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,

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

(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
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),

$$y_{0i} = a_0 t_i + b_0 + e_{0i},$$

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, $\delta J = \sum (e_0^2 - e_1^2)$. Estimated parameter values of both models, including $t_p$, are found by minimizing the sum of squared residuals. Values of $\delta J$ 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 $\delta J$ 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 $\delta J$ that is consistent with $H_0$. By repeating this sequence $10^4$ times, we build up a distribution of $\delta J$ that is consistent with $H_0$ and suitable for comparing against the actual, observed value of $\delta J$. 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.
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
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

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.
The most recent yield of available data in tons per hectare.

Wheat production; potential (Lobell et al 2009), though other parts of India are estimated to have yields nearer 50% of their 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.

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 may be influencing yields in Bangladesh and India.

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 found even though population has increased at above average rates. 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.

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 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 is 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.

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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).

### 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, $\delta J$; the 95% confidence level for $\delta J$; 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          | $t_p$ | $\delta J$ | 95% Power | 2007 % Global Wheat Prod | p-value | Yield |
|-----------------|-------|------------|-----------|--------------------------|---------|-------|
| Northern France | 1997  | 3.87       | 1.50      | 0.72                     | 0.00    | 7.05  |
| Southern France | 1995  | 0.06       | 0.03      | 0.68                     | 0.00    | 4.87  |
| France          | 1996  | 6.13       | 4.55      | 0.56                     | 0.00    | 6.96  |
| India           | 2001  | 0.32       | 0.18      | 0.76                     | 12.37   | 0.004 |
| Germany         | 2010  | 1.78       | 1.11      | 0.78                     | 3.40    | 0.010 |
| Western US      | 1993  | 1.86       | 1.68      | 0.60                     | 2.14    | 0.024 |
| United Kingdom  | 1997  | 4.18       | 3.75      | 0.58                     | 2.16    | 0.034 |
| Poland          | 1988  | 0.077      | 0.087     | 0.59                     | 1.36    | 0.092 |
| Egypt           | 2004  | 1.08       | 2.30      | 0.26                     | 1.20    | 0.155 |
| Pakistan        | 2007  | 0.01       | 0.02      | 0.47                     | 3.80    | 0.195 |
| Turkey          | 2000  | 0.17       | 0.49      | 0.66                     | 2.81    | 0.256 |
| Italy           | 1995  | 0.00       | 0.01      | 0.78                     | 1.17    | 0.390 |
| China           | 2009  | 0.00       | 0.29      | 0.07                     | 17.84   | 0.391 |
| Central US      | 2003  | 0.00       | 0.01      | 0.11                     | 5.78    | 0.416 |
| Argentina       | —     | 0.00       | —         | —                        | 2.69    | 2.46  |
| Canada          | —     | 0.00       | —         | —                        | 2.67    | 2.47  |
| Eastern US      | —     | 0.00       | —         | —                        | 1.19    | 4.06  |
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References

AGRESTE (Statistical Service of the French Ministry of Agriculture) 2010 Department-Level Wheat Yield (obtained through Arvalis: www.arvalisinstitutudevegetal.fr/en)
Alexandratos N 1999 Proc. Natl Acad. Sci. 96 5908–14
Brisson N et al 2010 Field Crops Res. 119 201–12
Brown L 2010 Plan B: Rescuing a Planet Under Stress and a Civilization in Trouble (New York: WW Norton and Company)
Bruinsma J 2009 Expert Mtg on How to Feed the World in 2050, The Resource Outlook to 2050: By How Much Do Land, Water and Crop Yields Need to Increase By 2050?
Bruinsma J (ed) 2003 World Agriculture: Towards 2015/2030: An FAO Perspective (London: Earthscan)
Cassman K G 1999 Proc. Natl Acad. Sci. 96 5952–9
Cassman K G et al 2003 Annu. Rev. Environ. Resour. 28 315–58
DEFRA (Department for Environment, Food, and Rural Affairs) 2011 Single Payment Scheme (available from: www.defra.gov.uk/farm-manage/single-pay/)
European Commission 2011 The Common Agricultural Policy Explained (available from: http://ec.europa.eu/agriculture/capexplained/index_en.htm)
Evans L T 1996 Crop Evolution, Adaptation, and Yield (Cambridge: Cambridge University Press)
FAO (Food and Agriculture Organization of the United Nations) 2008 Current World Fertilizer Trends and Outlook to 2011/12 (available from: ftp://ftp.fao.org/agl/agbl/docs/cwft011.pdf)
FAO (Food and Agriculture Organization of the United Nations) 2009 How to Feed the World 2050: Global Agriculture Towards 2050 (available from: www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf)
FAO (Food and Agriculture Organization of the United Nations) 2010 The State of Food Insecurity in the World: Addressing Food Insecurity in Protracted Crises (available at: www.fao.org/docrep/013/i1683e/i1683e.pdf)
FAO (Food and Agriculture Organization of the United Nations) Plant Production and Protection Division 2011 Fertilizer Use Statistics (available at: www.fao.org/ag/app/fertstat/index_en.htm)
FAO (Food and Agriculture Organization of the United Nations) 2012 Food and Agriculture Organization of the United Nations Crop Production and Trade Statistics (available from: http://faostat.fao.org/site/339/default.aspx)
Finger F 2009 Food Policy 35 175–82
Foley J A et al 2011 Nature 478 337–42
Frink C R et al 1999 Proc. Natl Acad. Sci. 96 1175–80
Hafner S 2003 Agric. Ecosyst. Environ. 97 275–83
Kalra N et al 2008 Curr. Sci. 94 82–8
Licker R et al 2010 Glob. Ecol. Biogeogr. 19 769–82
Lobell D B and Rothrock D A 2005 J. Clim. 18 886–91
Schreiber T and Schmitz A 2000 Physica D 18 346–82
Strang G 1988 Linear Algebra and Its Applications 3rd edn (Fort Worth, TX: Harcourt Brace Jovanovich College)
The World Bank 2010 World Development Indicators (available from: http://data.worldbank.org/data-catalog/world-development-indicators)
United Nations 2010 World Population Prospects: The 2010 Revision (available from: http://esa.un.org/unpd/wpp/index.htm)
USDA (United States Department of Agriculture) 2011 National Agricultural Statistics Service: County-level ‘Wheat All’ Yield (available from: www.nass.usda.gov/Data_and_Statistics/index.asp)
Young A 1999 Environ. Dev. Sustainab. 1 3–18