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Research investment implications of shifts in the global geography of wheat stripe rust

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Biological Obsolescence from Stripe Rust and its Implications for Funding Wheat Research[1]

Prior to the early 2000s, stripe rust occurred mainly in western Canada and the Pacific Northwest region of the United States, and was of little consequence elsewhere in North America[1,2]. Localized and sporadic outbreaks in Southern Argentina, Southern Brazil and higher-elevation Andean areas have been documented, with more persistent problems noted in the relatively cooler wheat areas of Southern Chile (see Germán et al.[3] pp. 625-626). The disease has been a frequent and long-standing foe of wheat farmers throughout the Atlantic zone of Europe, occasionally with outbreaks in Mediterranean areas, including Italy, Tunisia, eastern Algeria and Spain, when more favorable, cooler, seasons prevailed (pp. 360-361 in Zadoks and Bouwman[4]). Higher elevations in southern Africa (see p. 269 of Saari and Prescott[5]) and the cooler, wetter wheat growing areas of the Western Cape, eastern Free State and KwaZulu-Natal in South Africa (see p. 596 of Pretorius et al.[6]) as well as the coastal areas of northern Africa (Saari and Prescott[5], p.271) have been affected by the disease, as have the cooler and more elevated regions of northern India, Pakistan, Nepal and southern Afghanistan (Saari and Prescott[5], p. 266). The disease has been especially problematic in the winter-wheat growing areas of north-west, south-west and north China, and the spring-wheat areas of north-west China, with the first major epidemic in 1950, followed by serious losses from other epidemics in 1964, 1990 and 2002 (see Wan et al.[7], p.605). Historically, stripe rust has not been associated with substantive crop losses in the Philippines, Sri Lanka, Malaysia, Thailand and Burma (Saari and Prescott[5], p. 272). The first detection of the disease in Australia was in 1979, with subsequent incursions of new (to Australia) variants of *Pst* in 1999 and again in 2002[8]. But stripe rust is on the move, and therefore it is prudent to revisit and, where necessary, revise evidence on the production and economic consequences of the disease. This supplementary note supports and underpins the work described in the main text to do just that.

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[1] The methods and procedures reported here extend, update and substantially modify a general approach first proposed and deployed for stem rust by Pardey et al.[9]. As part of the modifications necessary to capture biological realities unique to stripe rust, the counterfactual scenarios were re-specified to reflect the expanding spatial extent of stripe rust infections relative to historical norms. Further, the forward-looking simulations used here factor in prospective changes in global wheat markets through to 2050 reported by Pardey et al.[10]. These changes capture both the prospective dynamics of disease and market evolution over subsequent decades. In addition, the stem rust results reported here were re-estimated to render them comparable with the stripe rust results.

Global Occurrence

To develop a perspective of the changing global incidence of stripe rust, we followed Wellings[11] and used a modified version of the scoring method described by Murray and Brennan[12] to elicit survey responses for 35 countries from 43 wheat rust scientists engaged in the Borlaug Global Rust Initiative (see www.globalrust.org). Survey respondents were queried on the frequency of occurrence of the disease in their country of expertise, along with the average area extent of infection and the reported crop losses in those infected areas. Several questions sought more specific annual estimates (based on data, the respondent's judgment, or both) of the national-level crop losses (including area and severity of losses) attributable to stripe rust. The survey facilitated responses to these specific questions for the past 100 years, but only nine (21 percent) of the respondents provided any information prior to 1960. These annual responses were tabulated as an overall national "severity score" for each of the reported years (Table S1). Finally, we inquired about the respondents' perceptions of or evidence on the reasons for possible increases in the incidence of the disease.

The survey was carried out by email in late 2013 following a survey briefing and launch with prospective respondents and other experts at the 2013 Borlaug Global Rust Initiative Workshop at New Delhi, India. The annual "severity scores" obtained by way of the survey were combined with similar information provided by Wellings[11]) and additional information gleaned from published professional and grey literature (see references 1 to 38), to develop an indication of the changing extent of stripe rust worldwide. Figure S1 plots a three-year moving average (dark blue line), starting in 1960, of the number of countries that had a severity score greater than one (indicating the country had at least a moderate intensity of stripe rust). The upward slope of the trend line (dashed blue line) implies an expanding geographical extent of moderate to extremely severe losses attributable to the disease. The inset figure gives the number of country-years for which at least moderate losses were reported. For the 39 countries for which data were compiled, an average 3.5 country-years were reported for the 1960-1999 period; the 2000-2012 period averaged 7.2 country-years. A different summary of the worldwide occurrence of stripe rust is provided in Figure 1, Panels a and b in the main text wherein these same data were reconfigured into mapped "occurrence scores" for the period 1960-1999 and 2000-2012.

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U.S. Occurrence

Long-run, spatially explicit U.S. data on the occurrence of stripe rust support the international evidence that the geographical extent and magnitude of the crop losses attributable to stripe rust in wheat have been increasing of late. The first reported occurrence of stripe rust in the United States was in 1915 when it was observed in Arizona, California, in trace amounts in Idaho, Montana and Utah, and in "considerable abundance" in Oregon and Washington State (see Carleton[13], p. 58). Smith[14] suggested that the pathogen was likely present in California at least as early as the 1700s, a notion that Line[15]supported, noting that prior to the turn of the 20th Century "[t]he disease was widely distributed and prevalent on native grass hosts in the West but absent in the East (p. 77)." However, for many years thereafter, stripe rust appeared to be of little commercial consequence. Line[15] (p. 82) reports that "[b]y the mid-1930s, there were no major research projects on stripe rust in North America and for almost 20 years, only occasional observations of stripe rusts on additional grass species appeared in the *Plant Disease Reporter*." Line[15] (p. 82) further observed that "[i]nterest in stripe rust was renewed when the disease appeared in central North America in the late 1950s." Infections were reported at various locations throughout Texas in 1953, 1956, and 1957, spreading to the Oklahoma panhandle in 1958[16,17]. That same year, infections on wheat and other grass species were also reported in western Kansas, Nebraska, Wyoming, Minnesota, and South and North Dakota (see Line[15], p. 83). In 1960 and 1961, stripe rust epidemics in the Pacific Northwest developed suddenly and without warning (Line[15], p.83), resulting in substantial losses: an estimated 25 percent of Washington state's wheat production in 1960 and 30 percent of that state's 1961 output[18].

These substantial losses spawned an era of renewed research to ameliorate crop-losses to the disease by identifying the evolving races of stripe rust, searching for genes to confer crop resistance to the (changing) disease, breeding resistant crops, and developing fungicides. The pathogen even attracted the attention of the U.S. army during the Cold War, both as a biological weapon that might be used to attack enemy crops and as a serious plant pathogen that could affect U.S. national security[19]. Line[15] (p.90) noted that military and civilian research on stripe rust (the latter funded in part by military expenditures) reached its zenith by the late 1960s. Thereafter, sole federal government responsibility for research on stripe rust was vested in the United States Department of Agriculture (USDA), where funding was scaled back (as it was for numerous other wheat rust research and breeding programs in the U.S. land grant universities), and the Department of Defense support ceased.

The pathogen nevertheless continued to evolve, with more-or-less susceptible wheat varieties to these new (and old) variants of stripe rust being used with different frequencies in different locations. Thus the crop production consequences of the disease were being managed but not eliminated, with the magnitude and geographical extent of the disease reflecting a host of biological, climatic, research and farmer practice outcomes. Figure 1, Panels c and d in the main text and Figure S1 in this report (solid red line for a three year moving average; dashed red line is the line of statistical best fit) indicate that the geographic extent of the pathogen within the U. S. has been increasing since the 1960s, just as it has among countries the world over. Among the contiguous U.S. states, an average of 1.3 state-years (2.7 percent of the total) recorded measurable commercial losses from stripe rust prior to 2000, increasing to an average of 3.7 state-years (7.7 percent) for the period 2000-2012 (Figure S1, inset).

U.S. Wheat Crop Losses Attributed to Stripe Rust

Prior to 2000, the majority of U.S. commercial losses were in states west of the Rockies, with a preponderance of the losses occurring in the Pacific Northwest and California (Figure 1, Panel c in the main text). The outbreaks noted in the central and south-central states during the 1950s were seemingly transitory, and limited in geographical scope. However, there appeared to be a change in the geographical pattern of U.S. losses beginning around 2000, with an increasing frequency and magnitude of wheat production losses being reported in the central U.S. states from Texas to Minnesota, and spreading into the (south) eastern part of the country.

Figure S2, Panel a provides summary annual estimates of the percentage wheat crop loss for the Pacific Northwest (including Oregon, Washington, Idaho) and California versus the rest of the country. The data reveal the spatially variable incidence and severity of the disease, underscoring that losses for any one (or a few) years for any particular (or a few) states is a biased estimate of the national-level losses over a period of time—the preferred estimate when seeking to assess a strategic research investment response to tackling this versus other crop production problems. For example, during the period 1959-1984, the Pacific Northwest and California averaged losses of 4.1 percent per year. In some years the losses exceeded 10 percent of the region's entire wheat crop—19.1 percent in 1960 (constituting a 25 percent loss in Washington state but no losses in neighboring Oregon that particular year), 23.8 percent in 1961

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and 11.3 percent in 1976—,while in other years the losses were negligible or non-existent. During this same period, the losses for the rest of the U.S. (constituting 86 percent of the total national wheat crop production during this period) were negligible, averaging just 0.02 percent per year. For this entire region, no measurable losses were reported for 20 (77 percent) of the years.

During the period 1985-1999, the average annual losses in the Pacific Northwest dropped to just 1.0 percent per year; a period when fungicides—which Line[15] (p. 108) noted were first introduced into the region in 1978—and resistant varieties were being used widely (Chen[2], p. 316). During this same period, the losses recorded throughout the rest of the U. S. were negligible (averaging 0.02 percent per year), but increased markedly thereafter, averaging 1.3 percent per year for the period 2000-2014.

This evidence suggests the changing geographical extent and magnitude of stripe rust losses within the U. S. can be parsed into three eras. The first is the period 1959-1984, when losses were limited mainly to the Pacific Northwest and were being managed by the use of resistant varieties. The second is the period 1985-1999, when the geographical consequences of the pathogen were still mainly limited to areas west of the Rockies, but in this period fungicides were extensively used in conjunction with resistant varieties, further suppressing the reported losses. In the final period, 2000-2014, resistant varieties and fungicides were still in use, but the geographical extent of losses had spread well beyond the (north) western states. In each of these eras, the year-on-year losses within any one state were extremely variable, with, for example, reported production losses in Idaho being 12.5 percent in 1980, 7.0 percent in 1981 and no more than 3 percent in each of the following 29 years, followed by 5.6 percent losses in 2011; whereas Indiana and Kentucky never lost more than 1.0 percent of their respective wheat crops in any year during the entire period 1959-2014.

The production losses reported by USDA, CDL reflect the outcome of a complex, and spatially and temporally variable pattern of rust dispersal, virulence, varietal development and deployment (especially, the location and timing of planting), along with associated crop management (especially fungicide use)[20]. Notwithstanding these crop genetics and management interventions, losses to farmers still occurred. Chen[21] documented the appearance of 121 new *Puccinia striiformis* f. sp. *tritici* races in the U. S. between 1963 and 2005, with varying virulence against available wheat varieties. Deploying a stream of locally adapted varieties of wheat with sufficiently broad and ever-upgraded resistance to these changing patterns of virulence is a tall order.

In sum, the evidence indicates that losses in any one state in any particular year are not representative of the extent of the national losses over a period of time. By extension, the losses for any given country in any year are also unlikely to be indicative of the global losses over a period of time. It is the more comprehensive loss estimates (in geographic scope and time) that are relevant for forming probabilistic estimates of the likely global losses that meaningfully inform strategic choices about the economically justifiable investment in crop breeding research to mitigate the global consequences of this (and other) pathogens.

Modeled Climate Suitability for Occurrence and Persistence of Wheat Stripe Rust

To estimate the potential distribution of *Puccinia striiformis* f. sp. *tritici* worldwide[2], we used the CLIMEX Compare Locations model[22,23] , run with the CliMond 1975H climatology[24]. The CLIMEX model uses information on the ecology and phenology of a species to assess the areas in the world that are suitable for the growth and development of the pathogen. Several suitability indicators are calculated for each pixel on the planet (in this case a 10 arc minute, grid cell). The annual Growth Index (GI_A) quantifies the climatic suitability for populations of the pathogen to grow, while the Ecoclimatic Index (EI) quantifies the overall potential for year-round persistence of the pathogen, discounting the GI_A with stresses accumulated during unfavorable weather.

Details of the stripe rust model are provided in Chai et al.[25]. The plotted GI_A and EI values are within the estimated extent of global wheat production in 2005 (as reported by You et al.[26]), adjusting the CLIMEX model to account for the effects of irrigation as appropriate (see below). Figure 2, in the main text maps the respective GI_A and EI indexes worldwide. Figure S3, Panels a-d, map the same GI_A, EI, and occurrence data on a regional basis for North America, Europe, Africa and South Asia, along with geo-referenced occurrence data compiled by the authors for this study.

[2] Coakely and various co-authors report on a series of climate matching models to notionally predict the disease severity of stripe rust on wheat in specific locations in the U.S. Pacific Northwest[27-31]. As their models were statistical in nature, and fit to particular locations and cultivars, it is difficult to interpret their findings in the context of a global assessment. However, Coakley et al.[31] found that "[m]ost of the variation in disease severity that occurs from year to year can be explained by variation in climate (p. 72)" implying the present exercise might be fruitful.

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Table S2 reports regional estimates of the wheat area and production that is seasonably susceptible to the disease (GI_A index). The table also reports the wheat area that can host the pathogen year-round (EI index), along with the production of that area. The risk of crop losses for farmers operating in areas where the pathogen persists inter-seasonally are likely higher than in areas where the pathogen typically arrives by way of highly variable wind-enabled dispersal processes. We estimate that 79.7 percent of the world's wheat growing area (173.4 million hectares in 2012) and 88.0 percent of production (591.0 million tonnes in 2012) is susceptible to the pathogen, while the spores that cause the disease can persist year-round on 26.1 percent of the world's 2012 wheat area. Around 93.6 percent of the U.S. wheat area (and 95.1 percent of 2012 U.S. wheat output) is susceptible to stripe rust, but only 8.6 percent of that area supports the pathogen year round. In stark contrast, the wheat growing areas of sub-Saharan Africa are especially susceptible—about 78.4 percent of that area is climatologically suitable for the occurrence *and* persistence of the pathogen, placing African farmers at significantly higher risk from losses to stripe rust. Thus, our global loss estimates, and the corresponding investment implications, are conservative.

Probabilistic Estimates of Counterfactual Production Losses

The HarvestChoice Spatial Allocation Model (SpAM) provides estimates of wheat yield, output and area in each of three production systems (irrigated, high-input rainfed and low-input rainfed) at 5 arc minute resolution. The CLIMEX state variables (EI and GI_A, see the main text) were spatially intersected with the wheat crop geography information from SpAM to create an integrated risk map, combining CLIMEX scenarios for both the irrigated and non-irrigated wheat growing areas, but excluding low-input areas (which are conservatively assumed to plant susceptible varieties in all periods). Following Saari and Prescott[5], the world was divided into 15 epidemiological zones constructed such that, in any given year, an epidemic in a given zone is likely to occur independently of epidemics in other zones due to the independence of climatological patterns among the zones[33]. Country-specific wheat production and area estimates from FAOSTAT (for years 1961-2010) and Pardey et al.[10] (for years 2011-2050) were aggregated across these fifteen zones. The share of each zone, z, that is suitable for stripe rust (β_z) was calculated as

$$\beta_z = \left[\boldsymbol{\alpha}'_{\mathbf{z}}(\mathbf{GI}_{\mathbf{z,i}} \circ \mathbf{I}_{\mathbf{z}}) - \boldsymbol{\alpha}'_{\mathbf{z}}\left(\mathbf{GI}_{\mathbf{z,n}} \circ (\mathbf{I}_{\mathbf{z}} - \mathbf{1})\right)\right] / \boldsymbol{\alpha}'_{\mathbf{z}}\mathbf{1}$$

where

$\boldsymbol{\alpha}_{\mathbf{z}}$ is a vector of the total irrigated and high-input rainfed wheat production area in zone z's cells;

$\mathbf{GI}_{\mathbf{z,i}}$ is a vector of binary seasonal suitability indicators under the irrigated scenario (1 if suitable; 0 otherwise);

$\mathbf{GI}_{\mathbf{z,n}}$ is a vector of binary seasonal suitability indicators under the non-irrigated scenario (1 if suitable; 0 otherwise);

$\mathbf{I}_{\mathbf{z}}$ is a vector of binary indicators set to one if any wheat area in the corresponding cell was irrigated and zero otherwise;

$\mathbf{1}$ is a vector of ones of the appropriate length, and " ∘ " is the operator indicating an element-by-element vector product.

Estimating Conditional Beta Distributions of the Losses Attributed to Stripe Rust

We used the reported losses in the United States to characterize the stochastic nature of stripe rust losses across the 15 epidemiological zones. We obtained the annual wheat losses to stripe rust from 1959 to 2014 from USDA[18] in the United States and parsed them into three eras 1959-1984, 1985-1999, 2000-2014 as discussed below. We chose to model losses as a conditional beta distribution with no autocorrelation:

$$f(l) = \begin{cases} p & \text{for } l = 0 \\ (1-p)\dfrac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} l^{a-1}(1-l)^{b-1} & \text{otherwise} \end{cases}$$

where $1 > l \geq 0$ is the reported proportional loss; p is the probability that no loss was reported, $\Gamma(\cdot)$ is a gamma function, and $a > 0$ and $b > 0$ are the parameters of the beta distribution conditional on a positive loss. The parameters p, a and b were estimated using the maximum likelihood routine in STATA and are reported in Table S3. Figure S4, Panels a-c plots the fitted crop loss distributions against the observed data for each of the three eras.

Construction of Counterfactual Yields

Using the estimated crop loss distributions, we applied two counterfactual scenarios to assess the economic benefits of deploying resistant varieties. In the "no-loss scenario", we benchmarked the analysis on a counterfactual that embeds the assumption that crop losses from stripe rust would be entirely avoided. In the "low-loss scenario," we benchmarked the analysis on an arguably more realistic counterfactual, namely the suppression (but not complete

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avoidance) of losses from stripe rust via the incomplete and not universally effective deployment of resistant crop genetics, fungicides and other management strategies. The continually evolving virulence of the pathogen coupled with an expanding geographical range (in more recent years) along with a highly stochastic (often climate mediated) spore dispersal process renders this low-loss option a more plausible point of reference for this analysis. The pattern of U.S. losses observed during the second era (1985-1999) was taken to be representative of this low-loss scenario in each of the 15 epidemiological zones.

Specifically, the 1959-1984 and 2000-2014 counterfactuals are calculated assuming that stripe rust losses are reduced to the low loss levels of the 1985-1999 era. For each era, the counterfactual yields in areas susceptible to stripe rust were calculated as:

$$Y_{tz}^{p}(l_{tz}^{A}) = \frac{Y_{tz}^{a}}{(1-\alpha_{tz}) + \alpha_{tz}\big(\beta_z(1-l_{tz}^{A}) + (1-\beta_z)\big)} = \frac{Y_{tz}^{a}}{1-\alpha_{tz}\beta_z l_{tz}^{A}}$$

where $Y_{tz}^{p}(l_{tz}^{A})$ is the average yield that would have been observed in year t and zone z if all stripe losses were eliminated; Y_{tz}^{a} is the actual observed yield in year t and zone z; α_{tz} is the proportion of zone z planted with rust resistant wheat varieties in year t; β_z is the proportion of the wheat production area in zone z that is suitable for stripe rust; and l_{tz}^{A} is the actual yield loss in zone z in year t. The counterfactual yield with a different scenario of loss was calculated as:

$$Y_{tz}^{cf}(l_{tz}^{A}, l_{tz}^{C}) = \Big[(1-\alpha_{tz}) + \alpha_{tz}\Big(\beta_z(1-l_{tz}^{C}) + (1-\beta_z)\Big)\Big] Y_{tz}^{p}(l_{tz}^{A}) = (1-\alpha_{tz}\beta_z l_{tz}^{C}) Y_{tz}^{p}(l_{tz}^{A})$$

where l_{tz}^{C} is the proportional yield loss that would have been observed in these regions under our counterfactual scenarios.

To implement the no-loss counterfactual, we set $l_{tz}^{C} = 0$ and $Y_{tz}^{cf}(l_{tz}^{A}, l_{tz}^{C}) = Y_{tz}^{p}(l_{tz}^{A})$. For the low-loss scenario, l_{tz}^{C} was estimated by random draws from the estimated beta distributions for the 1985-1999 era.

Estimating Counterfactual Losses

With counterfactual yields $Y_{tz}^{cf}(l_{tz}^{A}, l_{tz}^{C})$ derived as above for each of the two scenarios, we calculated the counterfactual production losses as:

$$L_{tz}^{cf}(l_{tz}^{A}, l_{tz}^{C}) = \Big(Y_{tz}^{a} - Y_{tz}^{cf}(l_{tz}^{A}, l_{tz}^{C})\Big)\, A_{tz}$$

where A_{tz} is the area of wheat production in zone z and year t.

These losses were aggregated across fifteen epidemiological zones for each year:

$$L_t^{cf}(l_t^A, l_t^C) = \sum_{z=1}^{15} L_{tz}^{cf}(l_{tz}^A, l_{tz}^C)$$

where l_t^A and l_t^C are vectors of the zonal losses. Finally, we calculated the values of the counterfactual losses by valuing the production losses using the 2009-2010 U.S. average wheat price[34].

Monte Carlo Crop Loss Simulations

The distributions for $L_t^{cf}(l_t^A, l_t^C)$ were constructed by randomly drawing two uniform variates for each zone and time period, and for 50,000 replicates, namely u_{tz}^r and v_{tz}^r where r represents the replicate. If $u_{tz}^r \geq p$, a yield loss in zone z and period t was assumed to have occurred. Given a loss, its size was calculated as $l_{tz}^r = beta^{-1}(v_{tz}^r, a, b)$. For l_t^A, the parameter estimates from the corresponding time period were used; for counterfactual loss l_t^C, we used $l_t^C = 0$ under the no-loss scenario and the parameter estimates from the 1985-1999 era under the low-loss scenario. The Monte Carlo simulation was implemented using Microsoft Excel 2010 with the Palisade @Risk add-in.

Probabilistic Consequence of Stripe Rust Losses

Table S4 summarizes the Monte Carlo simulation results of the annual stripe rust losses that could potentially be avoided (using resistant wheat varieties and/or adopting better disease management practices) within each time period under the two different counterfactual scenarios. We report the mean values of global average annual loss attributed to stripe rust, as well as the loss estimates at the 5, 20, 50 and 90 percent probability levels. Under the no-loss counterfactual scenario (where we assume that crop losses from stripe rust would be entirely avoided), the mean values of avoidable global annual losses to stripe rust were estimated at 1.24 and 6.19 million tonnes for the 1959-1984 and 2000-2014 eras, respectively; under the low-loss scenario (where we assume that crop losses from stripe rust would only be suppressed but not completely avoided), the mean values of global annual losses to stripe rust were, respectively, 0.88 and 5.47 million tonnes. For the 2000-2014 era under the low-loss counterfactual, there is a 90 percent chance of losing at least 4.70 million tonnes (equivalent to US$840 million at 2009-2010 prices).

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Economically Justified R&D Investments to Control Wheat Stripe Rust

The economically justified investment in wheat R&D to mitigate the losses attributed to stripe rust was estimated as:

$$V(r^r, r^c, r^m) = \max\left\{v: \Pr\left(\sqrt[60]{\frac{\sum_{t=2000}^{2050} p_t L_t^{cf}\,(1+r^r)^{2050-t}}{\sum_{t=1990}^{2050} v(1+r^c)^{1990-t}}} - 1 \geq r^m\right) > 0.95\right\}$$

where p_t is the price of wheat in year t, r^r is the reinvestment rate, r^c is the cost of capital, and r^m is the modified internal rate of return (MIRR). Using this equation, we calculate the annual investment amount for 1990 to 2050 that yields a MIRR of at least r^m (targeting 10 percent per year) with a probability of 0.95, given a reinvestment rate of r^r (assumed to be 3 percent per year) and cost of capital rate r^c (also assumed to be 10 percent per year). The MIRR method and assumed parameters are based on Hurley et al.[32]. Wheat production and area data from 1990 to 2050 were obtained from FAOSTAT and Pardey et al.[10]. Nominal wheat prices from 1990 to 2010 were obtained from USDA[34] and deflated into real values with base year 2010 using the U.S. implicit GDP deflator from the Department of Commerce, Bureau of Economic Analysis. The future wheat prices from 2011 until 2050 are set equal to the 2009-2010 U.S. average wheat prices.

Given the two counterfactuals and the assumed parameters, the resulting values are an estimate of the opportunity cost of research funding directed towards mitigating global stripe rust losses. Here, the more contemporary losses (i.e., those during the 2000-2014 era) are taken to be representative of the losses in each zone through to 2050 (see Footnote 1). Based on the Monte Carlo simulations of stripe rust losses, the maximum annual investment values were obtained using the optimal goal seeking function within the Palisade @Risk add-in for Microsoft Excel 2010 with 5000 iterations and 100 simulations. We estimate that an on-going annual average investment of US$ 32.0 million for the low-loss counterfactual and US$ 36.2 million for the no-loss counterfactual (Table S5). The last line of Table S5 reports the additional research investment that is attributable to changes in the geographical extent and virulence of stripe rust in recent years.

Price Sensitivity Analysis

Our analyses above uses the 2009-2010 U.S. wheat price (US$178.9 per ton) to value losses attributed to stripe rust. However, wheat prices fluctuate, and thus so do the costs and benefits of investments into loss-mitigating R&D. The real (inflation adjusted) price of wheat generally decreased from 1961 to 2000, and trended upward thereafter. The 2009-2010 price was lower than in the few years surrounding that date and generally representative of prices over the previous two decades, yielding a more conservative estimate than would more contemporary prices. To assess the sensitivity of our results to the wheat price used, we implemented two additional wheat price scenarios: (1) the average U.S. wheat price level during 1980-2000 (US$196.6 per ton, expressed in 2010 prices), and (2) the U.S. wheat price during 2013-2014 (US$236.0 per ton), again in 2010 prices. Both price levels are deflated into real values as described above. As both alternative prices were higher than the 2009-2010 price, they yield larger estimates of the level of economically justified R&D investments (Table S5, lower two sections): under the low-loss scenario with a 2000-2014 reference period, the estimate of economically justified R&D increases by 7.2 percent at the average 1980-2000 price and by just under a quarter at the contemporary (2013-2014) prices.

Re-estimating the Investments in R&D to Control Wheat Stem Rust

For wheat stem rust, Pardey et al.[9] report that a sustained investment of $51.1 million per year (2010 prices) to avert the global crop losses attributable to stem rust is economically justified. This result is based on estimating the losses in a counterfactual 1961-2009 world where the probabilistic structure of the losses was similar to that observed for the United States during the period 1918-1960. A 10-year lag between the initiation of R&D spending and the realization of benefits (from losses averted) attributable to that spending was assumed. To ensure compatibility with the stripe rust estimates presented here, we re-estimated the benefits attributable to research on stem rust by estimating the counterfactual losses averted for the period 1990-2050 with all other estimation details held constant. For this period we find a global investment of $50.9 million (2010 prices) per year is economically justified to control wheat stem rust, under the counterfactual scenario of the 1918-1960 structure of U,S. stem rust losses used by Pardey et al. [9]

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	Score	
	ID	Value
Severity Score		
Extreme Severe	ES	>20
Very Severe	VS	>10
Severe	S	>5
Moderate	M	>1
Light	L	>0.1
Negligible	NT	>0
No Losses	0	0
Occurrence Score		
Not recorded		0
Rare		1
Localised in some seasons		2
Localised in most seasons		3
Widespread in some seasons		4
Widespread in most seasons		5

Table S1. National severity and occurrence scores. Developed by authors based on data from Wellings[11] and Murray and Brenann[12].

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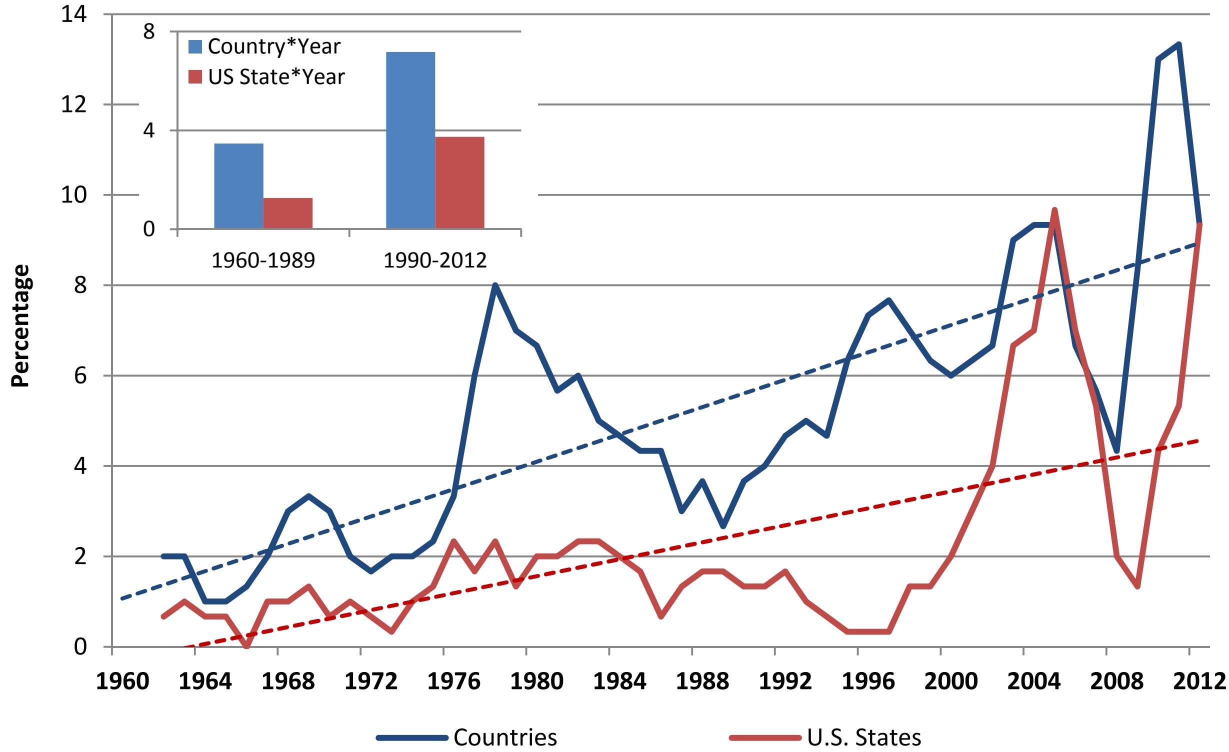
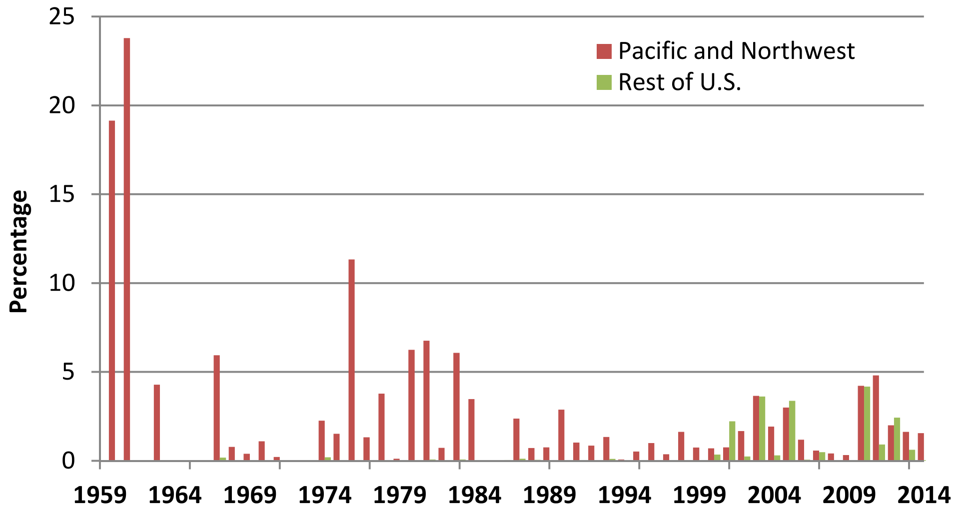


Figure S1. Increasing incidence of stripe rust worldwide and in the U.S., 1960-2012. Developed by authors using data from USDA[18], author survey, Wellings[11], and the Rust Occurrence References (1-38) listed above. The dotted lines show the best linear fit through the corresponding time series.

a



b

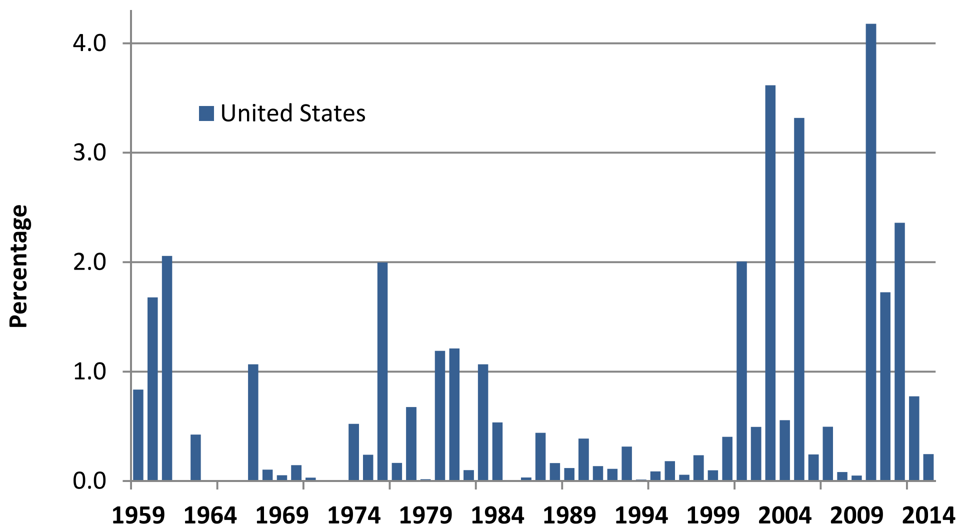


Figure S2. U.S. wheat yield losses attributed to stripe rust, 1959 to 2014. a, Stripe Rust Losses: Pacific North West vs. Rest of U.S. **b,** Stripe Rust Losses in the U.S. Developed by the authors using data from USDA[18]. In **a**, Pacific and Northwest includes all states west of the Rocky Mountains.

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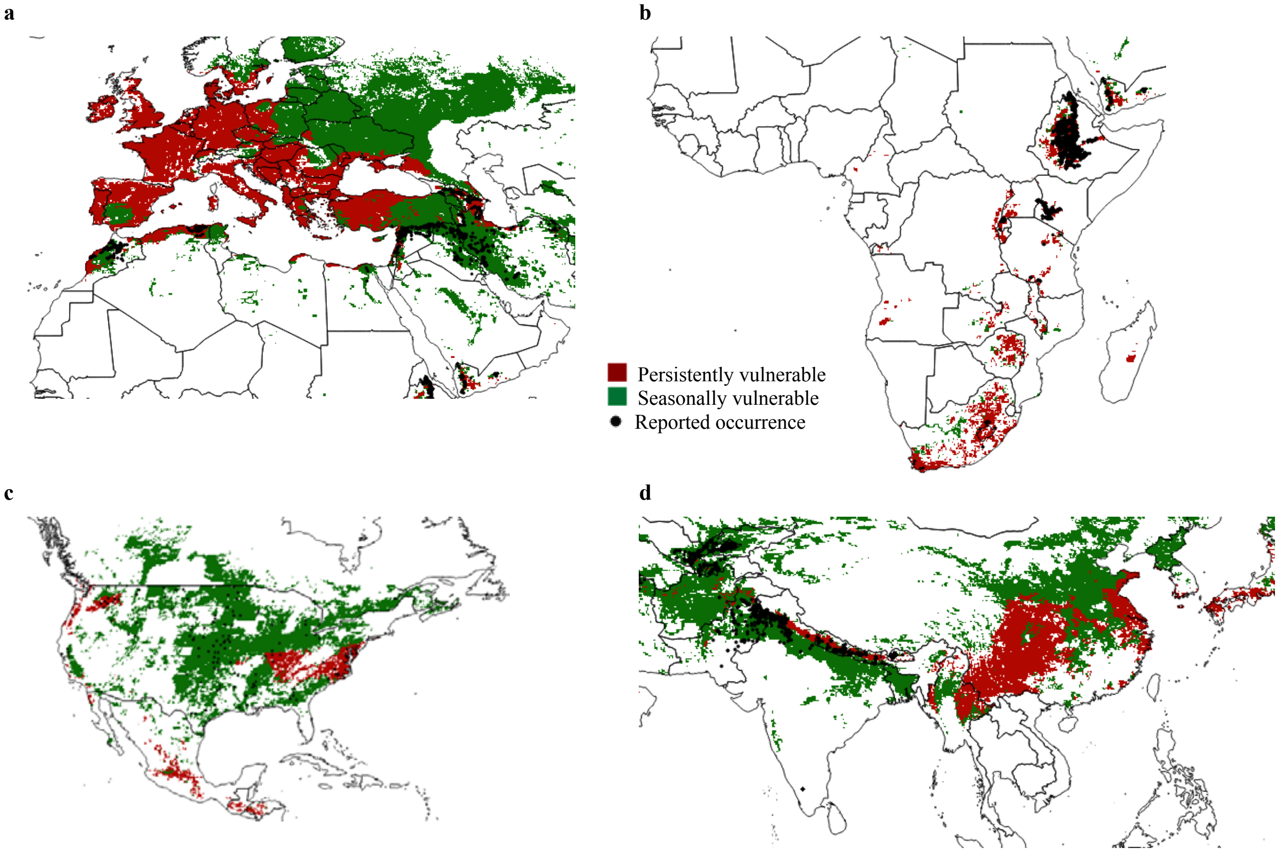

Figure S3. Modeled regional climate vulnerability for stripe rust. a, Europe, North Africa and the Middle East. B, Sub-Saharan Africa. c, Northern America. d, Asia. Vulnerability areas derived using parameter values from Chai et al.[25]. Reported occurrence (black dots) are mapped using data from CIMMYT (Hodson, D., unpublished data), USDA[18] and the University of Sydney Plant Breeding Institute (RP, C. Wellings and WC, unpublished data).

21

	Persistent Share of:		Seasonal Share of:	
	Region	World	Region	World
	(percentage share)			
Production				
Northern America	9.0	1.2	80.9	10.7
sub-Saharan Africa	75.6	0.8	79.8	0.8
LAC	73.9	2.2	90.3	2.7
Asia & Pacific	12.3	4.5	85.4	31.5
Europe (incl. Turkey)	89.0	20.5	99.9	23.0
FSU	11.2	1.4	76.5	9.4
Australasia	47.6	2.2	90.2	4.1
World	33.6	33.6	88.0	88.0
Area				
Northern America	5.8	0.8	78.1	10.5
sub-Saharan Africa	78.3	1.1	81.9	1.1
LAC	73.7	2.4	90.0	3.0
Asia & Pacific	11.3	3.5	77.9	23.9
Europe (incl. Turkey)	81.7	12.5	99.9	15.3
FSU	6.6	1.4	58.8	12.7
Australasia	45.6	2.9	88.6	5.7
World	26.1	26.1	79.7	79.7

Table S2. The global area and production of wheat subject to seasonal or persistent exposure to stripe rust. The table reports authors' estimates where persistent areas are those with a CLIMEX EI ≥ 5 and seasonal areas are those with a $GI_A \geq 5$.

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Parameter	1959-1984	1985-1999	2000-2014
p	0.231 (0.083)	0	0
a	0.865 (0.238)	0.955 (0.306)	0.859 (0.272)
b	121.764 (44.351)	600.393 (249.088)	61.914 (26.004)
Maximized Log-likelihood	65.185	81.682	49.478
Observations	26	15	15

Table S3. Conditional beta parameter estimates for reported U.S. stripe rust losses by period. Standard errors are in parentheses. For all entries, $p \geq 0.1$ (standard error could not be estimated for entries where $p = 0$).

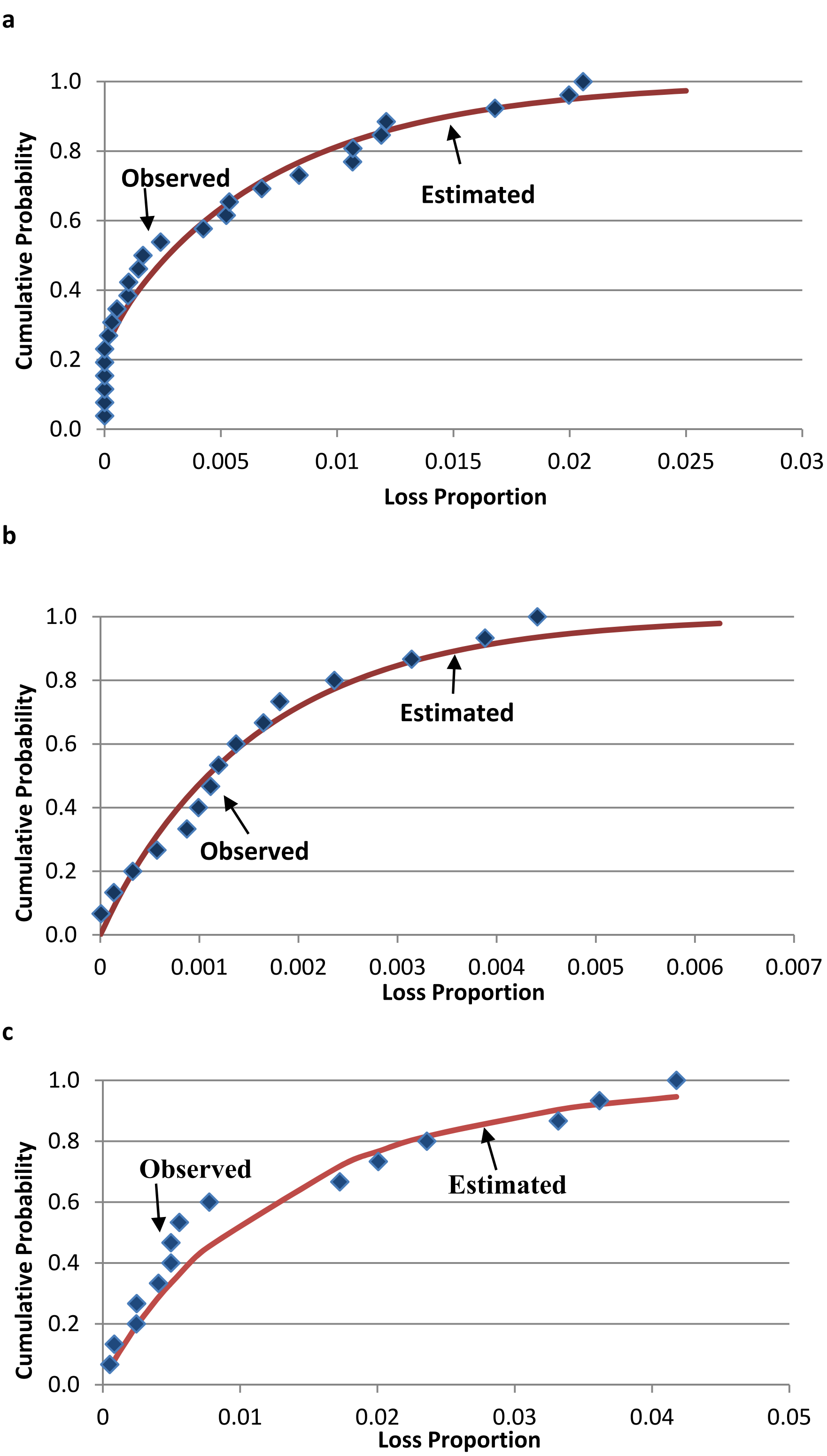

Figure S4. Distribution of observed and fitted stripe rust losses. a, results for 1959 to 1984. b, results for 1985 to 1999. c, results for 2000 to 2014. Plots were developed by the authors using the estimates described herein and observed data from USDA[18].

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Probability of Loss	Limited Area Extent		Extended Area Extent	
	Volume	Value	Volume	Value
(percentage)	*(million tonnes)*	*(million $US)*	*(million tonnes)*	*(million $US)*
Low-Loss Counterfactual				
90	≥0.73	≥130	≥4.70	≥840
50	≥0.88	≥157	≥5.45	≥975
20	≥0.98	≥176	≥5.98	≥1,071
5	≥1.09	≥195	≥6.54	≥1,170
Average	≥0.88	≥158	≥5.47	≥979
No-Loss Counterfactual				
90	≥1.06	≥190	≥5.32	≥951
50	≥1.24	≥222	≥6.16	≥1,102
20	≥1.36	≥244	≥6.77	≥1,211
5	≥1.49	≥268	≥7.39	≥1,322
Average	≥1.24	≥223	≥6.19	≥1,108

Table S4. Probabilistic Annual Losses Attributable to Stripe Rust*.* Data entries are annual values. The low-loss counterfactual reflects 1959-1984 U.S. losses. Values denominated in 2009-2010 average U.S. wheat price.

Wheat Prices	Loss Distribution Reference Period	Counterfactual	
		Low Loss	No Loss
		(US$ million per year)	
2009-2010 (US$178.9 per ton)	2000-2014	32.0	36.2
	1959-1984	9.5	13.8
	Difference	**22.5**	**22.4**
1980-2000 (US$196.6 per ton)	2000-2014	34.3	38.8
	1959-1984	10.2	14.8
	Difference	**24.1**	**24.0**
2013-2014 (US$236.0 per ton)	2000-2014	39.2	44.4
	1959-1984	11.7	16.9
	Difference	**27.5**	**27.5**

Table S5. Economically Justified Research Investments to Ameliorate the Production Consequences of Stripe Rust. The 2009-2010 and 2013-2014 prices represent the U.S. national average wheat price for that crop year, expressed in 2010 dollars; the 1980-2000 price is the period average price over the corresponding crop years, also expressed in 2010 dollars. These analyses assume a gestation lag of 10 years (see main text).