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Food system consequences of a fungal disease epidemic in a major crop

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Fungal diseases are major threats to the most important crops upon which humanity depends. Were there to be a major epidemic that severely reduced yields, its effects would spread throughout the globalized food system. To explore these ramifications, we use a partial equilibrium economic model of the global food system (IMPACT) to study a hypothetical severe but short-lived epidemic that reduces rice yields in the countries affected by 80%. We modelled a succession of epidemic scenarios of increasing severity, starting with the disease in a single country in southeast Asia and ending with the pathogen present in most of eastern Asia. The epidemic and subsequent crop losses led to substantially increased global rice prices. However, as long as global commodity trade was unrestricted and able to respond fast enough, the effects on individual calorie consumption were, to a large part, mitigated. Some of the worse effects were projected to be experienced by poor net-rice importing countries in sub-Saharan Africa, which were not affected directly by the disease but suffered because of higher rice prices. We critique the assumptions of our models and explore political economic pressures to restrict trade at times of crisis. We finish by arguing for the importance of 'stress-testing' the resilience of the global food system to crop disease and other shocks.

This article is part of the themed issue 'Tackling emerging fungal threats to animal health, food security and ecosystem resilience'.

1. Introduction

The most important sources of calories for the human population are rice, wheat and maize. Foods derived from these crops not only form the staple diets of the majority of the world's population but they are also used as animal feed (especially maize) and hence have a further indirect contribution to diets via meat, dairy and other animal-sourced food. A fourth major crop, soya beans, is grown primarily for animal feed. Trade in all four crops constitutes a major component of the globalized food system with an estimated 7%, 19%, 12% and 30% of rice, wheat, maize and soya bean production being traded internationally (average 1995–2010; [1]). Over the last 100 years, there has been intense research into the genetics and agronomy of these crops and maximum yields have increased steadily, especially during the period of innovation in the 1960s–1980s termed the Green Revolution [2,3]. Despite the rapid growth in world population, there has been a secular decline in the prices of these commodities over the last century, though punctuated by episodes of volatility associated with major wars, the oil price crisis of the 1970s, and most recently, the period of volatility between 2008 and 2011 (figure 1) [4]. The combination of lower staple food prices and higher incomes has contributed to a reduction in the percentage of the world's population that are calorie deficient and the fact that the hunger Millennium Development Goal was met in 2015 [5].

All four of these critical crops are subject to infection by fungal pathogens. In a recent review, Fisher *et al.* [6] highlighted the most important fungal

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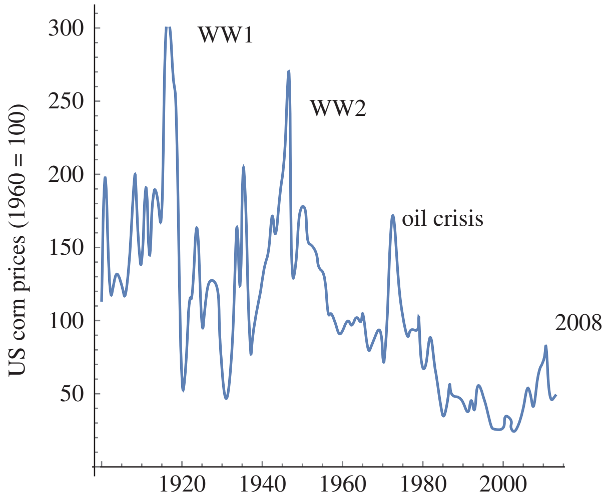

Figure 1. US corn (maize) prices since 1900 (from Baldos & Hertel [4]).

pathogen of each species, and the range of yield reductions for which they are currently responsible. Rice blast (*Magnaporthe oryzae*) is a widely distributed pathogen of rice, potentially found wherever this crop is grown (figure 2). It can cause 10–35% losses depending on crop variety and environmental conditions [7]. Wheat is attacked by the stem rust *Puccinia graminis* (and other *Puccinia* spp.) and in particular, the form *tritici* that can cause up to 70% crop losses [8]. Resistant varieties of wheat have been developed over the years leading to good control, though the emergence of a new virulent strain in Uganda in 1999 (UG99 or TTKSK) has raised concerns about the susceptibility of current varieties [9]. For maize, the most important fungal pathogen is corn smut, *Ustilago maydis,* which causes galling and other damage. Native to central and southern America, it has spread to most places where maize is grown and can lead to 20% crop losses [10]. Curiously, some consider the fungal gall (huitlacoche or Mexican truffle) a delicacy [11]. Finally, soya bean is attacked by the rust *Phakopsora pachyrhizi* that may cause up to 70% losses. Originally from Asia, it has spread to most areas where soya bean is grown. Soya bean is a legume, and this rust attacks other plants in the Fabaceae that can act as a reservoir for agricultural infections [12].

Control of fungal diseases is based on the breeding of resistant varieties plus the use of chemical fungicides [13]. Fungi can evolve to overcome plant resistance or fungicides and successful defence against this type of pathogen is akin to the Red Queen in Alice in Wonderland who has to run to keep still. There is a small but non-vanishing probability that a particularly virulent strain might arise that, at least for a few years, might substantially reduce yields over a broad geographic area. That this has not happened over the last 50 years provides some, but not great, comfort. In particular, the global spread of both plants and diseases means that once geographically restricted pathogens will encounter novel species with the opportunity for gene flow and recombination, providing new variation upon which natural selection can act [14]. Such events seem to underlie some of the fungal (and oomycete) diseases that have devastated particular tree species in Europe and North America [15,16]. Narrowing of the genetic base of crops can also increase their exposure to pathogens, as has been seen historically with grapevine [17] and is a current concern with dessert banana [18].

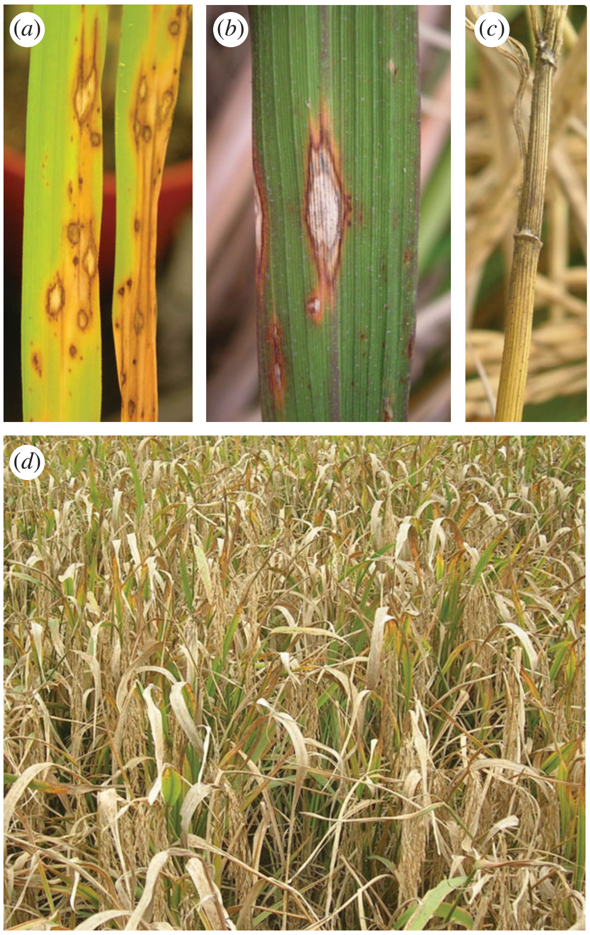

Figure 2. Rice blast disease symptoms. Rice blast disease is caused by the ascomycete fungus *Magnaporthe oryzae* (syn. *Pyricularia oryzae*). The fungus can infect leaves, stems and panicles of rice. (*a*) Leaf blast symptoms on 21 day old seedlings of rice. Seedlings can be killed by heavy leaf blast infection. (*b*) Mature disease lesion on a mature rice plant in Hunan Province, China. Disease lesions can reach more than 1 cm in length and produce 20 000 spores every 24 h for several weeks to spread the disease to adjacent plants. (*c*) Neck blast symptoms in mature rice plants in Hunan Province, China, when the fungus infects the neck of the panicle that holds the rice grain. Neck blast can lead to more than 90% yield loss. (*d*) View of a rice field, heavily infected by neck blast. The field suffered 80% yield losses. Photograph taken in Hunan Province, China in 2007.

The consequences of a major fungal disease epidemic will depend on the capacity of the global food system to absorb the shock, as well as on decisions made by relevant policymakers and other actors. The purpose of this paper is to explore this issue by assuming a severe disease epidemic that has a major effect on yields in a restricted geographical area. After consulting with fungal disease experts as to what might be a realistic worst-case scenario, we decided to model a rice disease (perhaps a variant of rice blast, figure 2) epidemic that causes an 80% loss of yield in a small to a large region of south and east Asia.

The rest of the paper is organized as follows. In §2, we discuss different ways of exploring the effects of a supply shock to the food system and introduce the modelling approach we take. Section 3 describes the results of the modelling, and §4 criticizes our study and suggests how it might be improved. Section 5 draws some conclusions.

2. Food system projections

What techniques are available for exploring future food systems and how they may respond to shocks such as major crop pathogen epidemics? Actually predicting future food systems is impossible; there are too many essentially unknowable factors that will affect food supply, demand and governance over the coming decades. However, we can take what we know about current food system dynamics, and combine them with scenarios about how the major drivers of the food system may change, and project the dynamics into the future, possibly subject to a policy intervention or supply shock. This approach can provide important insights into how the food system operates and the consequences of different policy decisions, but it should not be seen as a prediction [19].

Food system projections involve using a model (which may be phrased in maths or words, or a combination of the two) to map inputs into the food system onto outputs. The inputs (or exogenous drivers) include factors that can be estimated with some certainty over the next few decades, such as population growth, to those that require more assumptions to be made, such as country-specific economic growth. Biophysical processes may be included, some of which we are highly confident about (the Sahara will remain a low rainfall area this century), but others much less so (exactly how climate change will affect Asian monsoon patterns) [20]. Models differ in the number of drivers that are treated as exogenous and the usefulness of scenario projections depends of course on the validity of the assumptions underlying the inputs. The outputs of the model may be restricted to physical quantities such as weight of food produced and calories consumed, or it may seek to describe economic variables such as the prices of different food types.

The model underlying the food system projection may be purely statistical and incorporate no assumptions about mechanism. For very short-term projections, they may use simple statistical extrapolation of recent trends. Over a longer period, they typically involve establishing statistical relations between exogenous drivers and important food system variables. Thus, Tilman *et al.* [21] used data from the last 40 years to parametrize a function linking national gross domestic product (GDP, *per capita*) to individual total demand for calories (both consumed directly as plant food and indirectly through the consumption of animal-sourced food from livestock that themselves require calories from plants). They used this function to project total calorie requirements in 2050 which they suggested could be approximately 100% of current demand. On the supply side, they parametrized a function linking area in agriculture and nitrogen fertilizer use to total calorie production. Based on the assumption that calorie demand and supply should match, they explored the trade-off between nitrogen use and land in agriculture and what it might mean for greenhouse emissions, a very important issue for agricultural policymakers.

The statistical approach works well providing the system state stays in a region where the estimated functions remain valid. The further the state departs from the present and recent past the more problematic this becomes. One approach to mitigate this problem is to use expert judgement to assess when the statistical model moves outside its domain of applicability and to try to correct it. The Food and Agriculture Organization of the United Nations [22,23] has published a series of projections of future patterns of food supply and demand. These are based on statistical analysis of recent trends (in particular using the FAOSTAT, http://faostat3.fao.org/home/E) plus expert judgement of region and commodity specialists. The latest report [23] estimated that calorie demand would rise by 60% in 2050. Incorporation of expert judgement in projections allows for greater nuance and the identification of special cases, but it also risks the locking in of conventional and group thinking.

An understanding of how the food system works enables models to be built that are able to make projections into domains where statistical extrapolation fails. Different types of structural mechanism or process can be built into these models. For example, crop simulation models can be used to estimate the effects of novel weather regimes on crop yields. A very important class of models incorporates market processes and food and commodity prices. These fall into two broad subclasses: computable general equilibrium models that include complete economies, and partial equilibrium models that include only the food sector and treat the rest of the economy as exogenous [24]. While the former require fewer external inputs, in practice, they can only treat the food sector at quite a coarse level of resolution (though they are particularly useful in exploring changes in trade patterns). The projections in this paper were done using a partial equilibrium model called the international model for policy analysis of agricultural commodities and trade (IMPACT), which is described in more detail in §3.

The Tilman *et al.* [21] statistical model described above predicts that the demand for meat will increase substantially over the next 30 years as more countries enter the high-income classes and that this increase will have a substantial effect on demand for food and feed. However, the demand growth may lead to an increase in food prices that feeds back, at least partially, to suppress demand. Models that explicitly include markets are able to incorporate such economic feedbacks. This is a clear advantage, though in order to do so the model has to make multiple assumptions about the way actors in the food system, such as consumers, producers and merchants, make decisions based on the spectrum of food type and commodity prices they experience, as well as their intrinsic preferences. The underlying functions that embody these behaviours are to some extent parametrized from data, but the challenge of solving large economic models limits the complexity of the functions that can be used, and validation is very difficult. The usefulness of projections from market-based models depends on the validity of their depiction of underlying food system processes, which is very hard to assess.

Many studies of future food systems use scenarios: different, internally consistent narratives about the future [25]. For example, possible future food systems can be envisaged assuming different combinations of exogenous driver states: fast or slow global GDP growth, severe or moderate effects of climate change, expansion or contraction of global trade. Modern scenario studies originated in the military and were developed in the 1970s in the private sector—in particular at the oil company Shell [26]—and they are now used widely to help different actors explore alternative futures. Formally ensuring the consistency of the different components of a scenario can help to identify how drivers interact, while thinking about alternative futures can help avoid assuming the future will be very similar to the present. Critics of scenario analysis point to the number of arbitrary choices that have to be made and worry that the choice of scenario can constrain discussion and be used to frame debates about the future in particular ways [27]. We incorporate an element of scenario thinking in exploring how the results of our analysis can be extended.

3. Studying the effects of a fungal pathogen epidemic

(a) The epidemic

We make the simplest possible assumption about the nature of the rice disease epidemic: that it occurs in a single year (2016) and results in an 80% loss of yield in affected countries. We compare three scenarios: A, the epidemic occurs in Thailand alone; B, it affects most countries in Southeast Asia (Thailand, Myanmar, Laos, Cambodia, Vietnam, Indonesia and Malaysia); C, the epidemic also reduces rice yields in China. In §4, we consider the consequences of incorporating a more complex depiction of a rice pathogen epidemic.

(b) The model

We studied the effect of the rice pathogen epidemic on food system dynamics using IMPACT, which is developed by the International Food Policy Research Institute (IFPRI) in Washington, DC. A full description of the model can be found in Robinson *et al.* [28].

Briefly, IMPACT is a partial equilibrium economic model that explores the production and consumption of 62 agricultural commodities in 159 political units (which may be composed of subregions where political units encompass several water basins). Consumer diets are determined by income and food prices summarized by functions (elasticities) describing how they affect demand, whereas producer behaviour is determined analogously by commodity prices and input costs. Population, economic and technological or exogenous crop yield growth are treated as exogenous. IMPACT is linked to crop and hydrological models (that can themselves be driven by global climate models) to determine changing yield patterns. Different countries are linked by trade, and IMPACT works by finding global prices that clear commodity markets. IMPACT does not directly predict diets but patterns of calorie intake can be derived and compared with World Health Organization (WHO) guidelines for a healthy diet (approx. 2500 kcal for men and approx. 2000 kcal for women).

We ran IMPACT simulating the effect of an 80% drop in rice production for the areas specified in the three scenarios. If the country or region concerned were isolated from the rest of the world, then this shock would lead to a large increase in rice prices and a switch to other commodities, which would also increase in price. However, because IMPACT links countries by trade, the effects are blunted by an increase in imports (or the country may shift from being a net exporter to a net importer). IMPACT assumes world commodity prices equilibriate each year and the increased demand for rice from the affected countries will tend to increase global rice prices. This increase in prices will affect consumption patterns in countries beyond those immediately affected by the pathogen epidemic. They may also influence producers in non-affected countries to switch to growing more rice. To explore this we ran two versions of scenario B, the first (B1) assuming the area set to rice does not change in immediate response to the epidemic and the second (B2) that it does. Although in economic terms, it would be rational for producers to respond as in B2, various delays and frictions in the system make a very rapid response unlikely, and so B1 and B2 bracket the most likely outcome.

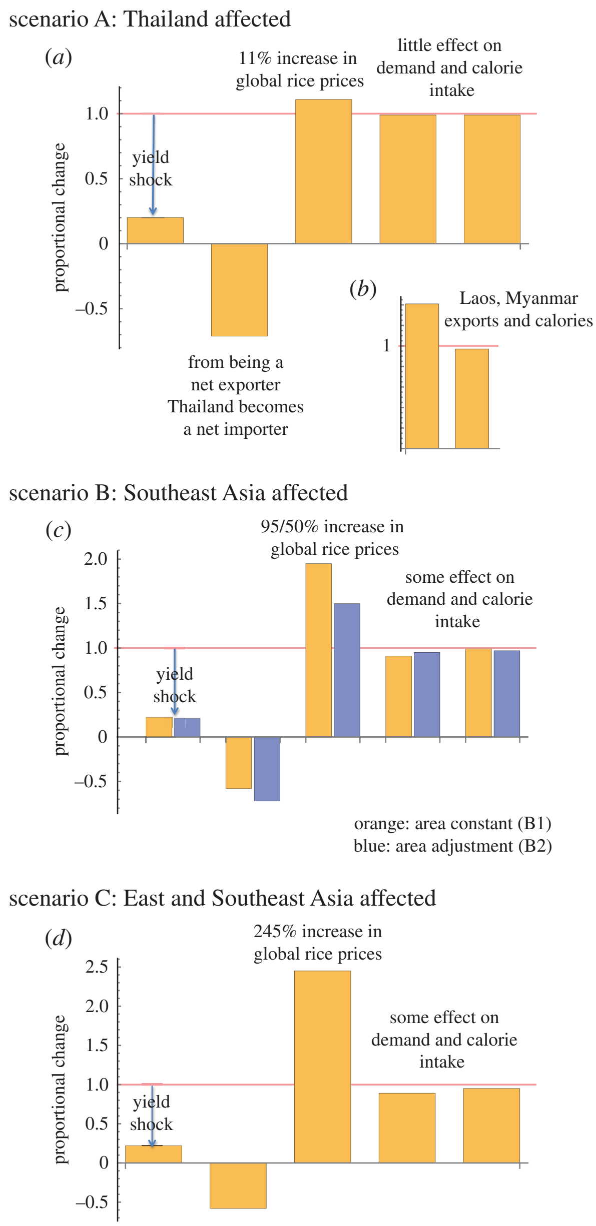

Figure 3. The effects of the different rice disease epidemic scenarios from the IMPACT model. The main parts of the figure (*a*,*c*,*d*) show the effects of the different epidemics on Thailand; the five bars are respectively the relative (i) yields, (ii) levels of imports/exports, (iii) global prices, (iv) demand, and (v) calorie intake. In (*c*), the two subscenarios assuming or not-assuming an increase in the global area of rice are shown. The inset figure (*b*) shows relative exports and calorie intake in Laos and Myanmar. See text for further explanation.

We had intended to run two versions of scenario C, the equivalents of B1 and B2, but were only able to solve IMPACT assuming producers in other countries respond to higher demand by planting more rice. This solution failure reflects the fact that IMPACT, like all market equilibrium models, cannot accurately represent major perturbations where it is unreasonable to assume markets equilibriate over an annual timescale.

(c) Results

We begin by focusing on Thailand and how it is affected by a local epidemic, and then explore epidemics affecting a greater

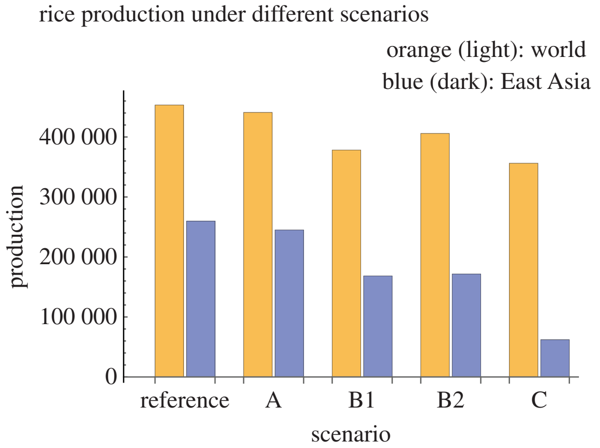

Figure 4. Global and East Asian rice production in 2016 without a disease epidemic and from the IMPACT model for the different epidemic scenarios (production in metric tonnes).

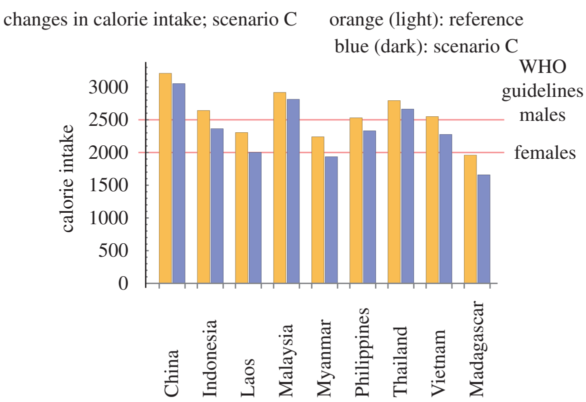

Figure 5. *Per capita* calorie intake from the IMPACT model for selected countries in the absence of rice disease and for the most severe epidemic (scenario C).

area of East Asia (scenarios A–C). With a local epidemic (A), Thailand switches from being a net exporter to a net importer (table 1) and, in consequence, there is an 11% increase in global rice prices (figure 3*a*). However, demand for rice in Thailand is virtually unchanged as is calorie intake. Trade clearly allows Thailand to weather the storm. Among the countries exporting to Thailand are its poorer neighbours Laos and Myanmar. They respond to the opportunities of higher global prices by exporting more, and both effects mean their citizens experience a reduction in calorie intake (figure 3*b*), which while not large is greater than in the richer adjacent Thailand.

A geographically more widespread epidemic (scenario B) has a much more severe effect on world food prices, leading to between a 50% and 90% (figure 3*c*) increase depending on the extent to which rice producers around the world switch to growing more of this crop. Again, Thailand is able to import rice to meet household demand, something that is easier in scenario B2 where area adjustment in other producing countries is allowed. Overall, there is still little effect on average calorie consumption in Thailand.

The most extreme shock we modelled is an epidemic affecting most of East Asia (scenario C) where, as discussed above, we could obtain results only if we assumed other countries adjust their rice production. Now, global crop prices jump by

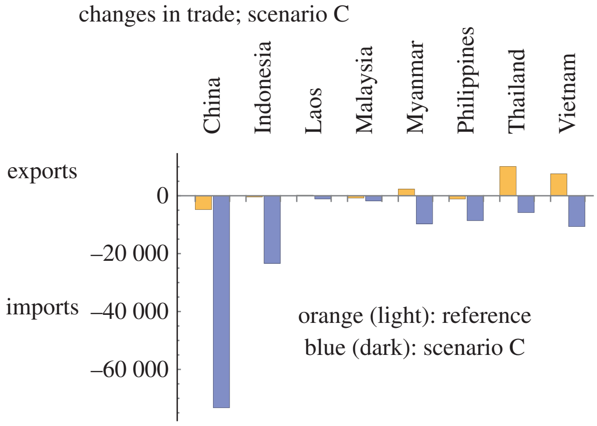

Figure 6. Imports and exports (in metric tonnes) for the IMPACT model for selected countries in the absence of rice disease and for the most severe epidemic (scenario C).

the very large factor of approximately 250% (figure 3*d*). Nevertheless, Thailand is still able to buy rice on global markets and, though demand and calorie intake are suppressed, the reductions are not very large and average calorie consumption stays comfortably above WHO guidelines.

Changes in global and East Asian rice production over the different scenarios are summarized in figure 4. The effect of progressively larger epidemics on East Asian rice production is clear and in scenario C, where China is affected, 76% is lost. Fifty-seven per cent global rice production comes from this region but shortfalls here can be partially made up by increased production elsewhere (compare scenarios B1 and B2 in figure 4). In the most extreme case (scenario C), a 76% reduction in East Asian rice production is reflected in a 21% drop in global production, a figure that would have been 44% without adjustment.

Rice is a staple crop throughout most of East Asia, and there is a clear concern that a production shock may lead to hunger and malnutrition. The estimated average calorie intake for countries in the affected region with normal rice production and for the most extensive epidemic (scenario C) is shown in figure 5 with the WHO guidelines for male and female daily intakes. The figures for Madagascar (the Malagasy Republic) are also included as an example of a poor country outside the region where rice imports are very important. Within the region, there is an effect of the severe epidemic on calorie consumption in relatively rich countries (China, Thailand and Malaysia) though they remain comfortably above WHO guidelines). For poorer countries (Indonesia, Philippines, Laos, Myanmar and Vietnam), where calorie consumption hovers around or is already below WHO guidelines, the epidemic is likely to lead to an increase in hunger, though this will depend on the demographic details of the people affected that IMPACT does not include. The case of Madagascar is particularly stark. Without a production shock predicted calorie intake is low and below WHO guidelines. Were global rice prices to rise as high as the model predicts, poor Malagasies would find it very hard to purchase the rice they require and average calorie intake would drop substantially below WHO levels.

Trade in the IMPACT model is critical in allowing countries to counteract the effects of a rice pathogen epidemic. The extent of this sensitivity is shown in figure 6 which compares imports and exports without an epidemic and for the most extreme example (scenario C). Those

Box 1. Model of a model.

A very simple stylized model of global rice supply and demand provides some insights into how IMPACT works. Let the global price of rice be p and the production of rice in country k be $S_k(p)$ which will depend on rice prices. A similar expression is defined for that country's demand for rice, $D_k(p)$, again a function of price. The global price of rice is that at which supply and demand for rice are equal

$$\sum_k S_k(p) - \sum_k D_k(p) = 0. \tag{3.1}$$

Now, assume that the k countries of the world are partitioned into two sets, i and j, and that the latter but not the former suffer a reduction in yield of $(1 - v)$ owing to a pathogen. Global prices are now defined implicitly by

$$\sum_i S_i(p) + \sum_j (1 - v)S_j(p) - \sum_k D_k(p) = 0. \tag{3.2}$$

We can implicitly differentiate equation (3.2) to see how global prices vary with the increasing severity of the epidemic

$$\frac{dp}{dv} = \frac{-\sum_j S_j(p)}{\sum_i (dS_i(p)/dp) + \sum_j (1 - v)(dS_j(p)/dp) - \sum_k (dD_k(p)/dp)}. \tag{3.3}$$

The price elasticity of demand for rice describes the change in the demand for rice given a change in price (e.g. a value of -0.5 indicates that a 10% increase in prices would lead to a 5% fall in demand). The price elasticity of supply is defined similarly. Let η_k and γ_k be the demand and supply elasticities that may vary across countries; elasticities are defined as

$$\eta_k = \frac{dD_k(p)}{dp}\frac{p}{D_k(p)} \quad \text{and} \quad \gamma_k = \frac{dS_k(p)}{dp}\frac{p}{S_k(p)}. \tag{3.4}$$

Substituting for the differentials in equation (3.3) and rearranging, we obtain

$$\frac{1}{p}\frac{dp}{dv} = \frac{\sum_j S_j(p)}{\sum_k -\eta_k D_k(p) + \sum_i \gamma_i S_i(p) + \sum_j (1 - v)\gamma_j S_j(p)}. \tag{3.5}$$

In words, the proportionate increase in global prices (the left-hand side) will be greater the larger the supply at threat (numerator of the right-hand side). The increase will be smaller as the denominator of the right-hand side increases either, because the price elasticity of demand becomes more negative (more 'elastic', so that price increases make consumers switch to other foods) or price elasticity of supply increases (farmers respond by planting more rice). The elasticities are weighted by total supply or demand in each country. Elasticities of supply in regions affected by the epidemic (j) are likely to be low (or 'inelastic') and start from a low base.

We can compare the predictions of equation (3.5) with those from IMPACT. Assume that there is no supply response (elasticities of supply, γ, are zero) and that the elasticity of demand is constant in all countries (η^*). Further, define Ω as the fraction of global supply in countries affected by the epidemic. Then, from equations (3.1) and (3.5), the proportionate increase in global food prices is $-v\Omega/\eta^*$. For an epidemic that reduces yields by 0.8 (v) in a country (Thailand) responsible for a proportion 0.05 of global production (Ω) and affects a commodity where consumers respond relatively inelastically (assume $\eta^* = -0.4$) to shortages then the proportionate increase in prices is 0.1, a good match to IMPACT (0.11). For an epidemic (scenario B1) that affects countries producing approximately 0.25 of global production the predicted increase in prices is 0.5 which is considerably less than predicted by IMPACT (0.95) assuming no response of producers. The reason for this is that for the bigger perturbation IMPACT captures many more of the knock-on effects on the global food system that the caricature of rice dynamics in equation (3.1) misses. Note also that even when IMPACT assumes no areal expansion of rice production, yields are endogenously a function of output prices as the model assumes farmers will invest more in inputs (such as fertilizers and labour) when prices are high.

countries that were net exporters beforehand (Myanmar, Thailand and Vietnam) become net importers, and trade inflows to existing importers increase dramatically. Note, in particular, the dramatic rise in imports required to meet the demand for rice in China and Indonesia.

(d) Underlying processes

IMPACT is a complex model but some insights into how it works can be obtained from exploring a 'model of a model'. Box 1 develops a simple model of global rice dynamics subject to a production shock of the type considered here. It suggests that with a number of simplifying assumptions the immediate proportional effect on global rice prices of the epidemic will be

$$\frac{\text{[Yield reduction][Proportion global supply affected]}}{\text{[Consumer response to higher price]}}.$$

The numerator describes the severity of the shock and the denominator describes the proportionate reduction in rice consumption as prices rise (technically the elasticity multiplied by -1; a value of zero equals no response while a value of -1 means an x% increase in prices leads to an x% drop in rice consumption). Box 1 also shows that if farmers respond globally to higher prices by planting more rice, this response reduces the increase in price. The approximation works well for scenario A but less well for larger shocks where the different complex feedbacks included in IMPACT need to be understood

(e) Summary

There are many limitations to the application of partial equilibrium multi-market models such as IMPACT to exploring production shocks that we shall explore in §4. Nevertheless, they do provide very interesting insights into how the food system might react to such events. Our analysis suggests that increasingly severe rice pathogen epidemics would have a major effect on global rice prices. Quite how large these will be depends on the extent to which the rest of the world responds to the East Asian crisis by producing more rice. IMPACT predicts that the effect of the production shock on diets and hunger in the affected region will be limited, though this is highly dependent on a fully functioning and rapidly responding global commodity trade system. Some of the most severe effects of the epidemic may be experienced in poor countries in other parts of the world that are reliant on rice imports to feed their population.

4. Critique

There are at least three ways that the projections in §3e may be misleading. First, they may accurately represent some, but not all of the consequences of the production shock for people's welfare. Second, to run the IMPACT model, a number of simplifications and assumptions about how the food system operates had to be made, and these might influence the projection. Finally, important features and processes of the food system that will affect outcomes may have been omitted entirely.

(a) Further consequences

An example of the first type of issue is the consequences to people and the economy of the rise in food prices. IMPACT predicts that, with varying success depending on average national income and the severity of the epidemic, the average person is able to maintain their calorie intake and avoid hunger. However, especially for the more severe scenarios, the cost of doing so will be great. There are likely to be significant knock-on effects on the spending power and welfare of individuals, and possibly on national economic activity, the precise effects depending on whether all the costs are borne by individuals or if governments intervene to subsidise rice [29]. Note that the effects of higher global rice prices are experienced in all countries, irrespective of whether they are directly affected by the pathogen.

Rice farmers will undoubtedly suffer a severe loss of income in countries afflicted by the epidemic, because higher rice prices will not compensate for the crop losses. The consequences to individuals will depend on the existence of welfare safety nets, unlikely to be present in the poorest countries where widespread destitution in rural communities is likely, possibly requiring foreign aid programmes for their alleviation. In rice-growing areas not affected by the epidemic, the rise in price for this staple is a clear economic opportunity. In these countries, different groups may suffer or benefit from increased rice prices depending on whether they are net producers or consumers.

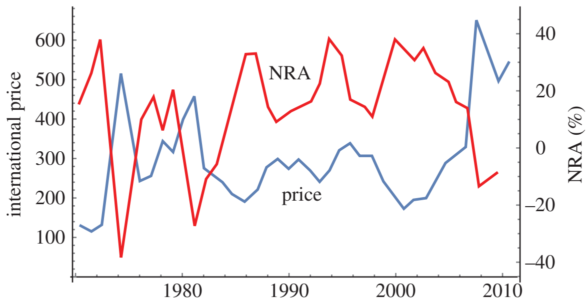

Figure 7. International rice prices 1970–2010 (US dollars per metric tonne) and a measure of average government intervention on prices (the nominal assistance rate, NRA; from Anderson & Nelgen [33]). Governments attempt to smooth fluctuations in international prices.

(b) Simplifications and assumptions

IMPACT assumes that markets clear (global prices equilibriate markets) each year. This assumption implicitly implies that global trade is able to respond to variations in supply and demand in different regions. This is perhaps a reasonable assumption for mild production shocks but more questionable for scenario C where China and Indonesia require very large increases in imports (figure 6)—is it feasible that the shipping and other transport infrastructure could be mobilized that fast, and the investment required to finance these trade movements raised in time? Delays in either would mean that regional prices would diverge and almost certainly be higher in affected regions. It would also lead to fewer incentives to increase rice production outside the epidemic countries, which would tend to exacerbate the problem (compare scenarios B1 and B2). Likely delays in the global trade response is one of the most important factors suggesting that IMPACT may underestimate the adverse effects of a major epidemic.

We assume a very simple epidemic that appears and causes a major yield reduction in a single year. A more realistic epidemic would take time to spread geographically and to increase in severity. This slower development of the epidemic would provide more time for the global trade system to anticipate and prepare for the supply shock and might possibly allow time for mitigating actions such as the discovery and planting of resistant strains, should they exist. On the negative side, the cumulative effect of the epidemic may be worse, especially if the most severe phase lasts more than a year.

We believe it would be useful to develop spatially explicit models of severe epidemics in a form that could be linked to IMPACT or other partial equilibrium market models to understand better their economic impacts.

(c) Omissions

Many countries maintain reserves of rice and other commodities that they can release onto the market at times of shortage. IMPACT does not include such reserves, because data on their size are difficult to obtain (many countries treat the data as market sensitive and China views the size of their reserves as state secrets) and decisions about their draw down or build up are in large part political rather than economic. It is generally thought that reserves (stock to use ratios) were particular low at the time of the 2008–2011 food price spike, and that this contributed to the price

Box 2. Effects of trade barriers.

Suppose that governments seek to buffer changes in global rice prices by trade tariffs so that domestic producers and consumers experience lower prices. Specifically, let local prices $p_i = a_i(p)$, be a function a of global prices, p. Equation (3.2) becomes

$$\sum_i S_i(a_i(p)) + \sum_j (1-v)S_j(a_j(p)) - \sum_k D_k(a_k(p)) = 0. \tag{4.1}$$

We can proceed exactly as before to obtain an expression equivalent to equation (3.5) for the effect of a production shock on global prices. If we further assume that there is no production response ($\gamma_i = 0$) and that the elasticity of the transmission of global to local prices is

$$\theta_i = \frac{\mathrm{d}a_i(p)}{\mathrm{d}p}\frac{p}{a_i(p)}, \tag{4.2}$$

then, substituting and rearranging, we obtain

$$\frac{1}{p}\frac{\mathrm{d}p}{\mathrm{d}v} = \frac{\sum_j S_j(p)}{\sum_k -\eta_k \theta_k D_k(p)}. \tag{4.3}$$

Simplifying further, assume that all elasticities are constant (denoted by *) and that Ω is the fraction of global production in affected regions. Now the effect of an epidemic on global prices is proportional to $-\Omega/(\eta^*\theta^*)$. Buffering of global prices implies $\theta^* < 1$ and hence will always tend to increase global prices (remember $\eta^* < 0$). In fact, when price interventions are uniform across the world, global prices adjust so that they have no net effect on local prices. For example, if the elasticity of price transmission to local economies is 0.5—a typical figure for rice [35]—then the expression above says that global prices double nullifying any benefits to local consumers. More realistically, price transmission will vary across countries and its effects on world prices will be determined by the mean of country-specific intervention elasticities weighted by the country's contribution to global demand.

volatility at that time [30]. Since then, stocks have increased (see http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1079), and were they to remain so at the time of a crop epidemic it might help buffer the markets against the shock.

A second major but inevitable omission concerns the political economy of rice prices and interventions by governments that result in local prices differing from the global market price [31]. Most often in the region considered here, imports are penalized to maintain local prices above global levels to protect rice growers who often form powerful political blocks. However, at times of high international rice prices, interventions may be directed to lower local prices to protect consumers [32]. Anderson & Nelgen [33] have collated information on such market distortions in rice (and other commodities), and find them to be pervasive (figure 7).

A price intervention by a single country can be effective in changing local prices if it acts alone (though if the intention is to protect poor producers or consumers then targeted protection is likely to be more efficient). However, in most cases, many countries act simultaneously, which can nullify the effects and increase volatility [34]. We can use the simple model developed in box 2 to look at the effects of trade barriers after a rice epidemic. Interventions that restrict the transmission of global to local prices tend to raise world prices and so undermine the intervention. In the limiting case where all countries impose the same measures, the increase in world prices exactly counteracts the interventions, so that local prices remain the same [35].

How countries would react to the threat of a rice epidemic is very difficult to predict but would be critical to the human outcomes. In 2008, many countries of the Association of Southeast Asian Nations (ASEAN) restricted exports as rice prices soared, which increased the prices paid by importing countries [34]. There was a general agreement that both exporting and importing nations did not gain from these greater restrictions, and limits to tariffs and quotas introduced by ASEAN countries dampened the volatility in rice prices in 2010/2011. However, the fluctuations in prices seen in 2008 and 2010 were considerably less than IMPACT suggests could occur with the more severe epidemic scenarios, and the political pressures governments will experience to intervene to protect their consumers and producers will be enormous.

The International Rice Research Institute maintains a partial equilibrium model, the International Global Rice Model, that is designed specifically to explore questions of trade in rice. It covers about 30 major rice-producing countries and incorporates many more of the specific details of national rice policies than is possible in IMPACT (though lacks the advantage of dynamic connection to the broader food system). It would be interesting to explore the consequences of a rice fungal pathogen, and the possible different political reactions to it, using this bespoke rice model.

5. Conclusion

The food system today is to a considerable extent globalized, which causes great concerns to some people, especially those whose world view includes a limited role for medium and large corporations. However, against these concerns must be set the importance of efficient global trade in providing food to major population concentrations such as the 'megacities' of the global south that (at least at the moment) cannot be fed by local agriculture, as well as providing the means of buffering the world against major production shocks, including the risk of major fungal crop epidemics that we have explored here.

Prompted by the 2008 financial crisis, there have been renewed efforts to 'stress-test' the global banking system. We see it as equally important to stress test the global food system. Recently, the insurers Lloyds of London sponsored a project to look at future scenarios involving a series of physical, biological and political shocks to the global food system, leading to severe price rises and major socio-political disruption [36]. The scenarios included crop epidemics, which though less serious than the one we explored here, affected different major crops simultaneously or in quick succession. Interestingly, the pathogens chosen were the major fungal diseases of wheat, rice and soya beans discussed in the Introduction. We see further modelling and scenario studies important to identify potential weak links in the food system and to advise where research, regulation and political attention are most needed. In the same way that responsible bankers now look back to 2000–2005 and curse their lack of foresight and appreciation of risk, food system policymakers should seek to avoid being in a similar position 10 years hence.

Authors' contributions. The authors together designed the project with the modelling using IMPACT carried out by D.M.d'C. and S.R. and the models in the Boxes by H.C.J.G. (checked by S.R.). H.C.J.G. wrote the first draft of the paper which was revised by all the authors.

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