variety of goods, which in itself increases welfare. However, when the value of the harvest increases as consumers get more variety, the individual is willing to exert more effort to increase income. When taken to the aggregate level, overharvesting increases which implies welfare is a hump-shaped function of trade openness.

The dynamics of open access also reverse the result that trade normally expedites recovery of countries hit by disasters. When there is open access, recovery is slower and hence economic repercussions following natural disasters are exacerbated by trade which also facilitates bio-economic collapse following small idiosyncratic shocks.

It was also shown that trade opens a channel by which a natural disaster in one

[31] In particular, assuming that the decreasing returns to effort apply to individual agents, there can be collapse following global shocks if $\beta < \frac{\theta - \alpha}{\theta}$ and following idiosyncratic shocks if $\beta < \frac{\theta - \alpha q}{\theta}$.

country can spill over to a man-made disaster in another country selling the same type of resource. When a disaster occurs in one country the world price of their good goes up which increases harvesting in competitor countries, potentially leading to cascading collapses of resources within the same category.

Finally, we generalized the model to account for a case where the trading partners are selling not a renewable resource but, rather, some manufactured goods such as shoes, tables or cars. Here we find that positive TFP shocks to one's trade partners can cause collapse to the renewable resource and may be welfare decreasing to a country if trade is extensive.

A large share of fisheries, forests and wildlife are essentially open access either due to property rights (or harvesting quotas) not existing or due to lack of enforcement leading to poaching, illegal forestry and illegal fishing. Others display political shortsightedness. The calibration of our model suggests that around 60 percent of the major fisheries in the world have a sufficiently low stock so that the extent of trade can be expected to be beyond the point where it starts to decrease welfare. These low levels also imply that trade indirectly enhances shocks in a manner implying a global disaster would actually be preferred over a local disaster. Furthermore, the calibration suggests around one in five fisheries are at such a low stock level so that any local negative shock could lead to bio-economic collapse.

A Derivations and proofs

A.1 Derivation of equations (6) (7)

Based on (1) and (3), the Lagrangian of the utility maximization problem facing the representative household in country i is

$$\mathcal{L} = \left(\int_0^J (c_i(j))^q \, dj \right)^{\frac{1}{q}} - AN_i^{\theta} + \lambda_i \left[p(i) N_i x_i^{\beta} - \int_0^J p(j) c_i(j) dj \right].$$

To simplify the notation, let

$$c_i \equiv \left(\int_0^J (c_i(j))^q \, dj \right)^{\frac{1}{q}}. \tag{21}$$

and

$$\tilde{p} \equiv \left(\int_0^J p(j)^{\frac{q}{q-1}} dj \right)^{\frac{q-1}{q}}. \tag{22}$$

Differentiating the Lagrangian with respect to the choice variables $\{c_i(j)\}$ and N_i delivers the first-order conditions

$$c_i(j) : \lambda_i p(j) = \left(\frac{c_i}{c_i(j)}\right)^{1-q}$$
$$N_i : \lambda_i p(i) x_i^\beta = \theta A N_i^{\theta-1}.$$

The first-order condition with respect to $c_i(j)$ can be rewritten as

$$c_i(j) = (\lambda_i p(j))^{\frac{1}{q-1}} c_i.$$

The consumption aggregate c_i is

$$c_i = \left(\int_0^J c_i(j)^q dj\right)^{\frac{1}{q}} = \lambda_i^{\frac{1}{q-1}} c_i \left(\int_0^J p(j)^{\frac{q}{q-1}} dj\right)^{\frac{1}{q}}$$

implying that

$$\lambda_i = \frac{1}{\tilde{p}}.$$

Substituting this in the first-order condition with respect to N_i yields

$$\theta A N_i^{\theta-1} = \frac{p(i)}{\tilde{p}} x_i^\beta. \tag{23}$$

The budget constraint (3) can now be rewritten as follows

$$p(i) N_i x_i^\beta = \int_0^J p(j) c_i(j) dj = \int_0^J p(j) \left(\frac{p(j)}{p}\right)^{\frac{1}{q-1}} c_i dj = \{(22)\} = \tilde{p} c_i$$

implying that

$$c_i = \frac{p(i)}{\tilde{p}} N_i x_i^\beta = \theta A N_i^\theta.$$

Combining this with (23) delivers equation (6)

$$U_i = c_i - A N_i^\theta = \theta A N_i^\theta - A N_i^\theta = (\theta - 1) A N_i^\theta.$$

The resource constraint for the good harvested in country i is

$$N_i x_i^\beta = \int_0^J c_j(i) dj = \left(\frac{p(i)}{\tilde{p}}\right)^{\frac{1}{q-1}} \int_0^J c_j dj \Rightarrow \frac{p(i)}{p(i')} = \left(\frac{N_i x_i^\beta}{N_{i'} x_{i'}^\beta}\right)^{q-1}. \tag{24}$$

From (23) we have that

$$N_i x_i^\beta = \left(\frac{1}{\theta A}\right)^{\frac{1}{\theta-1}} \left(\frac{p(i)}{\tilde{p}}\right)^{\frac{1}{\theta-1}} x_i^{\beta\frac{\theta}{\theta-1}}$$

giving

$$\frac{N_i x_i^\beta}{N_{i'} x_{i'}^\beta} = \left(\frac{p(i)}{p(i')}\right)^{\frac{1}{\theta-1}} \left(\frac{x_i}{x_{i'}}\right)^{\beta\frac{\theta}{\theta-1}} = \left(\frac{N_i x_i^\beta}{N_{i'} x_{i'}^\beta}\right)^{\frac{q-1}{\theta-1}} \left(\frac{x_i}{x_{i'}}\right)^{\beta\frac{\theta}{\theta-1}}$$

$$\Rightarrow \frac{N_i x_i^\beta}{N_{i'} x_{i'}^\beta} = \left(\frac{x_i}{x_{i'}}\right)^{\beta\frac{\theta}{\theta-q}}. \tag{25}$$

Using (24), the price of the good harvested in country i' can now be written

$$p(i') = \left(\frac{N_{i'} x_{i'}^\beta}{N_i x_i^\beta}\right)^{q-1} p(i) = \{(25)\} = \left(\frac{x_{i'}}{x_i}\right)^{\beta(q-1)\frac{\theta}{\theta-q}} p(i) \tag{26}$$

and the definition of the price index (22) gives equation (5)

$$\tilde{p} = \left(\int_0^J p(i')^{\frac{q}{q-1}} di'\right)^{\frac{q-1}{q}} = \left(\int_0^J \left(\frac{x_{i'}}{x_i}\right)^{\beta\frac{q\theta}{\theta-q}} p(i)^{\frac{q}{q-1}} di'\right)^{\frac{q-1}{q}}$$

$$= p(i) \left(\frac{\int_0^J x_{i'}^{\beta\frac{q\theta}{\theta-q}} di'}{x_i^{\beta\frac{q\theta}{\theta-q}}}\right)^{\frac{q-1}{q}} \Rightarrow \frac{p(i)}{\tilde{p}} = \left(\frac{\int_0^J x_{i'}^{\beta\frac{q\theta}{\theta-q}} di'}{x_i^{\beta\frac{q\theta}{\theta-q}}}\right)^{\frac{1-q}{q}}.$$

Substituting this in (23) and rearranging gives equation (7) where the * indicates an equilibrium

$$N_i^* = (\theta A)^{\frac{1}{1-\theta}} \left(\frac{p(i)}{p}\right)^{\frac{1}{\theta-1}} x_i^{\beta\frac{1}{\theta-1}} = (\theta A)^{\frac{1}{1-\theta}} \left[\frac{\int_0^J x_{i'}^{\beta\frac{q\theta}{\theta-q}} di'}{x_i^{\beta\frac{q\theta}{\theta-q}}}\right]^{\frac{1-q}{q}\frac{1}{\theta-1}} x_i^{\beta\frac{1}{\theta-1}}.$$

A.2 Proof of Proposition 1

A steady-state x_{ss} is characterized by

$$f(x_{ss}) = H(x_{ss}, J).$$

Treating x_{ss} as a function of J, the steady-state condition can be differentiated with respect to J

$$f'(x_{ss}) = H_x(X_{ss}, J)\frac{dx_{ss}}{dJ} + H_J(x_{ss}, J)$$

implying

$$\frac{dx_{ss}}{dJ} = \frac{H_J(x_{ss}, J)}{f'(x_{ss}) - H_x(x_{ss}, J)} \tag{27}$$

where subscripts denote partial derivatives. The numerator is positive while the denominator is negative for any stable steady state. This shows that the steady-state stock is decreasing in J which concludes the first part of point 1. Since harvest equals growth in steady-state and the steady-state stock decreases in J we can immediately conclude that steady-state harvest must be increasing in J whenever $f'(x_{ss}) > 0$ and vice versa. This can also be shown by fully differentiating steady-state harvest with respect to J

$$\begin{aligned}\frac{d}{dJ}H(x_{ss}, J) &= H_x(x_{ss}, J)\frac{dx_{ss}}{dJ} + H_J(x_{ss}, J)\\ &= \{(27)\} = H_J(x_{ss}, J)\frac{f'(x_{ss})}{f'(x_{ss}) - H_x(x_{ss}, J)}.\end{aligned}$$

Given that $H_J > 0$ and that the denominator is negative in all stable steady states, the conclusion follows. For the growth function (9) this gives the condition

$$f'(x) < 0 \Leftrightarrow x > \frac{1}{2}$$

which concludes the second part of point 1.

Equation (6) tells us that flow utility is increasing in induced effort N. In steady-state $N_{ss} = \frac{f(x_{ss})}{x_{ss}^{\beta}}$. Given that x_{ss} is decreasing in J, steady-state flow utility is increasing in J whenever $\frac{f(x_{ss})}{x_{ss}^{\beta}}$ is decreasing in x_{ss}. Differentiating the ratio yields

$$\frac{d}{dx}\frac{f(x)}{x^{\beta}} = \frac{f'(x)}{x^{\beta}} - \beta\frac{f(x)}{x^{\beta+1}} = \frac{1}{x^{\beta}}\left(f'(x) - \beta\frac{f(x)}{x}\right).$$

We can also derive the same result starting from the division of the aggregate effect into a stock and a variety effect given in equation (12). Using the partial derivatives of the expressions from (10) and (11)

$$H_J = \frac{1}{1-\theta}\frac{1-q}{q}\frac{H}{J},\ H_x = \frac{\beta\theta}{\theta-1}\frac{H}{x},\ U_J = \frac{\theta}{\theta-1}\frac{1-q}{q}\frac{U}{J},\ U_x = \frac{\beta\theta}{\theta-1}\frac{U}{x},$$

the full derivative of flow utility with respect to J is

$$\frac{dU_{ss}}{dJ} = U_J(x_{ss}, J) + U_x(x_{ss})\frac{dx_{ss}}{dJ} = \frac{\theta}{\theta-1}\frac{1-q}{q}\frac{U_{ss}}{J} + \beta\frac{\theta}{\theta-1}\frac{U_{ss}}{x_{ss}}\frac{dx_{ss}}{dJ}$$
$$= \{(27)\} = \ldots = \frac{\theta}{\theta-1}\frac{1-q}{q}\frac{U_{ss}}{J}\frac{f'(x_{ss}) - \beta\frac{H_{ss}}{x_{ss}}}{f'(x_{ss}) - H_x(x_{ss}, J)}.$$

Combining the steady-state condition $H_{ss} = f(x_{ss})$ and using that the denominator is negative we can, again, draw the conclusion that steady-state flow utility is increasing in J if and only if $f'(x_{ss}) - \beta\frac{f(x_{ss})}{x_{ss}}$ is negative. Using the specific growth function (9), this corresponds to

$$f'(x_{ss}) - \beta\frac{f(x_{ss})}{x_{ss}} < 0 \Leftrightarrow x_{ss} > \frac{1-\beta}{2-\beta}$$

which concludes point 2.

We will now consider the risk of collapse. Let

$$h(x, J) = H(x, J) - f(x) = (\theta A)^{\frac{1}{\theta-1}} J^{\frac{1}{\theta-1}\frac{1-q}{q}} x^{\beta\frac{\theta}{\theta-1}} - kx(1-x)$$

denote the net harvest function. The stock grows if and only if $h < 0$. We only consider $x \geq 0$ and for $x > 1$ $h(x, J) > 0$. Since $h(0, J) = 0$, $x = 0$ always constitutes a steady-state. There is a risk of collapse for a given J if the steady-state with $x = 0$ is stable. That is, if there is an $\epsilon > 0$ such that $h(x, J) > 0$ for all $x \in (0, \epsilon)$. The harvest function H is, for a given J, $x^{\beta\frac{\theta}{\theta-1}}$ times a constant. On the other hand. for small x, $f(x)$ behaves like kx. This implies that $x = 0$ is locally stable if $\beta < \frac{\theta-1}{\theta}$. There can be at most two additional steady-states. This can be seen by rewriting the net harvest function as

$$h(x, J) = (\theta A)^{\frac{1}{1-\theta}} J^{\frac{1}{\theta-1}\frac{1-q}{q}} x^{\beta\frac{\theta}{\theta-1}} \tilde{h}(x, J)$$

where

$$\tilde{h} = 1 - Dx^{1-\beta\frac{\theta}{\theta-1}}(1-x) \text{ and } D = \frac{k}{(\theta A)^{\frac{1}{1-\theta}} J^{\frac{1}{\theta-1}\frac{1-q}{q}}}.$$

D is decreasing in J. For any $x \in (0, 1)$, the sign of h is the same as that of $\tilde{h}$ and a steady-state, for a given J, corresponds to an x such that $\tilde{h}(x, J) = 0$. The dynamic behavior of the system can thus be determined by considering the sign of $\tilde{h}$ for $x \in (0, 1)$. Around the end points of the interval of interest we have that

$$\tilde{h}(1, J) = 1 \text{ and } \lim_{x\to 0}\tilde{h}(x, J) = \begin{cases} 1 & \text{if } \beta < \frac{\theta-1}{\theta} \\ 1-D & \text{if } \beta = \frac{\theta-1}{\theta} \\ -\infty & \text{if } \beta > \frac{\theta-1}{\theta} \end{cases}.$$

The partial derivative of $\tilde{h}$ with respect to x is

$$\begin{aligned}\tilde{h}_x(x,J) &= -D\left[\left(1-\beta\frac{\theta}{\theta-1}\right)-\left(2-\beta\frac{\theta}{\theta-1}\right)x\right]x^{-\beta\frac{\theta}{\theta-1}} \\ &= -D\left[\left(1-\beta\frac{\theta}{\theta-1}\right)(1-x)-x\right]x^{-\beta\frac{\theta}{\theta-1}}.\end{aligned}$$

For $\beta > \frac{\theta-1}{\theta}$, $\tilde{h}_x > 0$ for all $x \in (0,1)$. Since $\tilde{h}$ is negative for small x while $\tilde{h}(1,J) > 0$ there is exactly one steady-state with $x \in (0,1)$ and it is stable. This concludes the only if part of point 3.

For $\beta = \frac{\theta-1}{\theta}$, the net harvest function h can be simplified to

$$h(x,J) = (\theta A)^{\frac{1}{\theta-1}}\, J^{\frac{1}{\theta-1}\frac{1-q}{q}}\, x\,(1-D+Dx)\,.$$

If $D \leq 1$, this is positive for all $x > 0$ and $x = 0$ is the only steady-state which implies collapse. If $D > 1$, there is a unique steady-state with $x > 0$, it is given by $x = \frac{D-1}{D} \in (0,1)$ and it is stable. Since D is strictly decreasing in J, the first case is relevant when J is large and the second case is relevant when J is small. Within the second case, the steady-state value of x is decreasing in J. This concludes the if statement with regard to the equality of $\beta = \frac{\theta-1}{\theta}$.

For $\beta < \frac{\theta-1}{\theta}$, $x = 0$ is stable (for any $J > 0$) implying that collapse is always a possible outcome. Letting $\tilde{x} \equiv \frac{\theta-1-\beta\theta}{2(\theta-1)-\beta\theta}$, $\tilde{h}_x(x,J)$ is negative for $x \in (0,\tilde{x})$ and positive for $x > \tilde{x}$. This allows for three possible cases. Firstly, if $\tilde{h}\,(\tilde{x},J) > 0$, $x = 0$ is the only steady-state. Secondly, if $\tilde{h}\,(\tilde{x},J) = 0$, $x = \tilde{x}$ is the only steady-state with $x > 0$ and it is a saddle point. Thirdly, if $\tilde{h}\,(\tilde{x},J) < 0$, there are two steady-states with $x > 0$. There is one unstable steady-state with stock $x < \tilde{x}$ and one stable steady-state with $x > \tilde{x}$. Finally, since $\tilde{h}(\tilde{x},J)$ is increasing in J, a small J implies being in the third case with two steady-states (in addition to the steady-state at $x = 0$). As J increases, the two steady-states converges towards each other until the second case is reached where the two steady-states have converged to a saddle point. Further increases in J leads to the first case where there $x = 0$ is the only steady-state and there will be collapse regardless of the initial state x. This concludes the if statement of point 3 with strict inequality of $\beta < \frac{\theta-1}{\theta}$ which ends the proof.

A.3 Proof of Proposition 2

Point 1 follows from equation (26). Point 2 follows from equation (13) since harvest is increasing in the other countries' stocks. Point 3 follows from Point 2 since directly after the size shock harvest is higher under the idiosyncratic shock. Furthermore, if the stock would be of equal size under both shocks anywhere along the path back to steady state, then harvest will be higher at that point under an idiosyncratic shock. Point 4: A shock causes collapse if it decreases the stock enough to make $H_i > f(x_i)$ for the entire future. Since harvest is strictly larger for any stock $x_i < x_{ss}$ when the shock is idiosyncratic rather than symmetric, the range where collapse occurs is strictly larger under an idiosyncratic shock, implying the first statement of point 4. To see that the second statement of point 4 is true, rewrite (13), for given stocks in the other countries, as

$$H_i^* = G x_i^{\beta \frac{\theta}{\theta - q}}, \text{ where } G \equiv (\theta A)^{\frac{1}{1-\theta}} \left[\int_0^J x_j^{\beta \frac{\theta q}{\theta - q}} dj \right]^{\frac{1}{\theta-1} \frac{1-q}{q}}.$$

consider a situation where $\beta < \frac{\theta - 1}{\theta}$. As J increases, the stock in the stable steady-state with $x > 0$ decreases. Point 3 of Proposition 1 says that if J is increased above the level where the stock of the stable state is $x_{ss} = \frac{\theta - 1 - \beta\theta}{2(\theta - 1) - \beta\theta}$, the stock will always collapse. This can also be interpreted as that the harvest function with symmetric stocks is tangent to the biological growth function at that point. The harvest function following an idiosyncratic shock intersects the harvest function at the stable steady-state. Point 2 (of this Proposition) implies that the slope of the idiosyncratic harvest function is strictly lower compared to the slope of the symmetric harvest function. Continuity then implies the second statement in point 4 since there must be a J strictly smaller than the J such that $x_{ss} = \frac{\theta - 1 - \beta\theta}{2(\theta - 1) - \beta\theta}$ such that the implied steady-state is locally stable with respect to a symmetric shock but such that the harvest function following an idiosyncratic shock is higher than the biological growth function for all x below the steady-state.

A.4 Linearization with two groups of countries

We can write the dynamics of the system as

$$\begin{bmatrix} \dot{\check{x}}(t) \\ \dot{\hat{x}}(t) \end{bmatrix} = \begin{bmatrix} f(\check{x}(t)) - \check{H}(\check{x}(t), \hat{x}(t)) \\ f(\hat{x}(t)) - \hat{H}(\hat{x}(t), \check{x}(t)) \end{bmatrix}$$

with $\check{H}(\check{x}, \hat{x})$ and $\hat{H}(\hat{x}, \check{x})$ given by (14) and (15). Assume that $\check{x} = \hat{x} = x_{ss}$ is a steady-state of this system. In order to investigate the dynamics close to the steady-state we can linearize the system around the steady-state. The linearized system can be written

$$\begin{bmatrix} \dot{\check{x}}(t) \\ \dot{\hat{x}}(t) \end{bmatrix} \approx \Lambda \begin{bmatrix} \check{x}(t) - x_{ss} \\ \hat{x}(t) - x_{ss} \end{bmatrix}$$

where

$$\Lambda \equiv \begin{bmatrix} f'(x_{ss}) - \check{H}_{\check{x}}(x_{ss}, x_{ss}) & -\check{H}_{\hat{x}}(x_{ss}, x_{ss}) \\ -\hat{H}_{\check{x}}(x_{ss}, x_{ss}) & f'(x_{ss}) - \hat{H}_{\hat{x}}(x_{ss}, x_{ss}) \end{bmatrix}.$$

Differentiating $\check{H}$ and $\hat{H}$ delivers

$$\begin{aligned} \check{H}_{\check{x}}(x_{ss}, x_{ss}) &= H_{ss}\beta\frac{\theta}{\theta - q}\left[\frac{1-q}{\theta-1}\frac{\check{J}}{J} + 1\right]\frac{1}{x_{ss}} \\ \check{H}_{\hat{x}}(x_{ss}, x_{ss}) &= H_{ss}\beta\frac{\theta}{\theta - q}\frac{1-q}{\theta-1}\frac{\hat{J}}{J}\frac{1}{x_{ss}} \\ \hat{H}_{\check{x}}(x_{ss}, x_{ss}) &= H_{ss}\beta\frac{\theta}{\theta - q}\frac{1-q}{\theta-1}\frac{\check{J}}{J}\frac{1}{x_{ss}} \\ \hat{H}_{\hat{x}}(x_{ss}, x_{ss}) &= H_{ss}\beta\frac{\theta}{\theta - q}\left[\frac{1-q}{\theta-1}\frac{\hat{J}}{J} + 1\right]\frac{1}{x_{ss}} \end{aligned}$$

where H_{ss} is the steady-state value of $\check{H}$ and $\hat{H}$. Defining

$$\begin{aligned} \xi &\equiv f'(x_{ss}) - \beta\frac{\theta}{\theta - q}\frac{H_{ss}}{x_{ss}} \\ \check{\mu} &\equiv \beta\frac{\theta}{\theta - q}\frac{1-q}{\theta-1}\frac{\check{J}}{J}\frac{H_{ss}}{x_{ss}} \\ \hat{\mu} &\equiv \beta\frac{\theta}{\theta - q}\frac{1-q}{\theta-1}\frac{\hat{J}}{J}\frac{H_{ss}}{x_{ss}}, \end{aligned}$$

the matrix Λ is

$$\Lambda = \begin{bmatrix} \xi - \check{\mu} & -\hat{\mu} \\ -\check{\mu} & \xi - \hat{\mu} \end{bmatrix}.$$

Solving the equation $|\Lambda - \lambda I| = 0$ gives the eigenvalues

$$\lambda_1 = \left(\frac{x_{ss}f'(x_{ss})}{f(x_{ss})} - \beta\frac{\theta}{\theta - q}\right)\frac{H_{ss}}{x_{ss}} \text{ and } \lambda_2 = \left(\frac{x_{ss}f'(x_{ss})}{f(x_{ss})} - \beta\frac{\theta}{\theta - 1}\right)\frac{H_{ss}}{x_{ss}},$$

where we used that $H_{ss} = f(x_{ss})$, and the associated eigenvectors are

$$v_1 = \begin{bmatrix} 1 \\ -\frac{\check{J}}{\hat{J}} \end{bmatrix} \text{ and } v_2 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}.$$

The stability with respect to asymmetric shocks is thus determined by the sign of λ_1 while the stability with respect to symmetric shocks is determined by λ_2. We are here interested in considering small shocks where the system converges back to the steady-state. We thus assume that both eigenvalues are negative. Let

$$\Delta\check{x}(t) \equiv \check{x}(t) - x_{ss} \text{ and } \Delta\hat{x}(t) \equiv \hat{x}(t) - x_{ss}$$

denote deviations from the steady-state. Starting from some initial conditions $\Delta\check{x}(0) = \Delta\check{x}_0$ and $\Delta\hat{x}(0) = \Delta\hat{x}_0$, the paths of the state variables are given by

$$\begin{bmatrix} \Delta\check{x}(t) \\ \Delta\hat{x}(t) \end{bmatrix} = \eta_1 v_1 e^{\lambda_1 t} + \eta_2 v_2 e^{\lambda_2 t},$$

where η_1 and η_2 solves

$$\begin{bmatrix} \Delta\check{x}_0 \\ \Delta\hat{x}_0 \end{bmatrix} = \eta_1 v_1 + \eta_2 v_2 = \begin{bmatrix} \eta_1 + \eta_2 \\ -\frac{\check{J}}{\hat{J}}\eta_1 + \eta_2 \end{bmatrix} \Rightarrow \begin{cases} \eta_1 = \frac{\hat{J}}{J}\left(\check{x} - \hat{x}\right) \\ \eta_2 = \frac{\check{J}}{J}\check{x}_0 + \frac{\hat{J}}{J}\hat{x}_0 \end{cases}$$

This specifies the dynamics of the state variables following a small shock. The next step is to linearize the flow utility as a function of the state variables. Letting the flow utility in the steady-state be denoted by U_{ss}, flow utilities close to the steady-state can be approximated by

$$\begin{aligned} \check{U}(\Delta\check{x}, \Delta\hat{x}) &\approx U_{ss} + \check{u}_{\check{x}}\Delta\check{x} + \check{u}_{\hat{x}}\Delta\hat{x} \\ \hat{U}(\Delta\check{x}, \Delta\hat{x}) &\approx U_{ss} + \hat{u}_{\check{x}}\Delta\check{x} + \hat{u}_{\hat{x}}\Delta\hat{x} \end{aligned}$$

where

$$\check{u}_{\check{x}} = \frac{\partial\check{U}}{\partial\check{x}},\ \check{u}_{\hat{x}} = \frac{\partial\check{U}}{\partial\hat{x}},\ \hat{u}_{\check{x}} = \frac{\partial\hat{U}}{\partial\check{x}},\ \hat{u}_{\hat{x}} = \frac{\partial\hat{U}}{\partial\hat{x}}$$

are all partial derivatives evaluated at the steady-state. Using (6) and (7), the partial derivatives are

$$\begin{aligned} \check{u}_{\check{x}} &= U_{ss}\beta\frac{\theta q}{\theta - q}\left[\frac{\theta}{\theta - 1}\frac{1-q}{q}\frac{\check{J}}{J} + 1\right]\frac{1}{x_{ss}} \\ \check{u}_{\hat{x}} &= U_{ss}\beta\frac{\theta q}{\theta - q}\frac{\theta}{\theta - 1}\frac{1-q}{q}\frac{\hat{J}}{J}\frac{1}{x_{ss}} \\ \hat{u}_{\check{x}} &= U_{ss}\beta\frac{\theta q}{\theta - q}\frac{\theta}{\theta - 1}\frac{1-q}{q}\frac{\check{J}}{J}\frac{1}{x_{ss}} \\ \hat{u}_{\hat{x}} &= U_{ss}\beta\frac{\theta q}{\theta - q}\left[\frac{\theta}{\theta - 1}\frac{1-q}{q}\frac{\hat{J}}{J} + 1\right]\frac{1}{x_{ss}}. \end{aligned}$$

We can now compute the net value of the convergence back to the steady-state following a shock. Starting from (16)

$$\begin{aligned}
\check{V}\left(\Delta\check{x}_0, \Delta\hat{x}_0\right) \approx V_{disaster} &\equiv \int_0^\infty e^{-\rho t}\left(U_{ss} + \check{u}_{\check{x}}\Delta\check{x}(t) + \check{u}_{\hat{x}}\Delta\hat{x}(t)\right)dt \\
&= \int_0^\infty e^{-\rho t}U_{ss}dt + \int_0^\infty \check{u}_{\check{x}}\left(\eta_1 e^{(\lambda_1-\rho)t} + \eta_2 e^{(\lambda_2-\rho)t}\right)dt \\
&\quad + \int_0^\infty \check{u}_{\hat{x}}\left(-\frac{\check{J}}{\hat{J}}\eta_1 e^{(\lambda_1-\rho)t} + \eta_2 e^{(\lambda_2-\rho)t}\right)dt \\
&= \frac{1}{\rho}U_{ss} + \int_0^\infty \left(\eta_1\left(\check{u}_{\check{x}} - \check{u}_{\hat{x}}\frac{\check{J}}{\hat{J}}\right)e^{(\lambda_1-\rho)t} + \eta_2\left(\check{u}_{\check{x}} + \check{u}_{\hat{x}}\right)e^{(\lambda_2-\rho)t}\right)dt \\
&= \frac{1}{\rho}U_{ss} + \eta_1\frac{\check{u}_{\check{x}} - \check{u}_{\hat{x}}\frac{\check{J}}{\hat{J}}}{\rho-\lambda_1} + \eta_2\frac{\check{u}_{\check{x}} + \check{u}_{\hat{x}}}{\rho-\lambda_2} \\
&= \frac{1}{\rho}U_{ss} + \eta_1\frac{U_{ss}\beta\frac{\theta q}{\theta-q}\frac{1}{x_{ss}}}{\rho-\lambda_1} + \eta_2\frac{U_{ss}\beta\frac{\theta}{\theta-1}\frac{1}{x_{ss}}}{\rho-\lambda_2}
\end{aligned}$$

Substituting for η_1 and η_2, the linearized value can be written in two different forms

$$\begin{aligned}
V_{disaster} &= \frac{1}{\rho}U_{ss} + \frac{U_{ss}}{x_{ss}}\beta\left[\frac{\hat{J}}{J}\frac{\frac{\theta q}{\theta-q}}{\rho-\lambda_1} + \frac{\check{J}}{J}\frac{\frac{\theta}{\theta-1}}{\rho-\lambda_2}\right]\Delta\check{x}_0 \\
&\quad + \frac{U_{ss}}{x_{ss}}\frac{\hat{J}}{J}\beta\left[\frac{\frac{\theta}{\theta-1}}{\rho-\lambda_2} - \frac{\frac{\theta q}{\theta-q}}{\rho-\lambda_1}\right]\Delta\hat{x}_0 \\
&= \frac{1}{\rho}U_{ss} + \frac{U_{ss}}{x_{ss}}\beta\frac{\frac{\theta}{\theta-1}}{\rho-\lambda_2}\Delta\check{x}_0 \\
&\quad + \frac{U_{ss}}{x_{ss}}\frac{\hat{J}}{J}\beta\left[\frac{\frac{\theta}{\theta-1}}{\rho-\lambda_2} - \frac{\frac{\theta q}{\theta-q}}{\rho-\lambda_1}\right]\left(\Delta\hat{x}_0 - \Delta\check{x}_0\right).
\end{aligned}$$

In both of these versions the sign of the expression in the square bracket of the second term is important. From the first version of the expression it can be seen that the value of $V_{disaster}$ always is increasing in $\Delta\check{x}_0$ while the dependency on $\Delta\hat{x}_0$ is ambiguous. From the second version of the expression it can be seen that the $V_{disaster}$ is an ambiguous function of $\hat{J}$ since it only depends on the sign of the square bracket which is ambiguous. Substituting for the eigenvalues λ_1 and λ_2, the square bracket can be written

$$\frac{\beta\frac{\theta}{\theta-1}}{\rho-\lambda_2} - \frac{\beta\frac{\theta q}{\theta-q}}{\rho-\lambda_1} = \beta\frac{\theta^2}{\theta-1}\frac{1-q}{\theta-q}\frac{\rho - \left[\frac{x_{ss}f'(x_{ss})}{f(x_{ss})} - \beta\right]\frac{H_{ss}}{x_{ss}}}{\left(\rho-\lambda_1\right)\left(\rho-\lambda_2\right)}.$$

If this expression is negative, then $V_{disaster}$ is decreasing in $\Delta\hat{x}_0$. Furthermore, if this expression is negative, $V_{disaster}$ is decreasing in $\hat{J}$ if and only if $\Delta\check{x}_0 < \Delta\hat{x}_0$. This implies that when the expression is negative a country gains if other countries get shocks.

A.5 Deriving equation (18)

The utility function in country i is

$$U_i = \left[\sum_{j=1}^{J} c_i(j)^q\right]^{\frac{1}{q}} - AN_i^{\theta}.$$

The budget constraint in country i is

$$p(i)N_i x_i^{\beta} = \sum_{j=1}^{J} p(j)c_i(j).$$

The resource constraint for good j is

$$\sum_{i\in I} c_i(j) = \sum_{i\in I_j} N_i x_i^{\beta}.$$

Let

$$c_i \equiv \left[\sum_{j=1}^{J} c_i(j)^q\right]^{\frac{1}{q}}$$

and

$$\tilde{p} \equiv \left[\sum_{j=1}^{J} p(j)^{\frac{q}{q-1}}\right]^{\frac{q-1}{q}}.$$

The Lagrangian in country i is

$$\mathcal{L} = \left[\sum_{j=1}^{J} c_i(j)^q\right]^{\frac{1}{q}} - AN_i^{\theta} + \lambda_i\left[p(i)N_i x_i^{\beta} - \sum_{j=1}^{J} p(j)c_i(j)\right].$$

The first-order conditions are

$$c_i(j) : \left(\frac{c_i}{c_i(j)}\right)^{1-q} = \lambda_i p(j)$$
$$N_i : \lambda_i p(i) x_i^{\beta} = \theta A N_i^{\theta-1}.$$

The first-order condition with respect to $c_i(j)$ can be rewritten as

$$c_i(j) = (\lambda_i p(j))^{\frac{1}{q-1}} c_i.$$

The consumption aggregate is

$$c_i = [c_i(j)^q]^{\frac{1}{q}} = \lambda_i^{\frac{1}{q-1}} \left[\sum_{j=1}^{J} p(j)^{\frac{q}{q-1}} \right]^{\frac{1}{q}}$$

implying

$$\lambda_i = \frac{1}{\tilde{p}}.$$

Substituting this in the first-order condition with respect to N_i and rewriting delivers

$$N_i^* = (\theta A)^{\frac{1}{\theta-1}} \left(\frac{p(i)}{\tilde{p}} \right)^{\frac{1}{\theta-1}} x_i^{\beta \frac{1}{\theta-1}}.$$

Total supply of good j is

$$\sum_{i \in I_j} N_i^* x_i^\beta = (\theta A)^{\frac{1}{\theta-1}} \left(\frac{p(j)}{\tilde{p}} \right)^{\frac{1}{\theta-1}} \sum_{i \in I_j} x_i^{\beta \frac{\theta}{\theta-1}}.$$

Total demand for good j is

$$\sum_{i \in I} c_i(j) = \sum_{i \in I} \left(\frac{p(j)}{\tilde{p}} \right)^{\frac{1}{q-1}} c_i = \left(\frac{p(j)}{\tilde{p}} \right)^{\frac{1}{q-1}} \sum_{i \in I} c_i.$$

Equating demand and supply and solving for $p(j)$ we get

$$p(j) = \left[\frac{(\theta A)^{\frac{1}{1-\theta}}}{\sum_{i \in I} c_i} \right]^{\frac{(q-1)(\theta-1)}{\theta-q}} \left[\sum_{i \in I_j} x_i^{\beta \frac{\theta}{\theta-1}} \right]^{\frac{(q-1)(\theta-1)}{\theta-q}} \tilde{p}.$$

In order to simplify the notation, we define

$$X_j \equiv \left[\sum_{i \in I_j} x_i^{\beta \frac{\theta}{\theta-1}} \right]^{\frac{\theta-1}{\theta-q}}$$

so that

$$p(j) = \left[\frac{(\theta A)^{\frac{1}{1-\theta}}}{\sum_{i\in I} c_i}\right]^{\frac{(q-1)(\theta-1)}{\theta-q}} X_j^{q-1}.$$

Let j_i denote the type of good produced in country i. Comparing the price of good j_i to the price of some good j we have that

$$p(j) = \left(\frac{X_j}{X_{j_i}}\right)^{q-1} p(j_i).$$

The price index is then given by

$$\tilde{p} = \left[\sum_{j=1}^{J} p(j)^{\frac{q}{q-1}}\right]^{\frac{q-1}{q}} = \frac{p(j_i)}{X_{j_i}^{q-1}}\left[\sum_{j=1}^{J} X_j^q\right]^{\frac{q-1}{q}} \Rightarrow \frac{p(j_i)}{\tilde{p}} = \left[\frac{\sum_{j=1}^{J} X_j^q}{X_{j_i}^q}\right]^{\frac{1-q}{q}}.$$

Substituting this price ratio in the harvesting effort of country we arrive at

$$N_i^* = (\theta A)^{\frac{1}{\theta-1}} \left[\frac{\sum_{j=1}^{J} X_j^q}{X_{j_i}^q}\right]^{\frac{1}{q}\frac{1-q}{\theta-1}} x_i^{\beta\frac{1}{\theta-1}}.$$

Using (2) we arrive at equation (18)

$$H_i^* = (\theta A)^{\frac{1}{\theta-1}} \left[\frac{X_{j_i}^q + \sum_{j\neq j_i} X_j^q}{X_{j_i}^q}\right]^{\frac{1}{q}\frac{1-q}{\theta-1}} x_i^{\beta\frac{\theta}{\theta-1}}.$$

A.6 Linearization TFP

Starting from (19), the dynamics of the state x can be linearized around the steady-state $x_{ss,0}$ associated with $B = B_0$. Denoting the steady-state harvest by $H_{ss,0}$, we have that

$$\dot{x}(t) \approx \left[f'(x_{ss,0}) - \beta\frac{\theta}{\theta-q}\frac{H_{ss,0}}{x_{ss,0}}\right](x(t) - x_{ss,0}) - H_{ss,0}\frac{\Delta B}{B_0}.$$

Denoting the deviation of the stock

$$\Delta x \equiv x - x_{ss,0}$$

and defining the factor

$$\lambda \equiv f'(x_{ss,0}) - \beta\frac{\theta}{\theta-q}\frac{H_{ss,0}}{x_{ss,0}}$$

we have

$$\Delta \dot{x}(t) \approx \lambda \Delta x(t) - H_{ss,0}\frac{\Delta B}{B_0}.$$

Combined with the initial condition $\Delta x(0) = 0$ this differential equation has the solution

$$\Delta x(t) = \left(1 - e^{-\lambda t}\right)\frac{H_{ss,0}\Delta B}{\lambda B_0}.$$

In the following we will only consider the case where $\lambda < 0$ so that the initial steady-state is stable. Starting from the expression (6) for the flow utility, using that $N = Bx^{\beta\frac{q}{\theta - q}}$ and denoting the flow utility in the initial steady-state by $U_{ss,0}$, flow utility can be linearized around the steady-state as

$$\begin{aligned}
U \approx & U_{ss,0} + U_{ss,0}\left[\beta\frac{q\theta}{\theta - q}\frac{1}{x_{ss,0}}\Delta x + \theta\frac{\Delta B}{B_0}\right] \\
= & U_{ss,0} + U_{ss,0}\left[\beta\frac{q\theta}{\theta - q}\frac{1}{x_{ss,0}}\left(1 - e^{-\lambda t}\right)\frac{H_{ss,0}\Delta B}{\lambda B_0} + \theta\frac{\Delta B}{B_0}\right] \\
= & U_{ss,0} + U_{ss,0}\left[\beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{\lambda x_{ss,0}} + \theta\right]\frac{\Delta B}{B_0} - U_{ss,0}\beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{\lambda x_{ss,0}}\frac{\Delta B}{B_0}e^{\lambda t}.
\end{aligned}$$

The total discounted value can now be approximated by

$$\begin{aligned}
V_{TFP} \equiv & \int_0^\infty U_{ss,0}\left(1 + \left(\beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{\lambda x_{ss,0}} + \theta\right)\frac{\Delta B}{B_0}\right)e^{-\rho t}dt \\
& - \int_0^\infty U_{ss,0}\beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{\lambda x_{ss,0}}\frac{\Delta B}{B_0}e^{-(\rho-\lambda)t}dt \\
= & \frac{U_{ss,0}}{\rho}\left[1 + \left(\beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{\lambda x_{ss,0}} + \theta\right)\frac{\Delta B}{B_0}\right] - \frac{U_{ss,0}}{\rho - \lambda}\beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{\lambda x_{ss,0}}\frac{\Delta B}{B_0} \\
= & \frac{U_{ss,0}}{\rho} + U_{ss,0}\left[\frac{\theta}{\rho} + \beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{\lambda x_{ss,0}}\left(\frac{1}{\rho} - \frac{1}{\rho - \lambda}\right)\right]\frac{\Delta B}{B_0} \\
= & \frac{U_{ss,0}}{\rho} + \frac{U_{ss,0}}{\rho}\frac{\theta(\rho - \lambda) - \beta\frac{q\theta}{\theta - q}\frac{H_{ss,0}}{x_{ss,0}}}{\rho - \lambda}\frac{\Delta B}{B_0} \\
= & \frac{U_{ss,0}}{\rho} + \frac{U_{ss,0}}{\rho}\frac{\theta\left(\rho - f'(x_{ss,0}) + \beta\frac{\theta}{\theta - q}\frac{H_{ss,0}}{x_{ss,0}}\right) - \beta\frac{q\theta}{\theta - 1}\frac{H_{ss,0}}{x_{ss,0}}}{\rho - \lambda}\frac{\Delta B}{B_0} \\
= & \frac{U_{ss,0}}{\rho} + \frac{U_{ss,0}}{\rho}\theta\frac{\rho - f'(x_{ss,0}) + \beta\frac{H_{ss,0}}{x_{ss,0}}}{\rho - \lambda} = \{H_{ss,0} = f(x_{ss,0})\} = \\
= & \frac{U_{ss,0}}{\rho} + \frac{U_{ss,0}}{\rho}\theta\frac{\rho - \left[\frac{x_{ss,0}f'(x_{ss,0})}{f(x_{ss,0})} - \beta\right]\frac{f(x_{ss,0})}{x_{ss,0}}}{\rho - \lambda}.
\end{aligned}$$

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