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Cem Karayalcin
Harun Onder

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Abstract

Climate change will impose large and differentiated tolls across countries. This paper suggests that economic fragility and resilience against climate change-driven natural shocks are shaped by: (i) the elasticity of input substitution in resource-intensive sectors, (ii) the trade regime, and (iii) the property rights regime in nature-based assets. Using a structural transformation model, the paper shows, inter alia, that openness increases resilience against natural shocks, regardless of the property right regime. Additionally, openness reduces fragility when a social planner internalizes the social cost of natural resource degradation. However, it increases fragility in a decentralized economy with incomplete property rights in nature-based assets.

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The Fragility and Resilience of Nations*

Cem Karayalcin[†] and Harun Onder[‡]

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[†]Florida International University, Miami, FL.
[‡]Macroeconomics, Trade & Investment Global Practice, World Bank, Washington, DC

1 Introduction

Climate change is transforming the natural underpinnings of economic activity. Deteriorating weather, land, and water resources are inflicting an uneven economic toll across nations, thereby pressing the international aid architecture to adapt. The World Bank Group's draft "Evolution Roadmap" has recently proposed a fundamental shift in the organization's country-based operational model by introducing "resilience" as a central criterion for financial assistance. Such a realignment, however, would require a systematic investigation of country typologies in risk and resilience domains. To contribute to this effort, we analyze how differences in production technology, trade openness, and nature-based property rights can shape the fragility and resilience of nations in the presence of climate-driven natural shocks.

The idea here is that other things being equal, differences in how economies propagate natural shocks can drive diverging outcomes under climate change. For example, following an adverse natural shock, some economies may adjust by allocating a greater share of their productive resources, such as labor, to nature-intensive sectors. This automatic reallocation, however, changes the economy's vulnerability to the next natural shock. Whether resources are pulled into the nature-intensive sector or pushed out of it is influenced by (i) the elasticity of input substitution (e.g., labor, land, or water), (ii) the openness of the economy (trade with other countries), and (iii) property rights in nature-based assets.

To demonstrate these points, we use a general equilibrium model with two sectors, agriculture and manufacturing, following Matsuyama, 1992. While the former sector employs a nature-based input (land) along with labor, the latter uses only labor. Workers are mobile across the sectors and respond to differences in wages. Consumer demand is characterized by non-homothetic preferences, with a subsistence level of food consumption setting the income elasticity of demand for food to less than unitary. In the benchmark case, the economy is assumed to be closed and decentralized, with incomplete property rights in nature-based assets permitting dynamic distortions. This benchmark model is then modified to consider extensions including different elasticities of substitution between land and labor in agriculture, an open economy case, and a scenario with a social planner who addresses the common pool problem in natural assets. With analytical intractability, we use numerical simulations with common parameter values to compare alternative specifications.

To compare different cases, we rely on two key concepts from the economic sustainability literature: *fragility* and *resilience*. These concepts are sometimes used ambiguously or even erroneously as opposites,[1] but we distinguish between them based on the size of the output/welfare reduction over time relative to the initial impact. This approach helps to recognize an economic system's fragility (instantaneous resistance to shocks) and its resilience (the ability to recover from the impact). For comparison, we also consider welfare (or output) losses relative to natural resource losses in present value terms.

Our results show that all three institutional factors considered in this paper can shape the fragility and resilience of economies in the presence of natural shocks. First, economic fragility and resilience both increase monotonically in the elasticity of substitution between land and labor, and between different nature-based assets. This result holds in all property

[1]The dictionary definitions of these concepts suggest a weaker link between the two: while some objects can be fragile and not resilient (like glass), others can be both fragile and resilient at the same time (like water).

rights regimes and trade regimes. Second, openness increases resilience regardless of the property rights regime or the elasticity of input substitution. However, while openness reduces fragility under a social planner, it increases fragility in a decentralized economy. Third, an economy with a social planner is less resilient than a decentralized economy regardless of the trade regime or the elasticity of input substitution. However, while the social planner case is less fragile than the decentralized case in an open economy, it is more fragile in a closed economy.

The results of this study are primarily driven by differences in how economies propagate natural shocks under different institutional structures. For instance, openness increases the relative size of the natural resource-intensive sector in economies with comparative advantage in agriculture. Additionally, it fixes prices, thereby relaxing demand-side constraints that slow labor outflow from agriculture. Together, these factors increase the fragility and resilience of the economy. In comparison, with complete property rights in natural resources, the social planner internalizes the social cost of natural resource degradation. Therefore, it limits employment in agriculture, reducing fragility, especially in the closed economy case. These results have interesting policy implications. The finding on the fragility-increasing effect of openness in economies with incomplete property rights, but not in others, provides a possible additional motive for trade policy preferences in low-income countries. Similarly, while the presence of a social planner increases welfare and output in "normal" times, by maximizing the (ex-ante) discounted sum of future payoffs, it can lead to higher fragility and lower resilience. This constitutes a curious case of risk-return trade-off, where policies aimed at maximizing economic outcomes in a static manner may not be well suited to cope with increasing volatility.

This paper is concerned with issues that link three strands of literature: (i) the intersection of environmental and international economics, (ii) structural transformation, and (iii) the methodological approaches in assessing the impact of natural shocks across disciplines. Regarding the first strand, Copeland and Taylor, 2004 provide a systematic review of the environmental implications of trade policies and associated outcomes for trade flows and economic growth. Among this group of studies, Antweiler et al., 2001 consider the implications of trade policies for pollution, and Copeland and Taylor, 2009 consider how trade openness and international price movements can drive the endogenous setting of property rights regimes regarding natural resources, which otherwise suffer from common pool problems. Our results provide additional rationale for trade policy and property regime choices based on fragility and resilience concerns. Similarly, Jones and Olken, 2010 show empirically that the impacts of climate shocks for trade flows vary by the shock-receiving country's income level. To the extent that income levels are correlated with property rights regimes, our paper would suggest mechanisms that can potentially drive these findings. The second strand of literature, which focuses on structural transformation, is large, and it is not possible to do it justice in a short review. Among the papers of interest for our purposes are the works of Matsuyama, including Matsuyama, 2019 and Matsuyama, 1992, which characterize the role of openness and globalization in shaping domestic mechanisms that drive structural transformation across countries. We apply these ideas in the climate change domain and study both short- and long-term characteristics. Finally, the third strand of literature comprises discussions on how to measure resilience and fragility, which is particularly rich in natural sciences like ecology. Following Patrick et al., 2022, Pimm et al., 2019, and Rose, 2017, we adopt an approach that distinguishes between fragility and resilience concepts.

In what follows, we first describe a closed economy benchmark model with incomplete property rights. As part of this, we also analyze the mechanisms that drive the economic propagation of natural shocks and introduce the concepts of fragility and resilience formally. The third section analyzes the role played by alternative elasticities of substitution between land and labor, or between different nature-based assets, in agriculture in the benchmark model. The fourth section adds openness to this comparison. The fifth section introduces the social planner and considers all alternative specifications together. The final section concludes the paper by providing a discussion of our key results.

2 The Benchmark Economy

We start with an infinite horizon economy that is closed (autarkic) and decentralized (DC henceforth).[2] Following Matsuyama (1992), we consider two sectors: manufacturing and agriculture. The population of the economy under question is normalized to one, with the fraction of labor employed in manufacturing given by n. Production functions in the two sectors are given by

$$Y_t^M = MF(n_t) \tag{1}$$

$$Y_t^A = AG(T, 1-n_t),\ G_i > 0,\ G_{ii} < 0,\ G_{ij} > 0,\ i,j = T,L,\ L \equiv 1-n \tag{2}$$

where manufacturing productivity, M, reflects knowledge capital, and is given. T is a nature-based endowment (named land, for simplicity), and agricultural productivity, A, may reflect the level of technology and climate among other things. The functions F and G are strictly concave and have the property that $F(0) = G(0,0) = 0$.

Importantly, the benchmark model is also characterized by incomplete property rights in nature-based assets, which are considered a common resource.

Labor is perfectly mobile between the two sectors and responds to (only) wage differentials so that

$$AG_L(T, 1-n_t) = p_t M_t F'(n_t). \tag{3}$$

On the demand side, consumers have identical non-homothetic preferences given by

$$U = \sum_0^\infty \delta^t[\beta \ln(c_t^A - \gamma) + \ln c_t^M],\ \delta\epsilon(0,1],\ \beta,\gamma > 0 \tag{4}$$

where c^A and c^M denote the consumption of the manufacturing good and the agricultural good (called food for brevity), δ represents the discount factor, while γ is the subsistence level of food consumption and satisfies

$$AG(T,1) > \gamma > 0 \tag{5}$$

implying (i) that if all workers are employed in food production, they will be able to satisfy the subsistence needs of the population, and (ii) that with positive γ, preferences are

[2] Below we will contrast this decentralized equilibrium with that of the social planner.

non-homothetic and the income elasticity of demand for food is less than unitary. Further, we assume that all consumers have enough income, I_t, to consume more than γ units of food.

Given the budget constraint, where p denotes the relative price of manufactures,

$$c_t^A + p_t c_t^M \leq I_t, \tag{6}$$

the static first-order conditions for utility maximization yield

$$c_t^A = \gamma + \beta p_t c_t^M, \tag{7}$$

with the solutions for consumption given by

$$c_t^A - \gamma = \frac{\beta(I_t - \gamma)}{1+\beta},\ p_t c_t^M = \frac{I_t - \gamma}{1+\beta}. \tag{8}$$

In a closed economy demand for each good must equal its supply so that (given that population is normalized to one) $c_t^M = Y_t^M$ and $c_t^A = Y_t^A$. Using these with (1), (2), (3), and (7) yields

$$G(T, 1-n) - \beta G_L(T, 1-n)v(n) = \frac{\gamma}{A},\ v(n) \equiv \frac{F(n)}{F'(n)} > 0,\ v'(n) > 0, \tag{9}$$

which, in turn, solves for a unique labor allocation across sectors n_t such that $n_t = \varphi(A, T)$.

2.1 Economic propagation of natural shocks

We are interested in the effects of climate change that results in the loss of land resources in agriculture which, in turn, affects food production, technological change in manufactures, the rate of growth of the manufacturing knowledge base and the economy, and ultimately welfare. Our understanding of these fundamental effects hinges crucially on how natural shocks change the labor allocation, n, and thus on the sign of φ_T in $n_t = \varphi(A, T)$. To see this, note that:

$$\varphi_A = \frac{\gamma}{A^2[G_L - \beta v(n)G_{LL} + \beta G_L v'(n)]} > 0,\ \varphi_T = \frac{G_T - \beta v(n) G_{LT}}{[G_L - \beta v(n)G_{LL} + \beta G_L v'(n)]} \lesseqgtr 0, \tag{10}$$

where, given the properties of the production functions, the denominator of φ_n has a positive sign, while the sign of the numerator is ambiguous, and depends on the relative agricultural good demand parameter β and the properties of the two production functions: a fall in T reduces labor allocated manufactures if $G_T/G_{LT} > \beta F(n)/F'(n)$.

Intuitively, a decrease in the land endowment will have two opposing effects on the allocation of labor, n. First, it will reduce the marginal productivity of labor, MPL, in agriculture, lowering wages there and leading to a movement of labor out of agriculture into manufactures, i.e., an increase in n. Second, the decrease in land will lower agricultural output, creating an excess demand for the agricultural good, raising its relative price and decreasing the relative price, p, of the manufacturing good. Since the fall in p reduces the marginal revenue product of labor in manufactures and manufacturing wages, labor will move out of manufactures into agriculture, i.e., there will be a fall in n. The net effect of a decrease in the land endowment on n will thus depend on the relative strength of these two opposing channels.

To see the implications of the shocks on welfare and national income, use the solutions for consumption given in (8) to obtain the period indirect utility function of the representative agent.

$$e_t = \beta \ln \beta + (1+\beta) \ln \frac{(I_t - \gamma)}{(1+\beta)} - \ln p_t. \tag{11}$$

To determine the effects of changes in the land endowment, T, and agricultural productivity, A, on welfare, we need to determine the representative agent's income, I_t, which is equal to GDP per capita, Y_t (in terms of food), given by

$$Y_t = Y_t^A + p_t Y_t^M = AG(T, 1-n_t) + p_t M_t F(n_t). \tag{12}$$

Now, note that given A and T, equation (9) yields a time-invariant allocation, n, of labor across the two sectors. Given this n, equation (3) solves for p:

$$p = \frac{AG_L(T, 1-n)}{MF'(n)} \tag{13}$$

Equations (9), (12), and (13) can now be used to solve for per-capita GDP as[3]

$$Y(A,T) = \frac{(1+\beta)}{\beta} Y^A - \frac{\gamma}{\beta} \tag{14}$$

$$\frac{dY}{dA} = \frac{1+\beta}{\beta}(G - AG_L \varphi_A), \ \frac{dY}{dT} = \frac{1+\beta}{\beta} A(G_T - G_L \varphi_T)$$

where we dropped the time subscripts to emphasize that given A and T, per-capita GDP, Y, is also time-invariant, which makes period indirect utility given in (11) constant over time as well.[4]

2.2 Fragility and resilience

To analyze the mechanisms that can shape economic fragility and resilience in a given country, we first need to formally introduce these concepts. Fragility and resilience are sometimes used, rather casually, as antonyms against their technical definitions.[5] Therefore,

[3]Note that here GDP is expressed in terms of the numeraire, the agricultural good. In our simulations we deflate GDP by the price index $P = \upsilon p^{1/(1+\beta} + \gamma$, $\upsilon \equiv (1+\beta)\beta^{-\beta/(1+\beta}$ based on the logarithmic period utility function we use.

[4]In our simulations we use a monotonic transformation of the indirect utility for $e' = -\Omega/e$ ($\Omega > 0$) for ease of reference.

[5]The dictionary definition of fragility denotes the quality or state of being easily broken or destroyed, and that for resilience denotes the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress. Thus, the two concepts pertain to different stages of shock and recovery processes. While one object can be fragile and not-resilient, like glass, another one can be both

it is important to clarify at the outset how we use them, with the following definitions.

Definition 1 (Fragility) *The economy's fragility in a given indicator K with respect to a shock in $T_1^{(*)}$ is defined as*

$$\Phi^K \equiv \frac{d\ln K(0)}{d\ln T_1^{(*)}(0)}.$$

for $K = \{U, Y, ...\}$, where U is the representative agent's welfare and Y is total output.

Intuitively, our definition of fragility is the decline in welfare and total output given a negative shock to natural resources. Our output measure for fragility, Φ^Y, simply uses total output for utility. It is useful to see the connection between the fragility of total output and fragility of agricultural output. Using equation (14), we obtain the relation between Φ^A and Φ^Y as

$$\Phi^Y = \frac{(1+\beta)}{\beta}\frac{Y^A}{Y}\Phi^A. \tag{15}$$

We can now use (15) to examine the mechanisms behind our definitions of fragility in the benchmark economy. This will also help us to see how fragility changes in response to a series of shocks that reduce natural resources over time or how fragility changes depending on the size of the shock. In doing this, we would be using an alternative measure of fragility, which we will call T-fragility as this measure is inspired by the work of Taleb (see, for instance, Taleb (2018a,b) and Taleb (2022)), who points out that "...typically, when systems—a building, a bridge, a nuclear plant, an airplane, or a bank balance sheet—are made robust to a certain level of variability and stress but may fail or collapse if this level is exceeded, then they are particularly fragile..." In our model, if fragility Φ^i $(i = A, Y)$ increases as shocks reduce T_1, this would indicate T-fragility.

Definition 2 (T-Fragility) *The economy is T-fragile in a given indicator K with respect to a shock in $T_1^{(*)}$ when*

$$\frac{d\ln \Phi^K}{d\ln T_1} < 0$$

for $K = \{U, Y, ...\}$, where U is the representative agent's welfare and Y is the total output.

We next turn to define resilience, which is inherently a dynamic concept. To do this, we need to specify the dynamics of regeneration in nature-based assets. The literature on renewable resources makes use of the following difference equation to describe the time path of a renewable resource X

$$X_t - X_{t-1} = F(X_{t-1}) - Z_{t-1} \tag{16}$$

where $F(X_t)$ denotes a net growth function (the difference between birth and mortality), and Z_t represents the period t harvest. The change in the current stock of the resource is given by the difference between growth and harvest. If harvests were to consistently exceed growth, the renewable resource would decline and vice versa. The literature often focuses

fragile and resilient, like water.

on the existence and stability of steady-states, where the stock of the renewable resource remains constant over time.[6]

Given our assumption of incomplete property rights in the benchmark economy, the crucial feature of the model here is that individual agents do not internalize the resource constraint (16), a behavior that introduces a dynamic distortion and gives rise to an outcome reminiscent of "tragedy of commons," in that the realized "harvest" level is higher than the social optimum discussed below. To put it differently, the absence of complete property rights in renewable resources leads to an over-allocation of labor in "agriculture" relative to the social optimum.

We can now define our resilience concept, which will supplement our measure of fragility in this dynamic context. We follow the nascent literature in this area, including Rose, 2017 and Rose, 2014, which define resilience as "the extent to which the estimated direct output/welfare reduction deviates from the likely maximum potential reduction given an external shock, such as the curtailment of some or all of a critical input." Formally, for welfare, these measures are defined as follows:[7]

Definition 3 (Resilience) *The economic resilience of welfare with respect to a shock in* $T_1^{(*)}$ *is defined as*

$$R^U = 1 - \frac{\sum_{t=0}^{N} \delta^t [U(c_t^A, c_t^M) - U(c_0^A, c_0^M)]}{\sum_{t=0}^{N} \delta^t [\min U(c^A, c^M) - U(c_0^A, c_0^M)]}$$

where U *is the representative agent's welfare.*

Note that the denominator of R is the present discounted value of the maximum loss of welfare given a negative shock to natural resources.[8] This normalization helps us to focus strictly on recovery dynamics by abstracting away from the magnitude of the initial shock, which is captured by the fragility concept defined above. We also consider an alternative measure from Hallegatte, 2014. This measure uses the present value of welfare (or output) losses relative to the present discounted value of natural resource declines, as follows:

$$R_{alt}^U = \frac{\sum \delta^t \left\{ [U(c_t^A, c_t^M) - U(c_0^A, c_0^M)]/U(c_0^A, c_0^M) \right\}}{\sum_{t=0}^{N} \delta^t \left\{ (T_{1,t} - T_{1,0})/T_{1,0} \right\}}$$

where, as opposed to R^U, a higher indicator value denotes lower resilience. Note that this alternative indicator captures the sensitivity of losses with respect to the shock–capturing both fragility and resilience components, thus, is not strictly comparable to our preferred measure of resilience.

[6]Typically, the growth function $F(X_t)$ is modeled as dependent on an intrinsic growth rate, r, and a carrying capacity, K, with periods of rising and declining changes in the stock. A popular growth function is logistic, $F(X_t) = r(1 - X_t/K)$. In our simulations, we will use the growth function $F(X_t) = rX^\alpha - K$, $\alpha < 0$, $K > 0$ and the harvest function $Z_t = \varrho Y_t^a$.

[7]Mindful of the fact that losses in output do not have a direct effect on people's welfare and that for households what matters most are the utility losses from reduced consumption, our preferred measure of resilience uses welfare losses instead of output reductions. However, we report output resilience measures and point out differences between these measures throughout.

[8]A measure using percentage losses would be identical to R, given that both the numerator and the denominator would be divided by $U(c_0^A, c_0^M)$.

Having introduced the main analytical features of our benchmark economy and key concepts, we can now turn to comparing how deviations from the benchmark model in several dimensions, including in production technology, openness, and property rights in nature-based assets, can affect the fragility and the resilience of the economy.

3 The Role of Factor Substitution

Our first extension relative to the benchmark economy focuses on the role played by factor substitution in the transmission of climate shocks and on the allocation of resources across sectors. The idea here is that, as climate shocks reduce productivity and land availability in agriculture, the magnitude, or perhaps even the sign of, labor flows across sectors may change with different degrees of land-labor substitutability.

To explore this question further, we specialize the agricultural production function to a Constant Elasticity of Substitution (CES) one as follows:

$$Y^a = A\left[(1-\theta)T^{\xi} + \theta(1-n)^{\xi}\right]^{1/\xi} \equiv A\Omega^{1/\xi}$$

with $\xi \in (-\infty, 1]$, and the elasticity of substitution is given by $\sigma = 1/(1-\xi)$. Note that if $\xi \to 1$ the inputs are perfect substitutes, as $\xi \to -\infty$, they are perfect complements (the Leontief case), and if $\xi = 0$, we get the Cobb-Douglas case with

$$Y^a = AT^{1-\theta}(1-n)^{\theta} = \tilde{A}(1-n)^{\theta},\ \tilde{A} \equiv AT^{1-\theta},$$

with the following useful mapping:

$$\begin{aligned} -\infty < \xi < 0 \Rightarrow &\quad \sigma < 1 \\ \xi = 0 \Rightarrow &\quad \sigma = 1 \\ 0 < \xi < 1 \Rightarrow &\quad \sigma > 1 \end{aligned}$$

Given this CES production function in agriculture, we can now posit the relationship between climate shocks that reduce the availability of nature-based assets (land) and the equilibrium labor allocation across sectors in the benchmark economy, as follows.

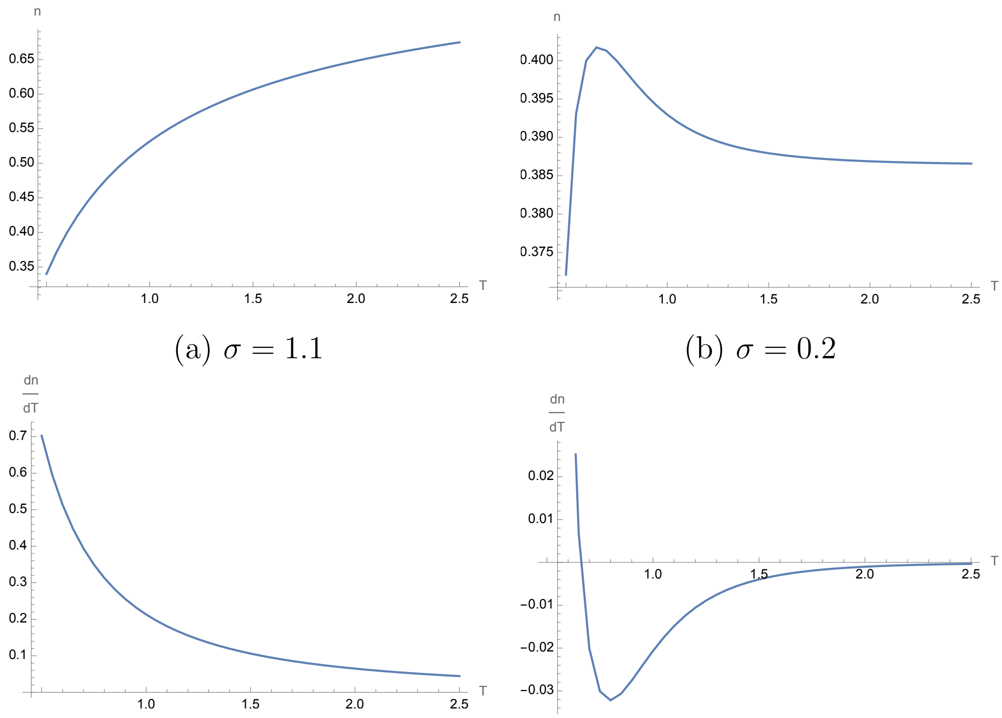
Result 1 (Relationship between factor substitution and labor allocation) *: In the benchmark economy, which is closed and decentralized, "land-reducing" climate shocks:*

1. *For high σ values, pull more labor into agriculture (lower n) at an accelerating rate ($\frac{\partial n}{\partial T} > 0$, $\frac{\partial^2 n}{\partial T^2} < 0$),*

2. *For low σ values and initial land endowments, pull more labor into agriculture (lower n) at an accelerating rate,*

3. *For low σ values and high initial land endowments, push labor away from agriculture (higher n) at a decelerating rate ($\frac{\partial n}{\partial T} < 0$, $\frac{\partial^2 n}{\partial T^2} > 0$).*

Figure 1: Manufacturing employment (n) and its change ($\frac{dn}{dT}$), by σ



(a) $\sigma = 1.1$

(b) $\sigma = 0.2$

(c) $\sigma = 1.1$

(d) $\sigma = 0.2$

To see the rationale behind these observations, note that:

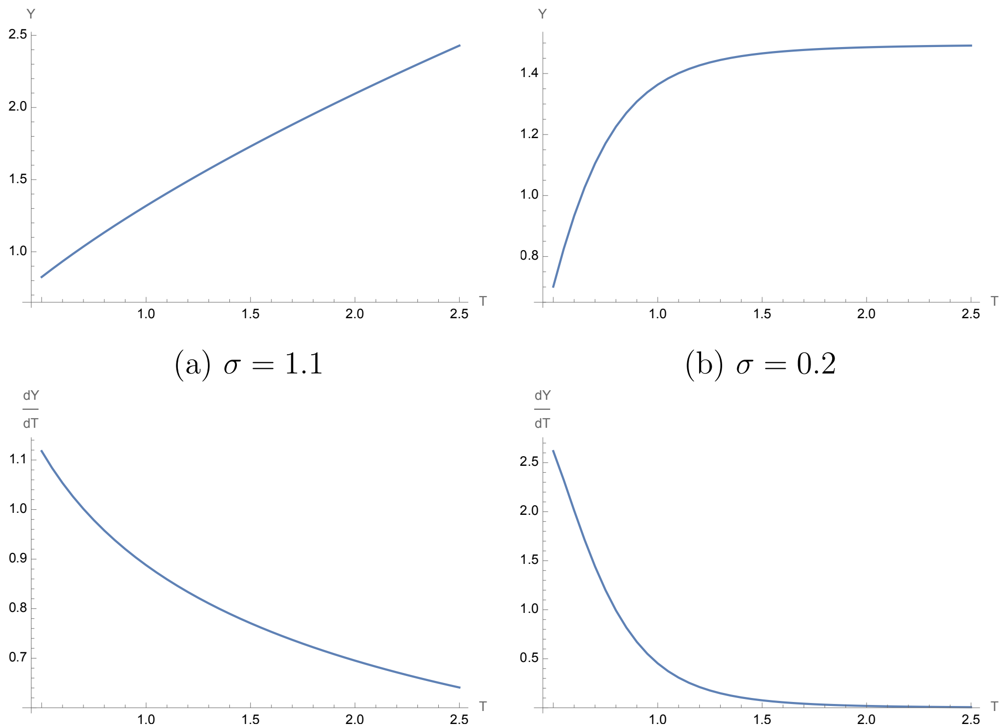
$$\frac{dn}{dT} \equiv \varphi_T = \frac{(1-n)}{T} \frac{\omega_T[(Y^A - \gamma)\xi + \gamma]}{\omega_T(1-\xi)(Y^A - \gamma) + \omega_L Y^A[1 + \beta v'(n)]}, \; \omega_T = 1 - \omega_L \equiv \frac{(1-\theta)T^\xi}{\Omega}$$

where given $\xi \in (-\infty, 1]$, the sign of the denominator is positive and the sign of the numerator is non-negative for $\xi \geq -\gamma/(Y^A - \gamma)$. Thus, T and n would be negatively related when land and labor are strongly complementary in agriculture (i.e. when $\xi < -\gamma/(Y^A - \gamma)$). There is thus a critical value of the elasticity of substitution such that for $\sigma \geq \tilde{\sigma} \equiv (Y^A - \gamma)/Y^A$ we have $\varphi_T \geq 0$. In other words, for a high enough elasticity of substitution, σ, between labor and land in agriculture, decreases in the "land" endowment caused by climate change result in an allocation of labor away from manufactures. This case is displayed in Figure (1a).[9] Figure (1b) shows the consequences of a low elasticity, σ, of substitution between land and labor in food production. In this case, as T falls, initially n may rise, but further declines in T lead to lower n, driving deindustrialization.

Intuitively, when the elasticity of substitution between the two production factors (land and labor) is high, the demand side effect of the climate shock dominates its productivity effects as far as labor allocation is concerned. That is, with excess demand for them, the relative prices of agricultural goods increase enough to offset the decrease in labor productivity and drive wages higher, pulling labor into agriculture. In comparison, the

[9]Underlying parameter values are reported in Table (1).

Figure 2: Total output (Y) and its change ($\frac{dY}{dT}$), by σ



(a) $\sigma = 1.1$ (b) $\sigma = 0.2$

(c) $\sigma = 1.1$ (d) $\sigma = 0.2$

opposite is true when the two inputs are more complementary except for when T is too low. This can also be seen in the following expression:

$$\frac{dG_L}{dT} = \frac{1}{\sigma} \frac{\omega_L}{(1-n)} \frac{\omega_T}{T} G(T, (1-n),$$

which indicates that the higher is the elasticity of substitution, σ, between land and labor in agriculture, the smaller is the decline in agricultural MPL and wages and the weaker is the productivity effect. Therefore, while labor is generally pulled into agriculture after the adverse shock to land when the land-labor substitutability is high (demand side effect dominates), it can be pushed away from agriculture when such substitutability is relatively low (the productivity effect dominates).

The next figure (1c) shows the crucial result concerning the fragility of the economies buffeted by climate shocks through one of our measures, the change in manufacturing employment as land endowment declines. When land and labor are substitutes ($\sigma > 1$), consecutive climate shocks have deeper negative effects in terms of employment in manufactures, n. Note, from (1d) that when the elasticity, σ, of substitution between land and labor in food production is low, the relation between dn/dT and n becomes non-monotonic, as was the case between n and T shown in (1b).

We can now explore the relationship between national income and welfare as indicated by the indirect utility function given in (11). To do this, we first model the combination of various natural resources (some of which may be renewable) in the production of the agricultural good by defining T as

$$T = \chi[\sum_i \lambda_i T_i^{(\rho-1)/\rho}]^{\rho/(\rho-1)} \equiv \Omega_T^{\rho/(\rho-1)}, \ \sum_i \lambda_i = 1.$$

It is useful for future purposes to note that

$$\frac{\hat{Y}^a}{\hat{T}_1} = \frac{(1-\theta)T^{\xi}}{\Omega} \frac{\lambda_1 T_1^{(\rho-1)/\rho}}{\Omega_T}.$$

Figure (2) shows how a decrease in T affects the output Y and how this effects changes as a function of T. These figures show that our results obtained using employment in agriculture continue to hold when we use national income, Y, and welfare (recall (11)) as our measures. As the economy is buffeted by climate shocks that reduce its effective land (natural resource) endowment, its national income declines and its households are made worse off. The effect of sequential shocks is such that latter ones have larger negative impacts as compared to initial shocks. This is measured in our simulations by the magnitude of dY/dT, which rises as T falls. Note that the declines in national income are more pronounced when land and labor are complements.

To further elaborate on the parallelism between the results for the equilibrium labor allocation and those for equilibrium output, we can shut down the resource allocation channel and keep n unchanged. This helps us identify the determinants of fragility and find out whether fragility rises or falls in response to persistent negative shocks. Given n, we have Φ^A as

$$\Phi^A \mid_{dn=0} = \frac{(1-\theta)T^{(\sigma-1)/\sigma}}{\Omega} \frac{\lambda_1 T_1^{(\rho-1)/\rho}}{\Omega_T} \tag{17}$$

For a given percentage change in T_1 the change in Φ^A can then be derived as

$$\frac{d\ln\Phi^A}{d\ln T_1} \mid_{dn=0} = \left[\frac{\theta(1-n)^{(\sigma-1)/\sigma}}{\Omega} \frac{\lambda_1 T_1^{(\rho-1)/\rho}}{\Omega_T} \frac{(\sigma-1)}{\sigma} + \frac{\lambda_2 T_2^{(\rho-1)/\rho}}{\Omega_T} \frac{(\rho-1)}{\rho}\right] \tag{18}$$

As equation (18) makes it clear, given a labor allocation n across the two sectors, if land and labor and different types of natural resources are complements, that is if $\sigma < 1$ and $\rho < 1$, we will have T-fragility in agricultural output. However, whether there will also be T-fragility in welfare or total income will depend on how n and share of agriculture in total output, Y^A/Y change as well. To combine these aspects and analyze the fragility and resilience of the economy as a whole against climate shocks, we run simulations with different elasticity of substitution values (σ and ρ). Numerical results are presented in table (1) and summarized below.

Result 2 (How factor substitution drives fragility and resilience) *In the benchmark (closed and decentralized) economy, higher elasticities of substitution between land and labor (σ), or between different nature-based assets (ρ), make the economy both more fragile (greater Φ) and more resilient (greater R) against climate shocks. This result holds for both welfare and income.*

Our simulations show that, in the benchmark economy, the fragility indicators for welfare (Φ^U) and income (Φ^Y) increase monotonically in the elasticities of substitution between land and labor (σ) and between different nature-based assets (ρ). For example, while $\Phi^U = 0.07$ and $\Phi^Y = 0.03$ with $\sigma = 0.8$ and $\rho = 0.5$, they are higher, $\Phi^U = 0.22$ and $\Phi^Y = 0.10$, when $\sigma = 1.2$ and $\rho = 1.5$. Interestingly, however, the resilience indicators (R^U and R^Y) do the same and increase in σ and ρ monotonically. Whereas $R^U, R^Y = 0.66$ when $\sigma = 0.8$ and $\rho = 0.5$, they are higher, $R^U, R^Y = 0.78$ when $\sigma = 1.2$ and $\rho = 1.5$. These can also be seen analytically, for example, by differentiating equation (17) where it is straightforward to show, given n, Φ rises with σ for $\ln T > 0$.

4 The Role of Openness

We now consider the open economy case. Suppose that the economy we discussed above, in the benchmark case, is a small open economy (in that, it is small enough that changes in its supply or demand for the two goods it consumes and produces will not affect the goods prices in the rest of the world) embedded in a world economy. We will assume that the rest of the world differs from our small open economy with respect only to its agricultural productivity A^* (asterisks indicate the rest of the world, *ROW*) and/or its manufacturing productivity M^*. Supposing that there is no international movement of labor or knowledge spillovers, the *ROW* equivalent of equation (3) will be given by

$$A^* G_L(T^*, 1 - n_t^*) = p_t^* M^* F'(n_t^*). \tag{19}$$

Taking the ratios of equations (3) and (19) yields

$$\frac{F'(n_t)}{G_L(T, 1 - n_t)} = \frac{A}{M} Q, \; Q \equiv \frac{M^*}{A^*} \frac{F'(n_t^*)}{G_L(T^*, 1 - n_t^*)}, \tag{20}$$

which, in turn solves for

$$n_t = n(T, A; M_t, Q), \; n_T = \frac{AQG_{LT}}{\Pi} < 0, \; n_A = \frac{QG_L}{\Pi} < 0, \; n_M > 0, \; n_Q = \frac{(A/M_t)}{\Pi} < 0,$$

where $\Pi \equiv MF''(n_t) + QG_{LL} < 0$. Among other things, we are interested in the effects of shocks originating in the *ROW* since these will help us formulate the differences between the fragility and resilience of closed and open economies.[10] To that end it is useful to see how climate shocks that affect the *ROW* (here modelled as declines in the land (natural resource) endowment, T^*, of the *ROW*). To see this, note that from (20) we have

$$\frac{dQ}{dT^*} = Q \left[\left[\frac{F''(n^*)}{F'(n^*)} + \frac{G_{LL}(T^*, (1 - n^*))}{G_L(T^*, (1 - n^*))} \right] \frac{dn^*}{dT^*} - \frac{G_{LT}(T^*, (1 - n^*))}{G_T(T^*, (1 - n^*))} \right], \; \frac{dQ}{dA^*} = -\frac{Q}{A^*}.$$

Note here that, with sufficiently high σ, we have $dn^*/dT^* > 0$, implying that $dQ/dT^* < 0$

[10] For example, Frankel, 2022 discusses the role of trade barriers in reducing economic resilience across the world during the Covid-19 pandemic.

and, therefore, $dn/dT^* = n_Q(dQ/dT^* > 0$.[11] That is, negative climate shocks in the ROW raise the share of manufacturing employment in the small open economy. Thus, trade helps mitigate the effects of climate change that affects all trading partners negatively.

Using equation (13) for the ROW it is easy to see that the world (and given the small open economy assumption, home) relative price of manufactures will be time invariant. In this case, we can use (3) to derive

$$n = \tilde{n}(T, A; p),\ \tilde{n}_A = \frac{G_L}{\Delta} < 0,\ \tilde{n}_T = \frac{AG_{LT}}{\Delta} < 0,\ \tilde{n}_p = \frac{-MF'(n)}{\Delta} > 0,$$

where $\Delta \equiv pMF''(n) + AG_{LL} < 0$. If we also assume that there is no international borrowing, $Y = E$ and

$$Y = \tilde{Y}(T, A; p),\ \tilde{Y}_A = G(T, 1-n) > 0,\ \tilde{Y}_T = AG_T > 0,\ \tilde{Y}_p = MF(n) > 0 \qquad (21)$$

as $dY/dn = 0$ from the envelope theorem.

Note that a key difference between a closed and open economy is in how they propagate a natural shock. Consider the shock in the Home economy. When the economy is closed, an adverse shock to T_1 has two opposing effects on n (the amount of labor in manufacturing production). First, by reducing the marginal revenue product of labor in agriculture, it reduces agricultural wages, thereby raising n. Secondly, the decline in the supply of the agricultural good, raises its price, and, thus reducing the relative price of manufactures and the marginal revenue product of labor employed in that sector, lowering wages there. This leads to a decline in n. In the simulations for the benchmark model, the net effect was a decrease in n on impact. In the open economy case, with prices given by the rest of the world, the price effect is absent. Consequently, n rises after the natural shock. We next analyze the implications of this difference for fragility and resilience in the two trade regimes.

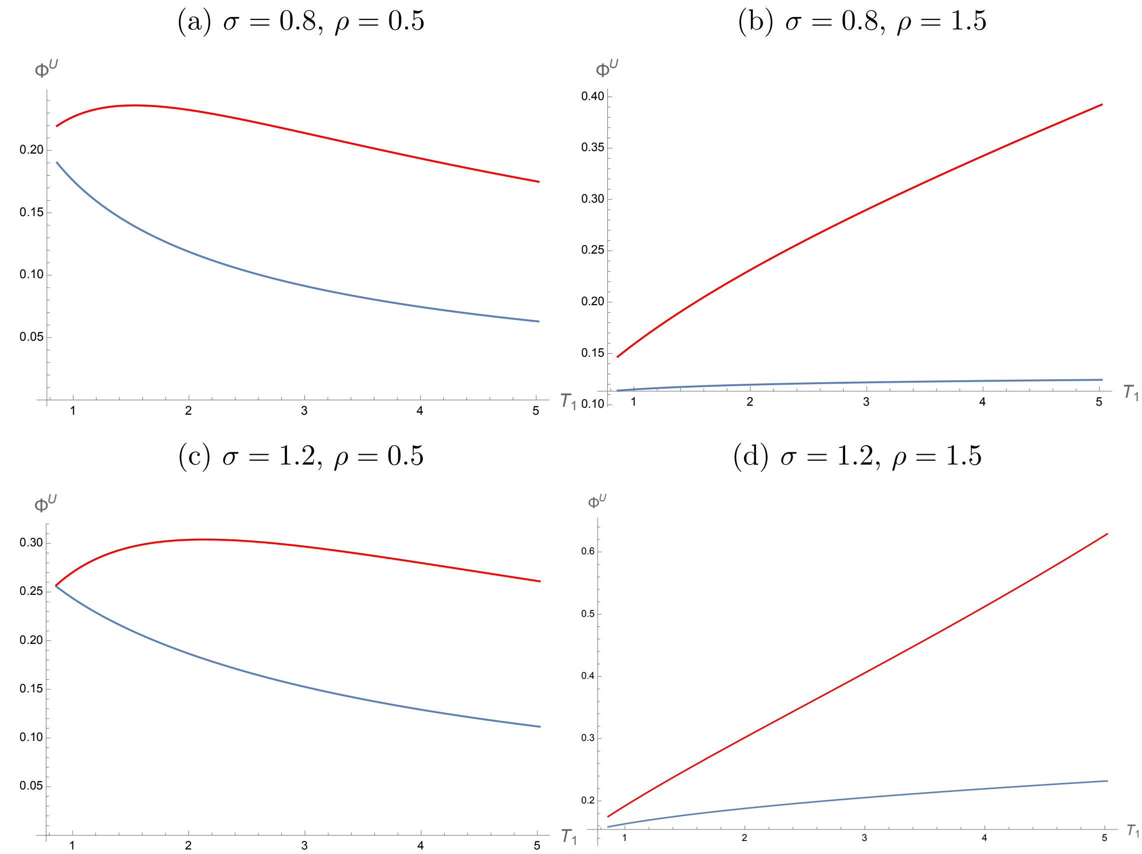
4.1 Fragility: Open economy vs. closed economy

We start by simulating the effects of adverse climate shocks that reduce T_1 in the home economy in both the closed and open economy cases. We report here four combinations of $\sigma = 1.2$, $\sigma = 0.8$, and $\rho = 1.5$, $\rho = 0.5$ in the simulations depicted in Figures (3) and (4), where blue lines indicate closed and red lines indicate open economy paths. Three results stand out here. First, the series of negative shocks to T_1 have Φ^U and Φ^Y registering higher in open economies than in closed ones. Second, as suggested above, for low levels of substitution elasticities σ and ρ, we observe T-fragility: fragility levels in general rise when the economy's natural resources decline with adverse climate shocks. The reverse conclusion holds when both substitution elasticities exceed unity. Third, in the open economy case, the economy is T-fragile for relatively high levels of the natural resource T_1 but turns anti T-fragile as T_1 declines and the economy's comparative advantage in agriculture is gradually eroded. We summarize these findings in the following result.

Result 3 (Fragility in open and closed economies) *Consider two otherwise identical*

[11] Recall that if σ is sufficiently low, decreases in T initially lead to high n, and then to low n, displaying a non-monotonic relationship.

Figure 3: Welfare fragility (Φ^U): Closed economy vs. open economy



Notes: Red (blue) lines show fragility in open (closed) economies. Shocks to Home country in both cases.

economies – one open and the other closed, which face land-reducing climate shocks. Our simulations show that:

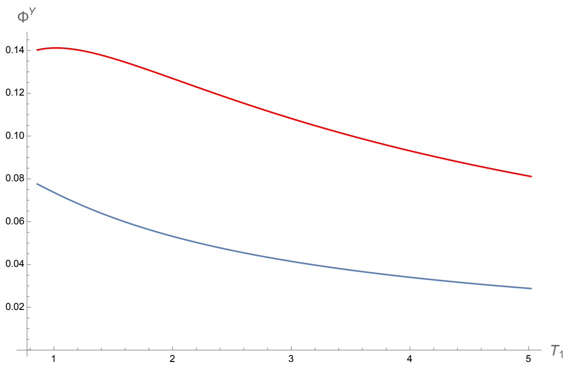
1. *The open economy is more fragile than the closed one both in output and welfare terms,*
2. *The closed economy exhibits T-fragility with low elasticities of substitution (σ or ρ) in agriculture, regardless of T,*
3. *The open economy exhibits T-fragility with low elasticities of substitution (σ or ρ) in agriculture when T is sufficiently high.*

Note that the open economy can also be exposed to shocks originating in the rest of the world. Consider the case where there are negative shocks to T_1^*. For the closed economy, this is trivial because the shocks to T_1^* have no effect to the home economy when it is not trading with the ROW. In the open economy case, as agricultural output declines in the ROW, pushing up the relative price of the agricultural good, a small open economy with a comparative advantage in this good benefits from the improvement in its terms of trade.

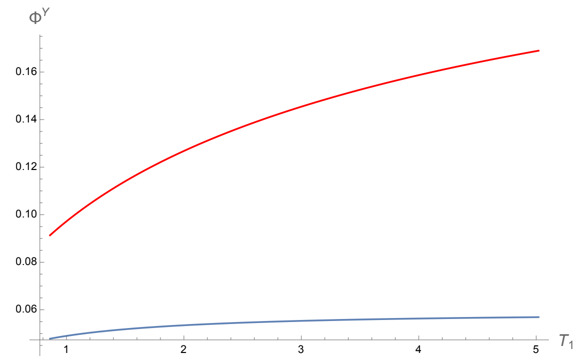
A more interesting case arises when persistent negative shocks to T_1^* are faced by a small open economy that has a comparative advantage in the manufacturing good. In this case, the

Figure 4: Income fragility (Φ^Y): Closed economy vs. open economy

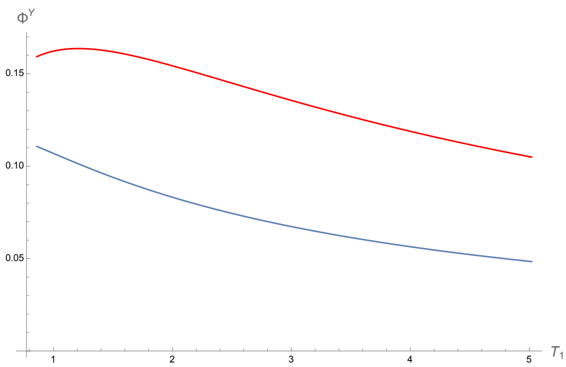
(a) $\sigma = 0.8$, $\rho = 0.5$



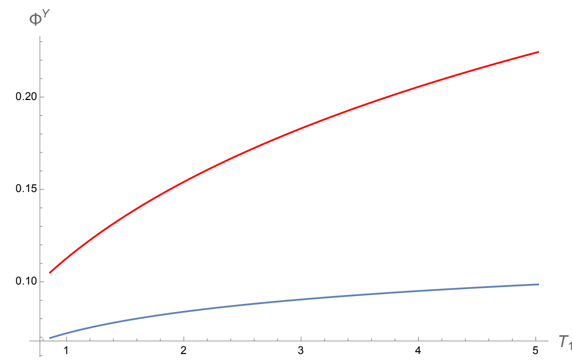
(b) $\sigma = 0.8$, $\rho = 1.5$



(c) $\sigma = 1.2$, $\rho = 0.5$



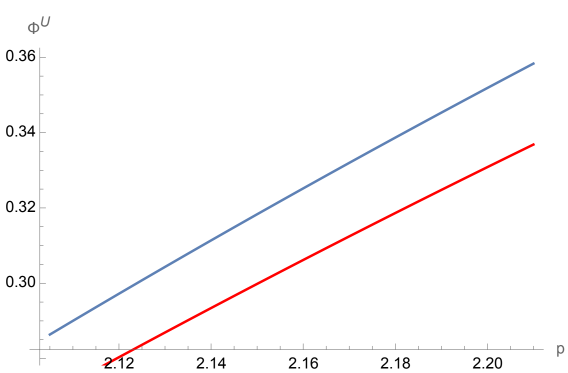
(d) $\sigma = 1.2$, $\rho = 1.5$



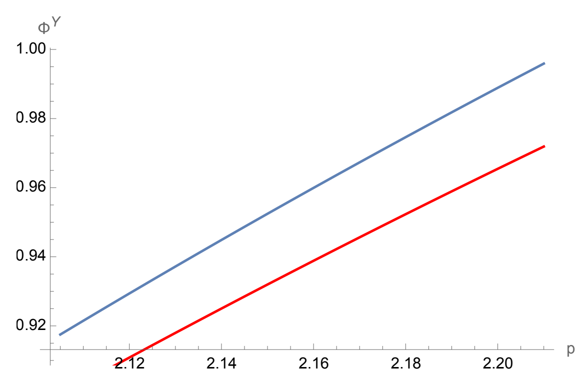
Notes: Red (blue) lines show fragility in open (closed) economies. Shocks to Home country in both cases.

Figure 5: Terms of trade (p) shocks and fragility

(a) Welfare



(b) Income



Notes: Figures show fragility in an open economy, which has comparative advantage in manufacturing, in the presence of terms of trade shocks driven by natural shock in rest of the world. Red line shows the baseline case and the blue line shows the case with an intermediate (agricultural or any natural resource intensive good) input used in manufacturing, which is imported by the Home country. Underlying parameter values are reported in Table (1).

small open economy faces two changes over time. First, its terms of trade decline, reducing its income. Second, ceteris paribus, the lower prices of the manufacturing good enable its consumers to purchase more manufactures. In the simulations, as T_1^* declines, initially the first effect dominates, lowering welfare, but as shocks reduce T_1^* further, the second effect starts to dominate. Regarding fragility as measured by both income and welfare levels, our simulations (an example of which is depicted in Figure (5) for the case of $\sigma = 1.1$, $\rho = 1.5$) indicate two results. First, as the economy's terms of trade deteriorate, fragility declines, displaying anti T-fragility. Second, incorporating an intermediate good (produced in the resource-intensive sector) in manufacturing production (which, given the Home country's comparative advantage in manufacturing, is imported) yields a higher level of fragility (shown as the blue curve in the figure) as expected.

4.2 Resilience: Open economy vs. closed economy

Next, we compare the resilience of open and closed economies to shocks to the home endowment of natural assets T_1, i.e., the dynamic adjustment profiles as labor is reallocated across sectors and the natural resource regenerates itself. Figure (6) shows the simulation results for welfare and national income when the elasticities of substitution are set as $\sigma = 0.8$ and $\rho = 1.5$ in the closed (indicated by solid blue paths) and open economies (indicated by solid red paths). Figures also show the renewable resource levels (indicated by dashed paths) as they adjust to the adverse climate shock. Based on the configuration of these figures, computed resilience indicators are as follows: (i) In welfare, $R^U = 0.89$ for the open economy and $R^U = 0.72$ for the closed economy, (ii) In income, $R^Y = 0.89$ for the open economy and $R^Y = 0.72$ for the closed economy. That is, the open economy proves more resilient than the closed economy in both cases. Panel B in Table (1) extends these results by allowing alternative specifications for the elasticities of substitution, σ and ρ. Results remain consistent and are summarized below.

Result 4 (Resilience in open and closed economies) *Consider two otherwise identical economies – one open and the other closed, which face land-reducing climate shocks. Our simulations show that:*

1. *The open economy exhibits a greater immediate loss in both welfare and output upon impact (more fragile),*

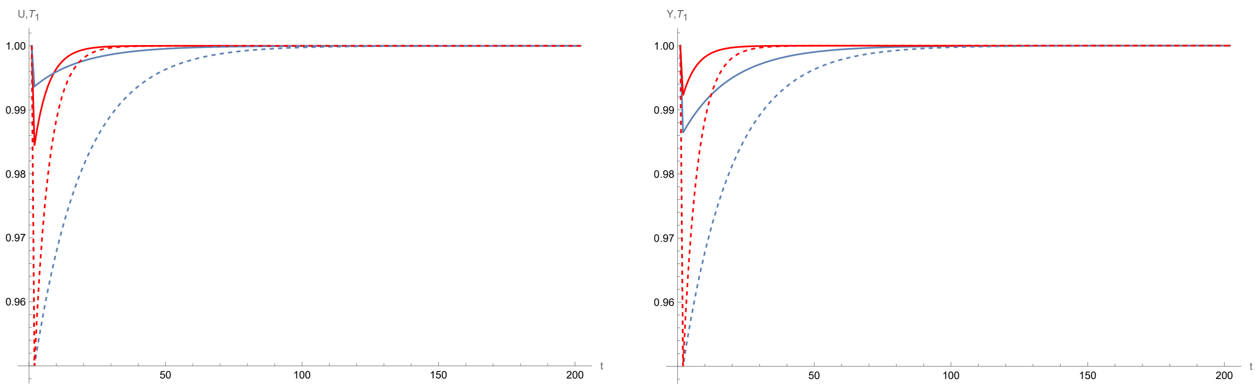
2. *However, the open economy also recovers faster and suffers a smaller loss over the projection horizon (more resilient).*

3. *Both the fragility and the resilience of both open and closed economies increase in the elasticity of substitution between land and labor and between different nature-based assets.*

To see the intuition behind such differential effect of adverse climate shocks on welfare in closed vs open versus economies, we should consider several factors at play here. First, note that with a renewable resource, the steady-state level of natural resources is no longer exogenous, but is determined endogenously in a general equilibrium framework and depends,

Figure 6: Transition dynamics in the decentralized case; closed economy vs. open economy

(a) Welfare (b) Income



Notes: Figures show welfare/income (solid lines) and land stocks (dashed lines) in open (red) and closed (blue) economies, normalized by using their initial steady state values, over time. Simulations based on $\sigma = 0.8$ and $\rho = 1.5$ and shocks to the Home country. Overall resilience indicators: (i) In welfare, $R = 0.89$ for the open economy and $R = 0.72$ for the closed economy, (ii) In income, $R = 0.89$ for the open economy and $R = 0.72$ for the closed economy. Underlying parameter values are reported in Table (1).

inter alia, on the trade regime. An economy that has a comparative advantage in the agricultural good will allocate more labor to it when open, "harvesting" more and will end up with a lower level of the natural resource ("land") at the steady state. Thus, on the one hand, unlike in standard models of trade with exogenously determined levels of factors of production, here, ceteris paribus, this will lower welfare in open economies. Secondly, the ability to trade with the rest of the world is welfare improving, with gains being an increasing function of the difference in autarkic and world relative prices. A third factor that needs to be emphasized here is that given the dynamic distortion involved when renewable resources enter the picture, we would expect there to be second-best paradoxes in the decentralized economy. When comparing closed and open economies in a decentralized setting, we would therefore expect that the distortion, which is magnified when the small open economy has a comparative advantage in the agricultural good and, therefore, allocates more resources to its production, might, under certain parameter configurations, to be such that its negative effects undo the positive effects of trade on national welfare. In the simulations above, as the economy recovers from an adverse climate shock, these two mechanisms give rise to alternating superiority of the two trade regimes in terms of welfare. The economy has higher welfare when closed at an initial state (not shown in Figure 6 due to normalization), reflecting the higher initial level of the renewable resource despite gains from trade. However, the latter dominates in the recovery period, until the closed economy once more attains a steady state with a higher level of the natural resource because of reduced harvesting.

5 The Role of Property Rights

The benchmark economy discussed so far has assumed that the property rights in renewable resources (such as fisheries, forests, lakes, rivers, etc.) are not complete with the implication that in a decentralized setting private agents do not internalize the resource constraint (16). In this section we introduce a case where private agents can be thought as having perfect property rights over the resources in question. However, given the empirically observed paucity of such complete rights, the discussion that follows should be taken to be a characterization of the social planner's solution to the problem.

5.1 Economic propagation of natural shocks with a social planner

The Social Planner (SP) maximizes the present discounted utility of the representative agent subject to the budget constraint (6) and the resource constraint (16). The Hamiltonian, $\mathbb{H}$, for this problem is

$$\mathbb{H} = \delta^t U(c_t^A, c_t^M) + \mu_{t+1}[F(T_t) - \varrho Y_t^a],\ \mu_{T+1} > 0$$

where μ_{t+1} denotes the shadow price of the renewable resource T_1.

The first order conditions yield, in addition to (7) and (16)

$$\mu_{t+1} = \frac{\delta^t}{p_t c_t^M} \frac{w_t^A - w_t^M}{w_t^A} \tag{22}$$

$$\mu_{t+1} - \mu_t = -\mu_{t+1}[\frac{w_t^M}{w_t^A - w_t^M} + F'(.)] \tag{23}$$

which, together with (16), yield the first-order difference equation

$$n_t = \varphi(n_{t-1}, T_{1t-1}) \tag{24}$$

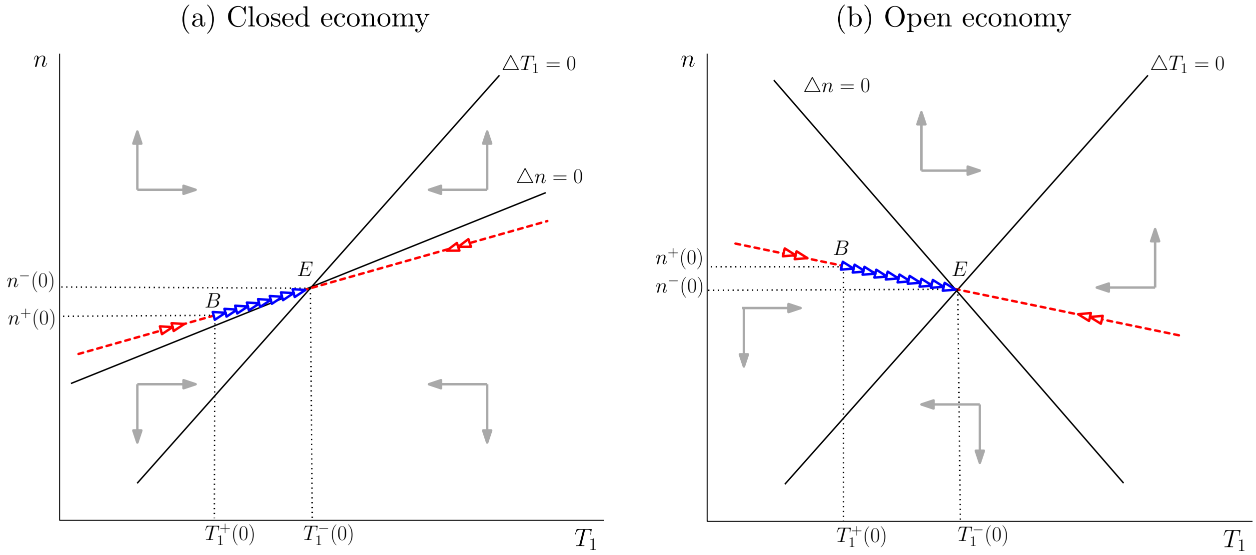
One immediate implication of the first-order condition (22) that needs to be highlighted is that the SP allocates labor across the two sectors by taking into account the negative externality (or, the dynamic distortion) involved in "harvesting" decisions, so that it allocates less labor to agriculture than private agents would if property rights were imperfect:

$$w_t^{M,SP} < w_t^{A,SP} \iff n_t^{SP} > n_t^{DC} \tag{25}$$

To derive the time paths of n_t and T_{1t} given by the difference equations (16) and (24), we start by replacing $p_t c_t^M$ with (8) using the appropriate expressions for income in the cases of closed and open economies.[12] Next, we note that at a steady state $(\mu_{t+1} - \mu_t)/\mu_{t+1} = 1 - 1/\delta$ and setting $x_t = x_{t-1} = \bar{x}$ for $x = n, T_1$ derive the implicit expressions for the steady-state values of the variables, which we then use to linearize the two difference equations at hand. Given the complexity of the analytical solutions, we conduct a set of calibration and simulation exercises to determine the time paths of the relevant variables. Simulation results show that, as expected, with one predetermined (T_1) and one jumping (n) variable

[12] Note the contrast between the point-in-time equilibria of the social planner and the decentralized economy cases. In a decentralized economy with incomplete property rights atomic agents do not internalize the constraint that dictates the time path of the renewable resource. As a consequence, they take the time path of the resource as parametric, making a sequence of static labor allocation decisions, which, in the aggregate, gives rise to a sequence of equilibria described in the section above.

Figure 7: Phase diagrams: Unexpected natural shocks under complete property rights



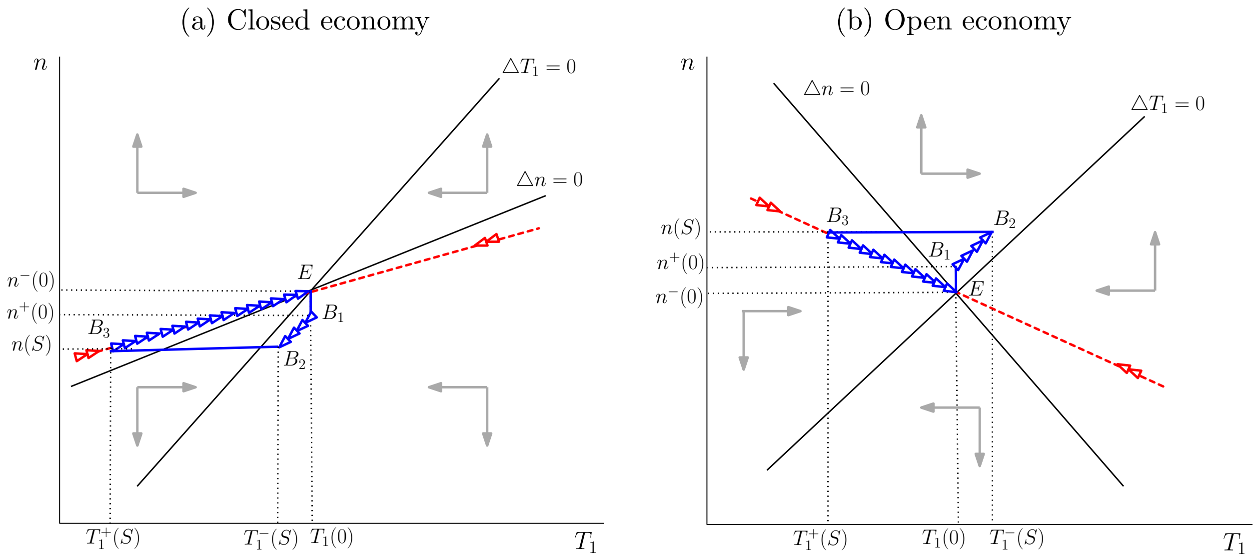
Notes: Figures show the dynamics of transition with unexpected shocks, where the red dashed lines show the stable arm of the saddle path and the blue arrows show the post-shock transition. Underlying parameter values are reported in Table (1).

the system is saddle-path stable. Further, regardless of the values of substitution elasticities ρ and σ, the stable arm of the saddle path slopes upward (downward) when the economy is closed (open) in the $n - T_1$ plane.

To get insight into how n and T_1 evolve over time in response to adverse climate shocks that reduce T_1 on impact, it is useful to examine the phase diagrams of the system of two difference equations for the two international trading regimes we study. As the figure (7) shows, when the economy is closed (panel a), both $\Delta n = 0$ and $\Delta T_1 = 0$ ($\Delta x \equiv x_{t+1} - x_t$) curves slope upward with the latter's slope exceeding that of the former. In contrast, when the economy is open to international trade, the $\Delta n = 0$ curve slopes downward, with the slope of the stable-arm of the saddle path consequently becoming negative as well (panel b).

We are now in a position to study the effects of expected and unexpected adverse climate shocks, starting with the analytically simpler case of the latter. As panels a and b in figure (7) show, an unexpected shock that decreases T_1 at time $t = 0$ moves the economy from the initial equilibrium (point E) to a point west of the initial steady-state on the stable-arm of the saddle path (point B). When the economy is closed (open) this implies a reduction (rise) in n, the share of labor in manufacturing. Intuitively, there are two competing forces at work here in both cases: the need to address the decline in agricultural output (and, thus, food consumption) and to attend, through harvesting, to the regeneration of the resource. The former need requires more and the latter less labor allocated to agriculture. When the economy is open, food consumption can be augmented by a reduction in net exports (thus the decline of labor in agriculture), while in a closed economy the exigency of dealing with the decline in food production requires the allocation of more labor to the agricultural sector. We summarize these results as follows.

Figure 8: Phase diagrams: Expected natural shocks under complete property rights



Notes: Figures show the dynamics of transition with expected shocks, which take place at time $t = S$. The red dashed lines show the stable arm of the saddle path, blue lines show the sudden jumps upon and the blue arrows show the post-shock transition. Underlying parameter values are reported in Table (1).

Result 5 (Transition dynamics with unexpected shocks) *: Consider two otherwise identical economies with complete property rights in nature-based assets – one open and the other closed. Our simulations show that an unanticipated adverse natural shock pulls more labor into agriculture (lower n) if the economy is closed, while it pushes labor away from agriculture in an open economy during the transition. In both cases, adjustment is monotonic after the initial shock.*

Next, consider expected shocks. Figure (8) shows the time paths of n and T_1 when the adverse climate shock is expected. To fix ideas, suppose that at time $t = 0$, information is revealed that an adverse climate shock will take place at some future point in time $t = S > 0$. At $t = 0$, the jumping variable n will change discretely (by $n^+(0) - n^-(0)$), moving to point B_1, dropping (jumping) in the closed (open) economy case. Given that the shock is not yet realized, for $0 \leq t \leq S$, the economy will follow the dynamics dictated by the initial steady state, with n and T_1 falling (rising) in the closed (open) economy until $t = S$. At $t = S$, when the shock hits and reduces T_1, the economy has to be at that point on the stable arm of the saddle path indicated by the lower level of T_1.[13] From $t = S$ onward the adjustment of the economy parallels that of the case of an unexpected shock. The following result summarizes these dynamics.

Result 6 (Transition dynamics: expected shocks) *: Consider two otherwise identical economies with complete property rights in nature-based assets – one open and the other*

[13]Note that when the shock hits, n has to be at the level determined by the intersection of the stable-arm of the saddle path and $T_1(S)$, i.e. at point B_2 as discrete changes in n after the revelation of new information at $t = 0$ are ruled out in this perfect foresight framework.

closed. Our simulations show that an anticipated adverse natural shock initially pulls more labor into agriculture (lower n) if the economy is closed, while it pushes labor away from agriculture in an open economy during the transition. The opposing changes in harvesting levels in these two cases lead to a decline (rise) in the level of natural resources in the closed (open) economy before the realization of the shock.

Having analyzed how the economy responds to anticipated and unanticipated shocks nature-based assets, we can now focus on assessing the implications of these adjustments for the key concepts of interest in this paper: the fragility and resilience of the economy under the social planner.

5.2 Fragility and resilience with a social planner

The first panel in Table (1) shows the fragility and resilience computations for open and closed economies with a social planner and various values of input elasticity of substitution. The first interesting observation is that, like in the decentralized case, both resilience and fragility increase monotonically in the elasticities of substitution in both closed and open economies. For example, whereas $R^U = 0.64$ and $\Phi = 0.27$ for a closed economy when $\sigma = 0.8$ and $\rho = 0.5$, they are greater, $R^U = 0.72$ and $\Phi = 1.04$ when $\sigma = 1.2$ and $\rho = 1.5$.[14] The second observation is that, like in the decentralized case, the open economy is more resilient than the closed economy regardless of the value of substitution elasticities. However, in contrast to our results in the decentralized case with imperfect property rights, in the social planner case, fragility (both output and welfare) is lower in open economies compared to closed economies. This contrast is also true when we compare decentralized and social planner cases directly, which constitutes the third interesting observation. Simulation results suggest that the social planner outcomes are generally less resilient for most elasticities of substitution values (with the exception of lowest elasticities) and both trade regimes. Moreover, they are more fragile in closed economies, but less fragile in open economies. For example, when $\sigma = 1.2$ and $\rho = 1.5$, the social planner results are $R^U = 0.72$ and $\Phi = 1.04$ in a closed economy and $R^U = 0.81$ and $\Phi = 0.32$ in an open economy. In comparison, the decentralized solutions are $R^U = 0.78$ and $\Phi = 0.22$ in a closed economy and $R^U = 0.90$ and $\Phi = 0.43$ in an open economy. We summarize these results below.

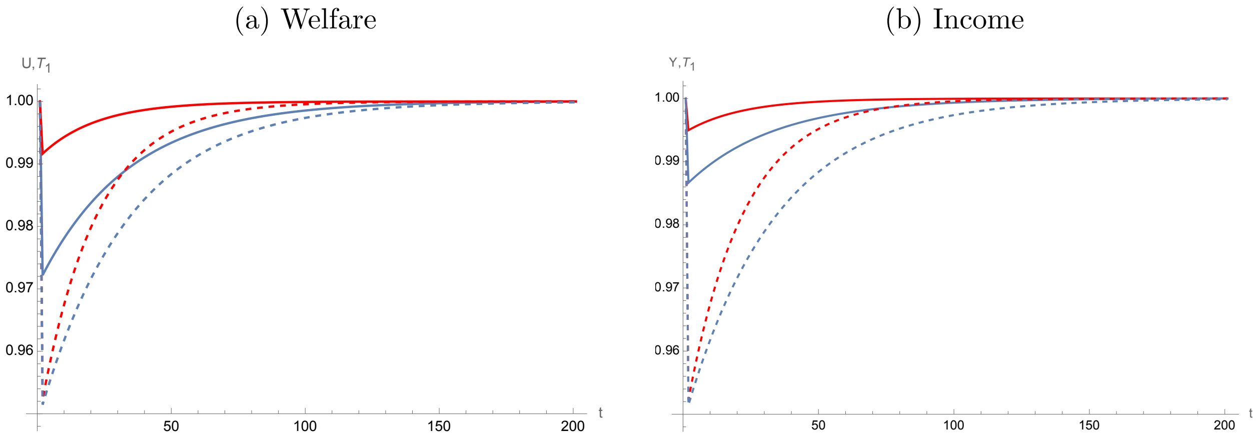
Result 7 (Fragility and resilience: property rights and trade regimes) *: Consider two otherwise identical economies which can differ over three dimensions: the property rights regime (decentralized vs. social planner), the trade regime (open vs. closed), and the elasticity of input substitution regarding nature-based assets (σ and ρ). Our simulations show, for a shock in the home country, that:*

1. *Both resilience and fragility increase monotonically in the elasticity of input substitution (σ and ρ) regardless of the property rights regime or the trade regime.*

2. *Open economies are more resilient than closed economies regardless of property right regimes or the elasticity of input substitution (σ and ρ). However, whereas an open*

[14]Note that the alternative resilience indicator conflates fragility and resilience effects: when R and Φ are aligned, R_{alt} parallels R. When they are not, R_{alt} contradicts R in the direction suggested by Φ.

Figure 9: Transition dynamics in the social planner case: closed economy vs. open economy



Notes: Figures show welfare/income (solid lines) and land stocks (dashed lines) in open (red) and closed (blue) economies over time, for $\sigma = 0.8$ and $\rho = 1.5$. Overall resilience indicators for open and closed economies: (i) Welfare: $R = 0.70$ and $R = 0.59$, (ii) Income: $R = 0.70$ and $R = 0.60$, respectively. Underlying parameter values are provided in Table (1).

economy is less fragile than a closed economy with a social planner, it is the opposite in a decentralized economy.

3. *A social planner case is less resilient than a decentralized one regardless of the elasticities substitution (except the lowest ones) and the trade regimes. It is also more fragile in the case of a closed economy, but less fragile when the economy is open.*

To see the intuition behind these results, note that the social planner balances the need to restore the diminished agricultural output after a natural shock with the objective to promote regeneration in nature-based assets–a motive that is missing in the decentralized case. This additional constraint under a social planner amounts to a relatively slow rebound from the shock, thereby reducing resilience compared to a decentralized case across all trade regimes and elasticity parameters.

To see why the closed economy is more fragile than the open economy in the SP case, with the opposite result in the DC case, note that there are several mechanisms at work in the economy's response to a given negative resource shock. First, note that in a closed economy the shock reduces food output and increases its price, reducing the consumption of food and, thus, utility. In an open economy, on the other hand, agents have access to food at unchanged prices and can import food from the rest of the world. This mechanism by itself would render the closed economy more fragile in both SP and DC cases.

However, two additional mechanisms are at work in the SP and DC cases, accounting for differences in fragility results. First, because the SP takes into account the negative externality involved, it allocates less labor to agriculture than the DC. One implication of this, with $G_{TL} > 0$, is that for a given allocation of labor, n, the decline in agricultural output following a negative shock will be larger in the SP case than the DC. However, a second mechanism works in the opposite direction. Recall that, when the economy is closed, a negative resource shock in the agricultural sector has two opposing effects on wages in this

Table 1: Summary Results

Panel A. Social planner solution with complete property rights

		R^U	R^U_{alt}	R^Y	R^Y_{alt}	Φ^U	Φ^Y
$\sigma = 0.8$, $\rho = 0.5$	Closed	0.64	0.27	0.64	0.16	0.27	0.16
	Open	0.78	0.12	0.78	0.07	0.13	0.07
$\sigma = 0.8$, $\rho = 1.5$	Closed	0.67	0.56	0.67	0.33	0.56	0.33
	Open	0.79	0.21	0.79	0.12	0.21	0.12
$\sigma = 1.2$, $\rho = 0.5$	Closed	0.69	0.52	0.70	0.27	0.53	0.28
	Open	0.79	0.19	0.79	0.10	0.20	0.10
$\sigma = 1.2$, $\rho = 1.5$	Closed	0.72	1.05	0.72	0.54	1.04	0.54
	Open	0.81	0.32	0.81	0.16	0.32	0.16

Panel B. Decentralized solution with incomplete property rights

		R^U	R^U_{alt}	R^Y	R^Y_{alt}	Φ^U	Φ^Y
$\sigma = 0.8$, $\rho = 0.5$	Closed	0.66	0.06	0.66	0.03	0.07	0.03
	Open	0.87	0.29	0.87	0.14	0.29	0.14
$\sigma = 0.8$, $\rho = 1.5$	Closed	0.72	0.13	0.72	0.06	0.13	0.06
	Open	0.89	0.31	0.89	0.15	0.31	0.15
$\sigma = 1.2$, $\rho = 0.5$	Closed	0.73	0.13	0.73	0.06	0.13	0.06
	Open	0.90	0.40	0.90	0.18	0.41	0.18
$\sigma = 1.2$, $\rho = 1.5$	Closed	0.78	0.22	0.78	0.10	0.22	0.10
	Open	0.90	0.43	0.90	0.19	0.43	0.19

Notes. Table shows different fragility and resilience indicators by different elasticities of input substitution (σ and ρ), trade regimes (open and closed), and property rights regimes for nature-based assets (a decentralized regime with incomplete property rights and a social planner case with complete property rights). The underlying parameters used in these simulations are as follows: $\beta = 0.3$, $\theta = 0.5$, $\gamma = 0.2$, $\lambda_1 = \lambda_2 = 0.5$, $r = 1.1$, $w = -0.2$, $K = 0.35$, $A = 0.5$, $M = 0.8$, $\delta = 0.98$, $T_2 = 2$, $F(n) = n^z$, and $z = 0.6$.

sector: (i) the shock reduces marginal productivity of labor but (ii) by increasing food prices raises its marginal revenue product. In the DC case, where labor allocation across sectors is governed by labor moving to the high-wage sector, this keeps more labor in agriculture when the economy is closed, thereby reducing fragility in the closed economy relative to the open. In contrast, labor is allocated by the SP to take into account the negative externality, and as such its allocation does not respond as much to wage differences across sectors. This means that when the economy is closed, the SP will not allocate as much labor to agriculture as DC, rendering the fragility of the closed SP economy higher than that of DC.

6 Discussion

This paper investigates the effects of three institutional factors on the fragility and resilience of economies in the presence of natural shocks: (i) the elasticity of substitution between inputs in agriculture (such as land, labor, or other natural assets), (ii) the trade regime (open economy vs. closed economy), and (iii) the property rights regime in nature-based assets (incomplete property rights in a decentralized regime vs. complete property rights with a social planner). The study demonstrates how these factors influence the economic propagation of a natural shock. Specifically, through their effects on the marginal productivity of labor in agriculture and on relative prices across sectors, these factors shape labor allocation across sectors in both the steady state and in transition. Therefore, they affect both the magnitude of the initial impact (fragility) and the pace of recovery over time (resilience).

The analysis builds on previous research in natural and social sciences, especially in ecology, such as Patrick et al., 2022, Pimm et al., 2019, and Pimm, 1984, to adopt a nuanced interpretation of the fragility and resilience concepts. Whereas fragility represents the immediate impact of the shock, resilience measures the speed of recovery from the shock.[15] We share with these papers the concern for not inadvertently conflating the two terms. For example, the initial economic impact of a given earthquake is determined by the structural integrity of buildings and infrastructure. By contrast, the persistence of the economic impact depends on the economy's ability to reallocate resources efficiently. Therefore, distinguishing between these two mechanisms is important for better targeting pertinent policies.

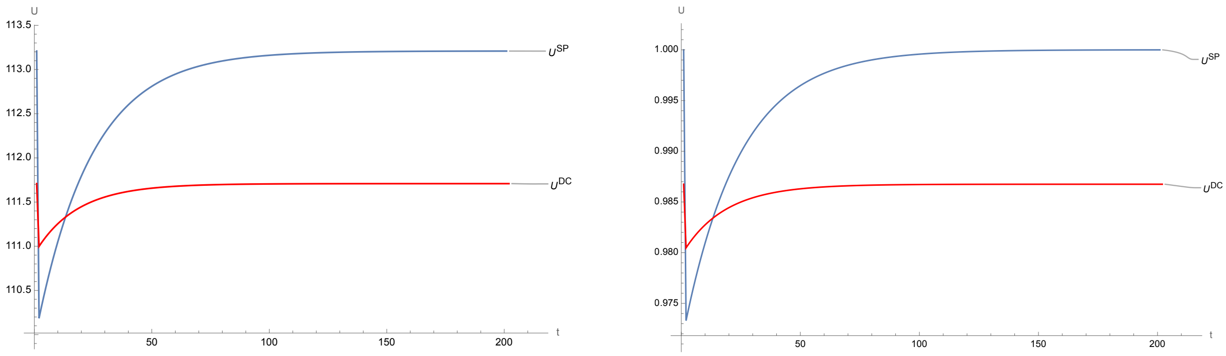
Our findings regarding the implications of openness for economic resilience contribute directly to recent policy discussions.[16] We demonstrate that open economies are more resilient than closed economies regardless of property rights regimes or the elasticity of

[15]For example Patrick et al., 2022 provide a comprehensive synthesis of coastal ecosystem susceptibility to tropical cyclones over two dimensions. First, intrinsic resistance (opposite to our fragility concept) captures the degree to which an ecosystem can remain unchanged despite disturbance. Second, intrinsic resilience (similar to our resilience concept) captures the ability of an ecosystem to return to the reference state after a temporary disturbance. Interestingly, their findings suggest a systematic tradeoff between intrinsic resistance and intrinsic resilience across different ecosystems and stressors like wind and rainfall – which is similar to our results. In our analysis, the tradeoff between the fragility and the resilience of closed and open economies in the decentralized case can be overcome by a social planner in favor of open economies.

[16]For example, in a recent Op-Ed, Jeffrey Frankel argued that the erection of trade barriers during the supply-chain problems associated with the COVID-19 pandemic have reduced economic resilience even in advanced economies (Frankel, 2022). Similarly, in his Per Jacobsson Lecture at the IMF, former IMF Chief Economist Raghuram Rajan suggested that backtracking on globalization will render climate change mitigation more difficult in the future (Rajan, 2022).

Figure 10: Welfare dynamics: Social planner vs. decentralized case

(a) Levels (b) Normalized Levels



Notes: Figures show the transition dynamics in welfare and income after a natural shock. The red lines show the decentralized case and the blue lines show the social planner case. In Panel B, series are normalized by using the social planner's initial steady state value.

input substitution in natural resource intensive sectors. However, open economies can also be more fragile than closed economies, even when we abstract from shocks originating from elsewhere in the world, if property rights in nature-based assets are not well defined. With complete property rights (the social planner case in our analysis), this result is reversed. To our knowledge, this recognition of the relationship between property rights in nature-based assets and the fragility implications of openness in the presence of natural shocks is novel and suggests an additional motive for trade policy preferences in developing countries, where property rights may be relatively less complete.

Furthermore, our analysis provides an interesting insight into the distinction between social planner and decentralized solutions. The social planner resolves the dynamic distortion problem in the decentralized economy by internalizing the social cost arising from excessive exploitation of nature-based assets. However, the social planner solution is less resilient and more fragile than the decentralized case in a closed economy (in the open economy, the decentralized solution is more fragile). This is due to the social planner's concern for the regeneration for natural assets, which leads to a smaller allocation of labor towards agriculture, resulting in a slower rebound from the shock (resilience) and a larger decrease in total output upon impact (fragility). Nevertheless, because the social planner maximizes the ex-ante sum of discounted future payoffs, in steady states before and after the shock, payoffs under a social planner are greater than those under a decentralized economy (Figure 10). This presents a curious case of risk-return tradeoff with important policy implications for climate change adaptation: policies aimed at maximizing economic outcomes in a static manner may not be well-suited to cope with increasing volatility.

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