

Reckoning wheat yield trends

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Abstract

Wheat yields have increased approximately linearly since the mid-twentieth century across the globe, but stagnation of these trends has now been suggested for several nations. We present a new statistical test for whether a yield time series has leveled off and apply it to wheat yield data from 47 different regions to show that nearly half of the production within our sample has transitioned to level trajectories. With the major exception of India, the majority of leveling in wheat yields occurs within developed nations—including the United Kingdom, France and Germany—whose policies appear to have disincentivized yield increases relative to other objectives. The effects of climate change and of yields nearing their maximum potential may also be important.

Keywords: statistical test, crop yield, food security

 Online supplementary data available from stacks.iop.org/ERL/7/024016/mmedia

1. Introduction

Given projections for global population to reach 9.3 billion by 2050 (United Nations 2010), increased preference for animal products, and the conversion of food to fuel, global food production will need to increase from 2005 levels by 70% (FAO 2009) or more (Alexandratos 1999). Although it may be possible to increase the area under cultivation (Bruinsma 2009), global agricultural area has actually decreased during the past decade and may continue to do so in the future (Young 1999, Cassman *et al* 2003). Therefore, the ability to increase the amount of food produced per unit area, i.e. yield, is of critical importance for meeting future food demands. Worldwide, cereal yields have risen nearly linearly since the advent of the Green Revolution in the mid-20th century through improved cultivars and management techniques, as well as from the use of chemical fertilizers, irrigation, and pesticides (Evans 1996, FAO 2010). Some counties in Idaho now produce seven times as much wheat per hectare as in 1961 (USDA 2011). However, there are some indications that wheat yield trajectories have leveled off in France (Brisson *et al* 2010) and Switzerland (Finger 2009), and it has been suggested that other nations also show signs of yield stagnation (Hafner 2003).

Distinguishing between a continued linear trend and an actual deceleration in rates of yield is non-trivial. It is

important to account for intrinsic interannual variations and their autocorrelation, changes in the variance of interannual yields, the fact that the intervals tested for deceleration are selected from inspection of the wheat yield records themselves (Percival and Rothrock 2005), and differences in the degrees of freedom between models that represent a trend and stagnation. This last feature was accounted for in a recent study (Brisson *et al* 2010), but the others appear not have been explicitly treated. Here, we present a more complete test for whether yield has leveled off, apply it to wheat data from around the globe, and then discuss the mechanisms potentially responsible for the patterns of leveled yield that emerge.

2. Methods

2.1. A statistical test for leveling

Given annual yield records, we wish to evaluate the hypothesis, H_1 , that yields have stagnated. Following Brisson *et al* (2010), this scenario is represented by a linear change in yield that culminates in a horizontal plateau,

$$y_{1i} = \begin{cases} a_1(t_i - t_p) + b_1 + e_{1i} & i < p, \\ b_1 + e_{1i} & i \geq p. \end{cases} \quad (1)$$

The y_i represent yield on year t_i and change at a rate of a_1 tons per year until the inflection point, t_p , at which point yield

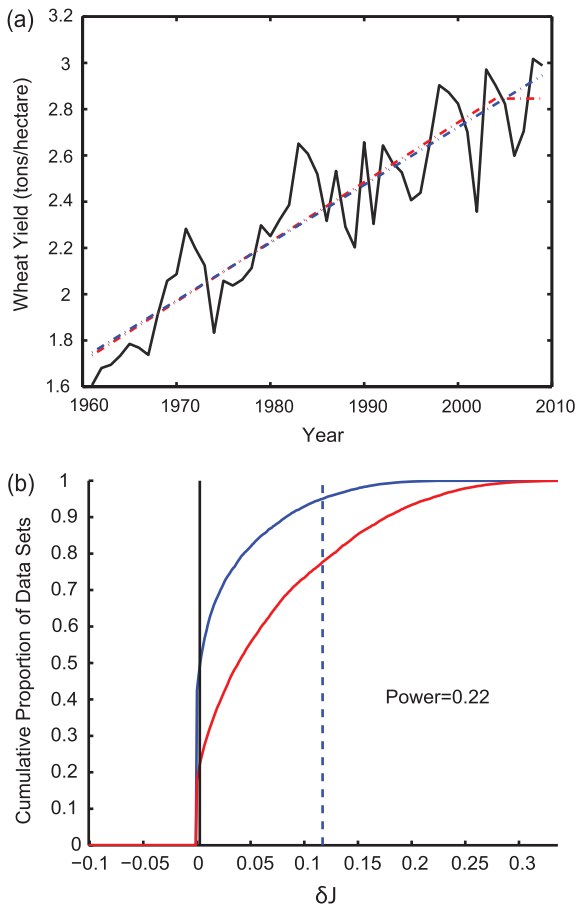


Figure 1. Statistical test applied to average US wheat yield. (a) Yields are fit with the null (blue) and alternative (red) models, where the latter presumes that yields level off. (b) The cumulative distribution of δJ for the null hypothesis (blue) shows that it can be rejected with 95% confidence for $\delta J > 0.12$ (indicated by the vertical dashed line). The alternative model fits the observations better than the null ($\delta J = 0.003$, indicated by the vertical solid line), but insufficiently better to permit rejection of the null. The cumulative distribution for the alternative model (red) shows that the probability of correctly rejecting the null model if a plateau is truly present, i.e. the power of the test, is only 0.22.

levels off at b_1 tons per hectare per year. The e_i represent departures of the observations from the model. The null hypothesis, H_0 , is a simplification of (1),

$$y_{0i} = a_0 t_i + b_0 + e_{0i}, \quad (2)$$

where yield changes at a constant rate (figure 1(a)) with random contributions from the e_{0i} . Of course, there is no assurance that actual yields will follow the variations described by either (1) or (2), but the simplicity of this representation is useful for distinguishing between scenarios of stagnating and linearly increasing yields. Moreover, we find that these models do capture the majority of observed variability in historical wheat yields over the period that they are applied. (In contrast, the fit of these models to historical rice yields is poor and not amenable to drawing substantive conclusions.)

The statistical question is how much better should H_1 fit the observations before we can confidently reject H_0 ? To

answer this question, we fit (1) and (2) to individual wheat yield records by minimizing the sum of the squared residuals and then take the difference in the sum of squared residuals between the two fits, $\delta J = \sum_i (e_{0i}^2 - e_{1i}^2)$. Estimated parameter values of both models, including t_p , are found by minimizing the sum of squared residuals. Values of δJ are always zero or greater because the linear trend represented by (2) is a subset of the yield scenarios represented by (1).

A surrogate data technique is used to estimate the distribution of δJ associated with H_0 . In particular, we phase randomize (Schreiber and Schmitz 2000) the values of e_{0i} to realize surrogate residuals. Phase randomization is the process of taking the Fourier transform of a set of points, randomizing the phases of the component periodic functions, and reconstituting them as a surrogate data set, which preserves the variance and autocorrelation of the original set. These surrogate residuals are then added to the original estimate of the linear trend, and from this synthetic data realization, we calculate a realization of δJ that is consistent with H_0 . By repeating this sequence 10^4 times, we build up a distribution of δJ that is consistent with H_0 and suitable for comparing against the actual, observed value of δJ . We use the same methodology to estimate the distribution of H_1 , but with adding the phase randomized e_{0i} to the rising-plateau fit (figure 1(b)). (The use of the e_{0i} , which are at least as large as the e_{1i} , leads to a conservative estimate for the power of our test but does not influence the estimated statistical significance of the result.)

Some yield time series also show evidence of increasing variance, as might be expected from processes that change proportionally with yield, given the presence of trends in yield. For the quarter of the records in our sample that have squared residuals showing a significant trend in variance, we fit (1) and (2) assuming that the variance of the e_i increases linearly with time for both H_0 and H_1 (see supplementary materials available at stacks.iop.org/ERL/7/024016/mmedia). Taken together, these techniques permit for assessing the probability that yield has leveled off in a manner that accounts for the differences in the degrees of freedom between H_0 and H_1 , autocorrelation in the residuals, and heteroskedasticity in the variance about the model fit.

2.2. Determining representative yields for regions with small-scale data

Although national yields are the only publicly available long-term data for most countries, detailed data are also available for subregions of the United States (USDA 2011) and France (AGRESTE 2010) for the 1960–2008 and 1951–2007 intervals, respectively, allowing for assessment of yield trends at the county and department level. Yield variability shows strong spatial correlation, as nearby regions share similar weather patterns, soil quality, access to water resources, and management practices, particularly within the boundaries of a single nation.

To distinguish intranational regions that follow distinct yield trajectories, we perform a singular value decomposition on subnational yields, after subtracting the annual average

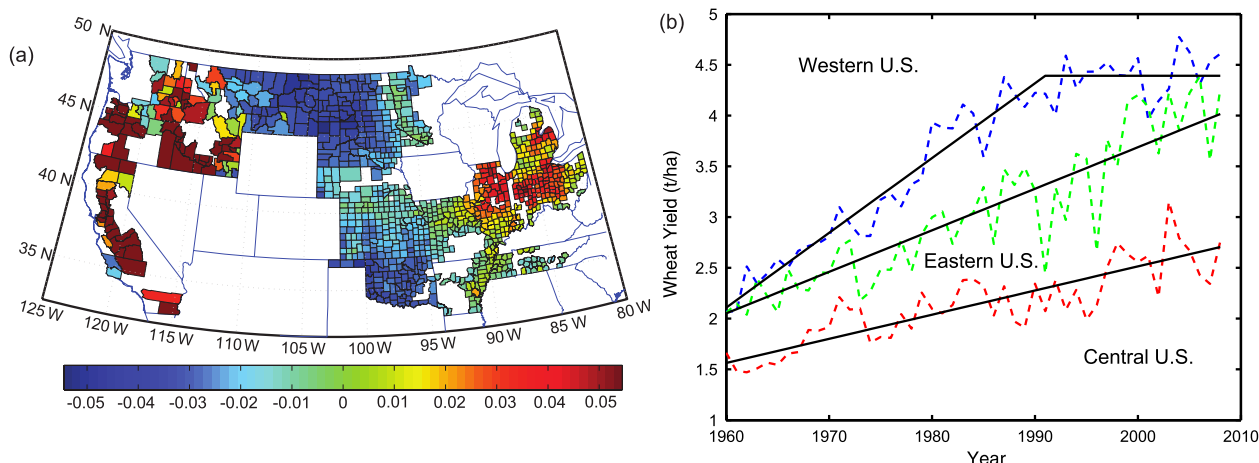


Figure 2. County-level variations in US wheat yield. (a) The loading associated with the first singular vector describing trends in wheat yield. Three distinct regions are evident in the Western, Central and Eastern US. (b) Mean wheat yields in the three regions delineated by 92°W and 110°W lines of longitude. The alternative rising-plateau model is significant at the 95% confidence level for Western yields, whereas a single linear trend cannot be rejected for Central and Eastern US wheat yields.

yields (Strang 1988). The first mode associated with US wheat yield anomalies explains 73% of the space-time variability in yield anomalies and indicates the presence of three distinct growing regions that can be roughly divided zonally by 110°W and 92°W (figure 2(a)). A similar analysis for France (see supplementary materials available at stacks.iop.org/ERL/7/024016/mmedia) shows a gradient in yield variability from the north to the south, with northern yields increasing more quickly, suggesting that these data be divided into two regions along 46°N . This process demonstrates that a single yield timeseries can adequately represent the yield trajectories of groups of small regions with covarying yields, though it also points to the utility of conducting similar, more-detailed analyses for other nations that encompass diverse environments and practices, insomuch as finer resolution data of sufficient temporal length become available.

3. Results

The foregoing statistical test is applied to regional wheat yield data between 1961 and 2010 (FAO 2012). Our sample excludes wheat yield records from nations that are missing yearly data from more than 10% of this interval, show the same yield for three or more consecutive years, or for which (1) was unable to fit the variability with a Pearson product correlation of at least 0.7. Through this process, two major wheat producers were excluded. Australian wheat yields feature large interannual variance that precludes the fitting of any smooth linear function, and Russian wheat yields are not available prior to 1992. The remaining sample comprises data from 47 different nations that are reasonably complete, show no obvious errors in reporting, and are well fit by our model. Note that although multiple-cropping is a concern for the reliability of much yield data (Foley *et al* 2011), wheat is only harvested at most once per year from a given field. Figure 3 shows average wheat yield in 50 distinct regions

worldwide between the year 2000 and the most recent year of available data. The 50 regions account for 47 countries wherein the US and France are subdivided.

Of the 50 regions tested for yield stagnation, 27 show yields that have leveled off when performing the test at the 80% confidence level, including the Western US, the majority of Western Europe, India, Bangladesh, Romania, Colombia, Albania, Egypt, Hungary, Japan, Pakistan, South Korea and Zambia (figure 4). Using 2007 numbers, wheat accounts for 19% of the total calories of food produced, and the 47 countries sampled in our analysis account for 75% of the total global wheat production (FAO 2012). The 27 regions with confirmed plateaus at the 80% confidence level account for 35% of global wheat production (FAO 2012, USDA 2011). We prefer to report values at 80% confidence so as to reduce the probability of false negatives, but note that 18 regions have leveled off with at least 95% confidence and that they still account for 28% of global wheat production. Results for top wheat producing regions are given in table 1.

4. Discussion

The regional pattern of leveling wheat yield provides some basis for exploring the causes of changes in agricultural productivity. The focus will be upon on those regions identified to have leveled off, as this behavior represents a departure from the status quo linear trend. Although speculative, we attempt to distinguish between regions where yields have leveled despite socio-economic demands for increase and those where yields have leveled for other reasons because this distinction, insomuch as it can be made, should provide insight into prospects for future yield increase.

With some of the highest yields globally (figure 3), Western Europe contains the majority of nations showing a leveling in wheat yield at 80% confidence, with only Spain and Italy showing linear trends (figure 4). These results confirm prior findings that France (Brisson *et al* 2010) and

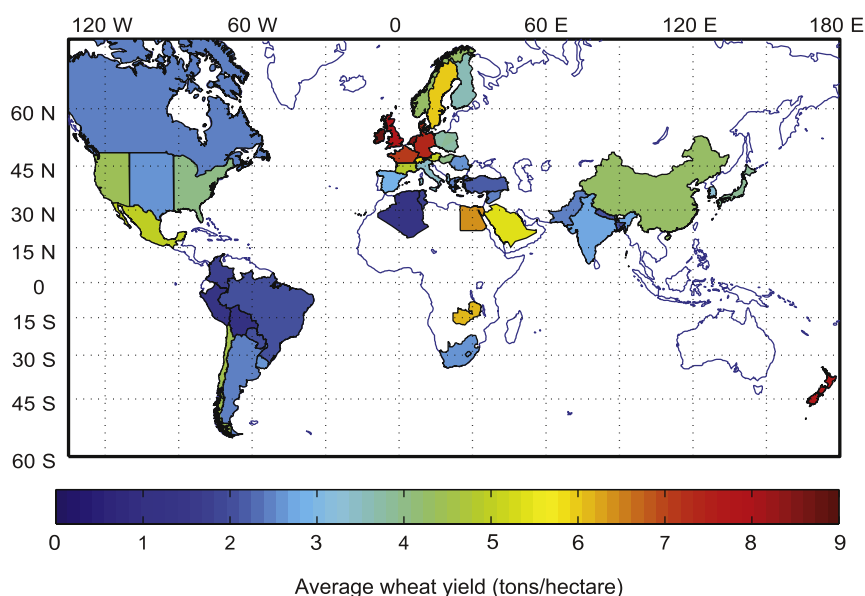


Figure 3. Average wheat yield for each region considered in metric tons per hectare. Averages are between 2000 and 2010 for individual nations, 2000–8 for individual US regions, and 2000–7 for French regions.

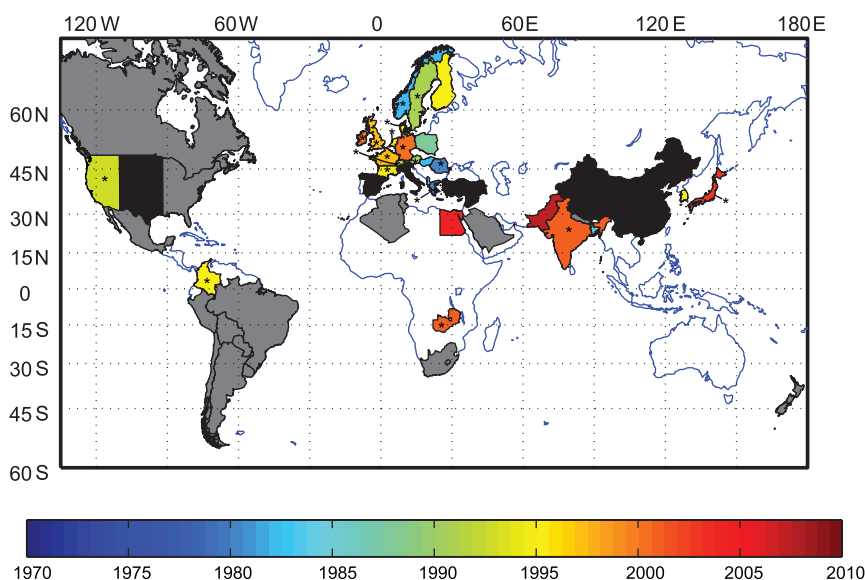


Figure 4. Map showing regions found to have leveled off in yield with at least 80% confidence. Regions with a ‘*’ are also significant at the 95% confidence level. Color indicates the year in which the plateau initiates. Black shading indicates that the null model could not be rejected, and gray shading indicates that the null and alternative models provide the same linear fit.

Switzerland (Finger 2009) have stagnating wheat yields. Western Europe’s wealth, low rates of population growth, and present status as a net exporter of wheat (FAO 2012) afford flexibility in trading off gains in yield for other policy goals, and it appears that leveling corresponds well with specific policy and management choices. Near the time that leveling is generally observed, the European Union shifted away from a policy that rewarded high agricultural production through price guarantees to a policy that pays flat subsidies that do not increase with production and triggers taxes when production limits are exceeded (Alexandratos 1999, European Commission 2011).

Ecological considerations also prompted the European Union to implement policies in 2003 that reduced pesticide and inorganic fertilizer application (FAO 2008, DEFRA 2011). Excepting Austria and Greece, every Western European nation that shows level yields has reduced fertilizer use during the intervals in which they show flat yield, relative to the preceding decade (The World Bank 2010). Conversely, 18 of the 22 linearly increasing nations show increased fertilizer use during the last decade relative to the one prior. Here, we use total inorganic fertilizer consumed across all crops divided by cereal area as a proxy for fertilizer usage (The World Bank 2010). However, we note that the decrease in fertilizer usage may be partly or

Table 1. Test results for major wheat producers. Columns from left to right are region; year of changepoint in the fitted rising-plateau model, t_p ; observed difference in sum of residuals, δJ ; the 95% confidence level for δJ ; the power of the test; % of 2007 global wheat production; p -value; and average wheat yield between 2000 and the most recent year of available data in tons per hectare.

Region	t_p	δJ	95%	Power	% 2007	p -value	Yield
Northern France	1997	3.87	1.50	0.72	—	0.000	7.05
Southern France	1995	0.06	0.03	0.68	—	0.000	4.87
France	1996	6.13	4.55	0.56	5.35	0.002	6.96
India	2001	0.32	0.18	0.76	12.37	0.004	2.72
Germany	2010	1.78	1.11	0.78	3.40	0.010	7.42
Western US	1993	1.86	1.68	0.60	2.14	0.024	4.42
United Kingdom	1997	4.18	3.75	0.58	2.16	0.034	7.80
Poland	1988	0.077	0.087	0.59	1.36	0.092	3.78
Egypt	2004	1.08	2.30	0.26	1.20	0.155	6.37
Pakistan	2007	0.01	0.02	0.47	3.80	0.195	2.48
Turkey	2000	0.17	0.49	0.66	2.81	0.256	2.25
Italy	1995	0.00	0.01	0.78	1.17	0.390	3.40
China	2009	0.00	0.29	0.07	17.84	0.391	4.29
Central US	2003	0.00	0.01	0.11	5.78	0.416	2.62
Argentina	—	0.00	—	—	2.69	—	2.46
Canada	—	0.00	—	—	3.27	—	2.47
Eastern US	—	0.00	—	—	1.19	—	4.06

wholly compensated for by an increase in efficiency of fertilizer application (Frink *et al* 1999). Another possibility is the recent shift of European land use from cereal to oil crop cultivation, though we consider this shift an unlikely explanation. Although cereals use roughly three times as much fertilizer as oil crops (FAO 2011, 2012), our metric for fertilizer use intensity would increase from such a shift in cultivation, counter to the observed trend.

These results are nearly opposite to those of Hafner (2003), who generally found that higher yielding and more wealthy regions are not stagnating. We have re-computed our results using the shorter time records used by Hafner (2003), but it appears that the most important distinction is our accounting for both autocorrelation in yield residuals and the differing degrees of freedom between the null and alternative models (see supplementary material available at stacks.iop.org/ERL/7/024016/mmedia).

India and Bangladesh provide something of a contrasting case to that of Western Europe, given that level yields are found even though population has increased at above average rates and inorganic fertilizer application has continued to increase throughout the period of level yields. A possible explanation has to do with approaching yield potentials. Wheat yields in Bangladesh (Mondal 2011) have been estimated to be near 75% of their potential yield judged against maximum local yields, and estimated to be near or above 80% in parts of India (Punjab, Haryana and Gujarat) using modeled potential yield (Bruinsma 2003), though other parts of India are estimated to have yields nearer 50% of their potential (Lobell *et al* 2009, Licker *et al* 2010). Inevitably, there exists a gap between the yield potential of a given cultivar and the actual yield because of limitations related to water, nutrients, pests, or disease. Even in optimized agricultural operations, yields rarely attain greater than 80% of their yield potential (Cassman 1999), and because yield

potentials appear not to have increased in the last several decades, as indicated by prize-winning yields (Lobell *et al* 2009), yields may be expected to stagnate once they approach their potential.

Recent studies (Kalra *et al* 2008, Lobell *et al* 2011) also indicate that warming in Bangladesh and India have reduced wheat yields by approximately 20% of their average trend since 1980 (Lobell *et al* 2011). The deleterious effects of climate change may be expected to decrease yield potential and, coupled with yields already near their maximum potential, may have contributed to the observed leveling in India and Bangladesh. Western European wheat yields were also found to have incurred disproportionate losses from regional warming (Lobell *et al* 2011) and may be near their yield potential (Licker *et al* 2010), suggesting that similar factors as discussed for Bangladesh and India may have acted in conjunction with policy changes to cause leveling in that region.

Widespread leveling of wheat yield has implications for food security. In considering how to feed the world in 2050, the Food and Agricultural Organization found that 90% of the needed increases in food production will come from higher yields and more crop rotations, requiring exponential growth in yield (FAO 2009). Here, we find that yields associated with half the wheat production in our sample are no longer increasing even at linear rates, though there are several mitigating factors. First, it may be possible to increase yield in many currently level regions through standard economic incentives or policy revisions. Even where stagnation results from approaching 80% of the potential yield, this more likely reflects an economic threshold at which further investment of resources are no longer financially profitable (Lobell *et al* 2009). It follows that increases in demand would make higher yields more economically feasible.

Another consideration is that level wheat yields are generally found in regions with adequate food security, whereas regions with historically greater food insecurity generally show continued increases—and local yield increases are more effective at alleviating local food insecurity (Alexandratos 1999). However, India and Bangladesh are important exceptions, showing stagnating wheat yields despite increased fertilizer application and population growth. Furthermore, other nations excluded from this analysis because of insufficient data quality may also have level yields. The majority of future population growth is also expected to occur in food insecure regions, so that even continued linear trends may not be adequate to meet increased demand without substantial increases in food imports (FAO 2009). Of course, these conclusions only relate to wheat yield, and changes in the yields of other crops could compensate for or exacerbate these issues.

Finally, it is worth emphasizing that short-term leveling of yield has often led to erroneous predictions of inadequate food supply (Evans 1996), largely because the full scope for adaptation and innovation is difficult to capture in any forecast. Nonetheless, this should not blind us to the challenges associated with sufficiently increasing production to feed a growing population under conditions of changing resources and a changing climate (Brown 2010).

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