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LETTER

The elasticity of global cropland with respect to crop production and its implications for peak cropland

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Abstract

Trends in average crop yield i.e., crop output per unit area, are the basis for numerous forecasts of the future global expanse of agriculture. Although a number of studies predict a sizable expansion in global cropland area through the year 2050, some argue, to the contrary, that peak cropland is at hand. This paper analyzes historical trends in the 'correlation' between annual global cropland and annual crop production using a new measure called the elasticity of cropland with respect to production (crop output). Three different statistics of elasticity—the mean, the frequency of different combinations of directional changes in crop area and output, and time trend, each computed over different but fixed time intervals (5, 10, 15 and 20 years, which were chosen arbitrarily) suggest that the global area of cropland is set to increase with consumption. Achieving an absolute reduction in global cropland hinges on increasing crop yields beyond anything seen in the last fifty years. While this is consistent with several existing forecasts, the salience of an elasticity-based analysis is that it captures the effect of changing marginal as well as average crop yield as opposed to just the latter. The elasticity-based approach is applicable to trends in the exploitation of other scarce natural resources as well as releases of different pollutants.

1. Introduction

In the book, Half-Earth, E O Wilson, the distinguished biologist and conservationist, argues for setting aside half of the earth's land and sea surface for nature [1]. One major obstacle to such a massive scale of nature reserves could be the expanse of agricultural land, which is already vast and faces pressures that portend further expansion [2, 3]. Recent estimates suggest agricultural land accounts for about 38% of the earth's ice-free land surface area, with cropland area accounting for about 32% of agricultural land, with the rest taken up by pasture [4]. The focus here is only on the size of global cropland. Between 1961 and 2013 global harvested area increased 35% from 960 to 1300 million hectares (mhec) and it continues to grow [5]. The work described here is on the relationship between changes over time in annual harvested area (used interchangeably with the term cropland) and annual crop production (henceforth, simply production or output) and what a new measure of the 'correlation' between these two variables (defined in section 2) suggests about the amount of cropland that would be required to provide both food and fuel for a larger and wealthier (on average) global human population.

Forecasts of future global cropland are numerous and wide ranging. A few select studies, all of which exploit the same global agricultural data set—the United Nations Food and Agricultural Organization (FAO) statistical database [5], are highlighted here. A study that forecasts substantial expansion in global cropland is Tilman *et al* ([6]). This study groups the nations of the world under seven different categories based on average per capita income during the years 2000–2007, and then computes the relationship between income and calorific demand (and likewise with protein demand) for each group. Assuming an 2.5% annual growth in real per capita income, with some variation around this number for each category, and using United Nations (UN) projections for population, it predicts a doubling in global calorific and protein demand by 2050 relative to 2003 levels. A forecast of cropland needed to meet this demand is then made for different management scenarios based on trends in average crop yield. Their most optimistic forecast, which assumes strategic intensification in currently under-yielding nations, involves a 200 million hectare increase in cropland by 2050. Their pessimistic forecast, which is predicated on continuation of recent trends, is an increase in cropland by 1 billion hectares.

At the other extreme is the forecast of Ausubel, Wernick and Waggoner [7]. They argue that global peak cropland is at hand and that encroachment of cropland into nature is ending if it has not already. The optimism about peak cropland is based on the evidence that land productivity (henceforth, simply productivity or yield) for almost all major crops and crop categories (such as cereals, sugars and oilseeds) have been increasing on average on a global scale over a long period, and the plausible assumption that such trends will be sustained. These imply that increasingly smaller areas of cropland will be needed per unit of output. At the same time, a declining growth rate of global population and rising affluence are combining to slow the rate of growth in food demand. This leads to their forecast of an impending stabilization followed by an absolute decline in global cropland.

An FAO study [8] forecasts a 70 million hectare increase in global arable land area in 2050. This contradicts the notion of peak cropland but is more optimistic (about restricting cropland expansion) relative to Tilman *et al*'s forecasts. This study builds up its global forecast from country by country and commodity by commodity projections. Interestingly, this study forecasts only a 60% increase in global agricultural output by 2050 relative to 2005/07, which might explain its relatively smaller but comparable forecast to Tilman *et al*'s [6]'s best case scenario. The net increase in arable land is comprised of an increase in developing countries but a decrease in developed countries. It should be pointed out that arable land in [8] is different from harvested or sown area, which is what [6] and [7] forecast. Arable area refers to distinct physical parcels of land under crops, whereas harvested or sown area does not. For instance, a parcel of land that produces two harvests per year is counted twice under the harvested area definition. To determine the distinct physical parcels of cropland one would need to adjust the quantity of total cropland for parcels that deliver more than one harvest per year. Therefore, an analysis of harvested area, which is the focus of this study could overstate the expansion of cropland into non-cultivated land. While well documented estimates of multi-cropping intensity is available for specific locations such as rice growing areas in Asia, and winter-wheat and maize growing areas in northern China [9], the importance of multi-cropping to current global crop production and crop area appears small [10]. It is also predicted that significant proportion of the areas that are ripe for cropland expansion such as Africa's Savannah are characterized by long dry seasons and rain-fed agriculture. This limits the potential to mitigate the expansion of arable land through multi-cropping [11]. Another issue in focussing on changes in either harvested or arable area is that one might not be tracking the same parcels of land over time as the agricultural frontier might be shifting due to abandonment of cropland.

The studies discussed above are representative of a larger literature forecasting future cropland based on trends in average crop yield. The variation in the forecasts might be attributed to different assumptions regarding rates of population growth, income growth, food demand, and dietary shifts. While variability and uncertainty is acknowledged in some studies, the forecasts generally are derived based on average crop yield for a region. The analysis here considers additional (descriptive) statistics to the mean.

The point of this letter is that an analysis of average crop yield (or more generally, average efficiency of any productive activity with respect to an input) ignores additional information discernible from data on total input(s) and total output(s). For instance, it is difficult to conclude based simply on trends in average crop yield whether it is outpacing the rate of growth in output, which is a necessary condition for cropland to decrease without an accompanying reduction in output. Otherwise, even though average crop yield might increase, cropland will continue to grow. To see why this is the case, let L_t, Q_t and $\overline{y}_t$ denote total cropland area, total output and average crop yield in year t, and Δ denote change. Then

$$L = \frac{Q}{\overline{y}*}.$$

Taking logarithms and differentiating with respect to time,

$$\frac{\Delta L_t}{L_t} = \frac{\Delta Q_t}{Q_t} - \frac{\Delta \overline{y}_t}{\overline{y}_t}. \qquad (1)$$

Equation (1) shows that if the percent change in average crop yield between two points in time exceeds that of quantity of crop produced, then percentage change in cropland will be negative. In other words, less land is needed in absolute. It will be shown later that there is scant evidence to support this assumption for the major crops (both in terms of their supply of calories and proteins, and share of global cropland) barring a few exceptions for wheat during the 1980s and 1990s.

With the objective of deriving only empirical, data-driven insights, the rest of the discussion describes a pure analysis of historical trends. While trend analysis is not a reliable predictor of the future, it makes explicit the extent of change needed to actually

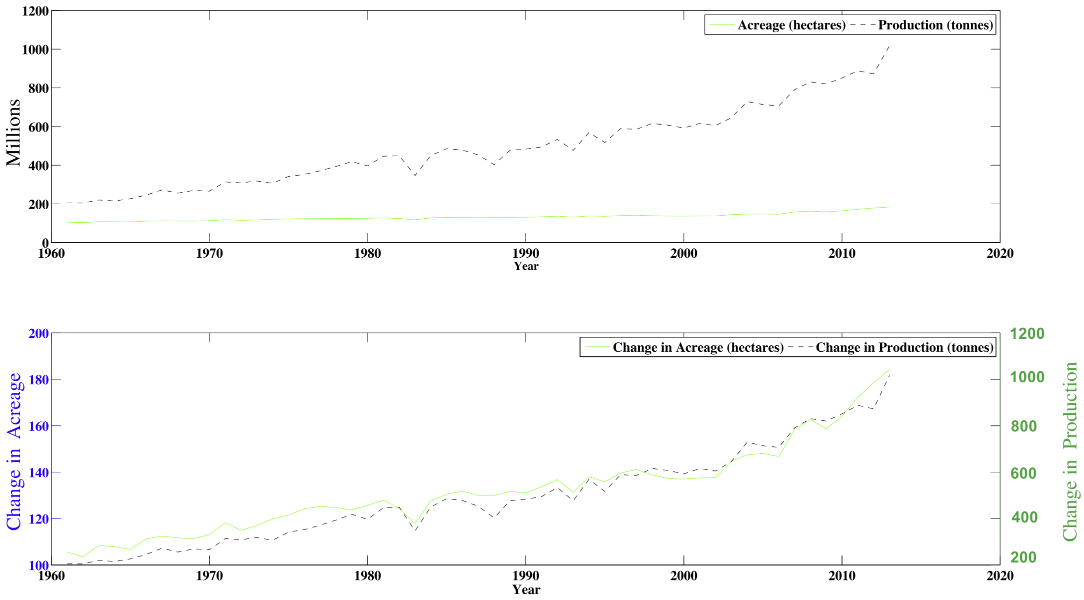

Figure 1. Two different representations of the data on trends in annual global harvested area and output of maize.

achieve peak cropland, and it also provides a basis for predicting outcomes under a business as usual scenario.

2. Analysis of elasticity

The focus of this paper is on a new measure of the correlation between cropland and crop output. This metric, which is termed as the elasticity of cropland with respect to output is the ratio of the percentage change in cropland to the percentage change in output during a given time interval. Let A denote area of cropland and Q denote output in a given year t, and ΔA_t^{t+k} and ΔQ_t^{t+k} denote the change in area and output respectively between years t and $t + k$, then the elasticity for the time interval $\{t, t + k\}$ is

$$\eta_t^{t+k} = \frac{\Delta A_t^{t+k}}{A_t} \Big/ \frac{\Delta Q_t^{t+k}}{Q_t} = \bar{y}_t * \frac{\Delta A_t^{t+k}}{\Delta Q_t^{t+k}}. \qquad (2)$$

A unit value of elasticity means that a doubling of output is associated with a doubling of cropland. When elasticity is positive an increase (decrease) in output implies an increase (decrease) in crop area, which is intuitive. Negative elasticities can arise when either crop area declines and output increases, or crop area increases and output decreases, i.e., average crop yield decreases. Equation (2) also shows how elasticity is related to average crop yield at time t, $\bar{y}_t$. It is simply the ratio of average crop yield to 'gross marginal yield', which is the ratio of the change in output to the change in cropland, $\frac{\Delta Q_t^{t+k}}{\Delta A_t^{t+k}}$.

The intuition underlying gross marginal yield needs elaboration. Marginal analysis is an analysis of infinitesimal. In the context case of land use change, it is meaningful at the scale of a single production unit such as a single farm, household or factory and for small time intervals. Given that the changes analyzed here are on a country-scale, and on yearly and decadal time scales, the concept of 'gross marginal yield' is introduced. Since 'average marginal yield' could be interpreted as the marginal change averaged across different small production units, the term gross marginal yield is preferred.

Gross marginal yield captures the combined effect of a change in output due to a change in yield on land that is already under the cultivation of any given crop as well as the change in output due to the expansion (or contraction) in the harvested crop area. Basic economic intuition suggests expansion of cropland should proceed from more productive to less productive parcels of land, i.e., toward marginal parcels. This should cause the average yield to decrease. But when there is a productivity shock, say due to technological change or change in weather, the change in total output reflects shocks to crop yield from the already existing parcels (in economic terms, the intensive margin) as well as the output from the newly added parcels (in economic terms, the extensive margin). One possibility is that a large technical shock (which typically, raises productivity) or a favorable weather shock, increases output from the existing land base by such an extent that even after taking into account the lower average yield from the newly added parcels, the gross marginal yield is greater than the average crop yield prior to the shock.

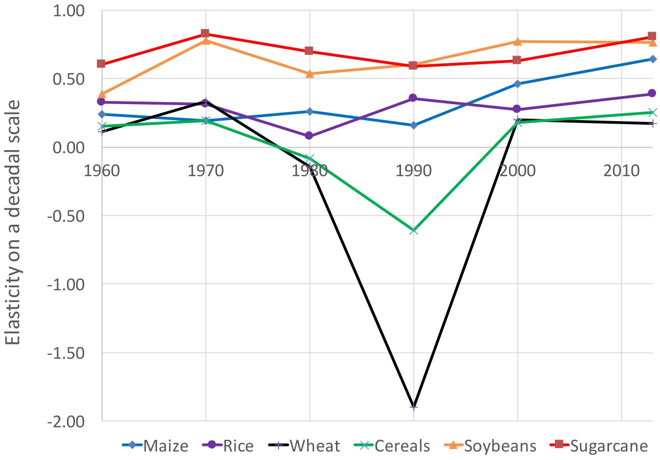

Figure 2. Elasticity on a decadal scale. The value shown for the decade 1960 actually denotes the elasticity for the change in cropland and production between 1961 and 1970 and so on. However, the final observation for each crop denotes the elasticity for the period 2004–2013, which is the latest year in the data set.

Conversely, when there is large negative shock then gross marginal yield will be smaller than the than the average crop yield prior to the shock. A combination of different types of positive and negative shocks at different spatial scales will have an ambiguous effect. This justifies the introduction here of the concept of gross marginal yield.

The value of analyzing elasticity trends as opposed to simply trends in yield can be grasped from figure 1. The top panel depicts the increase in the total global output of maize over the last five decades as well as a gradual change in total land area under maize cultivation. It suggests that the increase in global cropland is negligible compared to the increase in global output since 1961. In contrast, the bottom panel depicts the change in output per year, as well as the change in cropland, which shows how closely the two trends are correlated when these are plotted along different axes. What is not obvious from figure 1 is how the percentage change in land use per unit change in output is trending, and it is the trend in elasticity that is crucial to future scenarios. If elasticities are positive and staying roughly the same then there is little hope of peak land. If the elasticities are positive but steadily declining then perhaps peak land is a plausible possibility. The rest of the paper discusses the result of the elasticity analysis for select major crops on a global scale for period 1961–2013.

Before discussing results, a weakness that afflicts the forecasts referenced above as well as the analysis conducted here needs acknowledgement. Several concerns exist about the quality of agricultural data sets in general, and specifically, in the context of this study, about the reliability of FAO's country-level data on cropland and productivity. These concerns are particularly severe for certain types of crops and certain regions of the world. For instance, the standards for data collection are deemed subpar for the entire group of sub-saharan African nations with some exceptions [12, 13]. Therefore, the past on which forecasts are constructed is itself uncertain l*et al*one future uncertainty. However, this limitation is beginning to be addressed. With respect to cropland area, satellite imagery and remote sensing technologies are enabling more accurate estimation of global land cover on a fine spatial and temporal scale [14]. At the same time, albeit in their infancy and requiring further validation, the use of global positioning systems, Computer Assisted Personal Interviewing and use of mobile phones are helping improve the quality of farm survey data [12]. Lastly, through initiatives such as the United Nations Statistical Commission's Global Strategy to Improve Agricultural and Rural Statistics, a common set of standards and best practices are being developed for the estimation of a core set of agricultural indicators [12]. Such data related issues notwithstanding, the point being made here is that elasticity of cropland with respect to output is analytically a superior measure relative to average crop yield for evaluating whether global cropland has peaked or is close to peak. In any case, this study also relies on the same data set as the studies on average yield.

The following is an analysis of FAO data on two variables, annual global harvested area and annual global output, for five crops—maize, rice, wheat, soybeans and sugarcane, and a cereals aggregate (which is all grains aggregated in rice-milled equivalents), for the time span 1961–2013. Figure A1 in the appendix shows trends for five out of these six crops, with respect to the amount of land required to produce

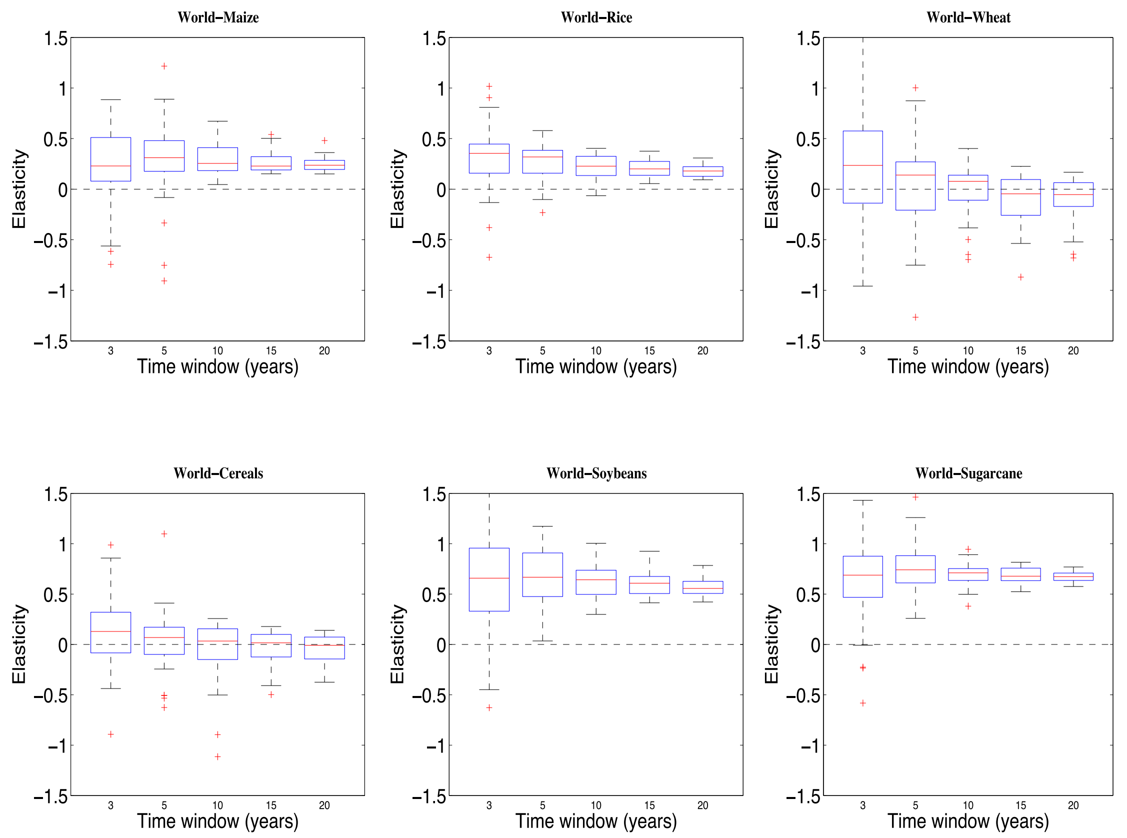

Figure 3. Box plot of elasticity between different pairs of years computed at each different time intervals (*X*-axis) for select crops. Figure shows the greater dispersion of elasticities computed on an annual basis relative to elasticities computed at longer time intervals. For ease of viewing, the range of values displayed is restricted to the range $[-2, 2]$ with values outside this region represented by a + mark on the along the dashed line.

one metric tonne of grain. It shows that while less and less land is needed with time to produce a metric tonne of harvested crop matter, the rate at which land intensity is declining is slowing down. Stated differently, the rate of growth in average yield is slowing. This is apparent from the flattening of the trend for each crop shown, a fact which is also pointed out in [8].

Figure A2 in the appendix shows that global area under four groups of crops—cereals, oilseed crops, pulses and sugarcane (which together comprise over 85% of global cropland), as well as total cropland, are all higher relative to 1961 levels and the global area under each appears to be expanding more rapidly since 2000. An exception to these trends, not shown here, is fibre crops, which is a category dominated by cotton, whose area is declining while output is increasing. However, fibre crops account for only 3% of global cropland whereas cereal crops account for 60%, oil crops account for about 20% while leguminous crops that are not used for oil extraction (classified by FAO as pulses) account for 6%.

Figure 2 depicts the elasticity computed on a decadal (10 year) time frame. It is worth keeping in mind that wheat, maize and rice are the three major components of cereals and so trends in any one of them can have a strong effect on trends in cereals. During 1980s and 1990s wheat experienced massive growth in productivity, which saw wheat area decline while output increased, and this explains the elasticity trend in cereals as well. For all other crop-decade combinations shown elasticity has remained positive and does not show signs of abatement. The selection of the decadal time window as well as the initial and end years for this time window was arbitrary. A question that arises in the calculation of elasticity is that the interval over which changes in area and output are measured. As a result of random weather fluctuations elasticity on an annual basis tends to be more noisy relative to elasticity computed over longer time intervals. Figure 3 shows that for each crop, the variability in elasticity diminishes as the interval over the elasticity is calculated widens. Therefore, elasticity is analyzed at four different arbitrarily chosen fixed time intervals—5, 10, 15 and 20 years.

The first statistic analyzed is the mean elasticity across all pairs of years in the data set that are separated by a fixed time interval. The mean elasticity, $\bar{\eta}$, across all pairs of years in the time span $\{T_1, T_2\}$, which are k years apart, is calculated

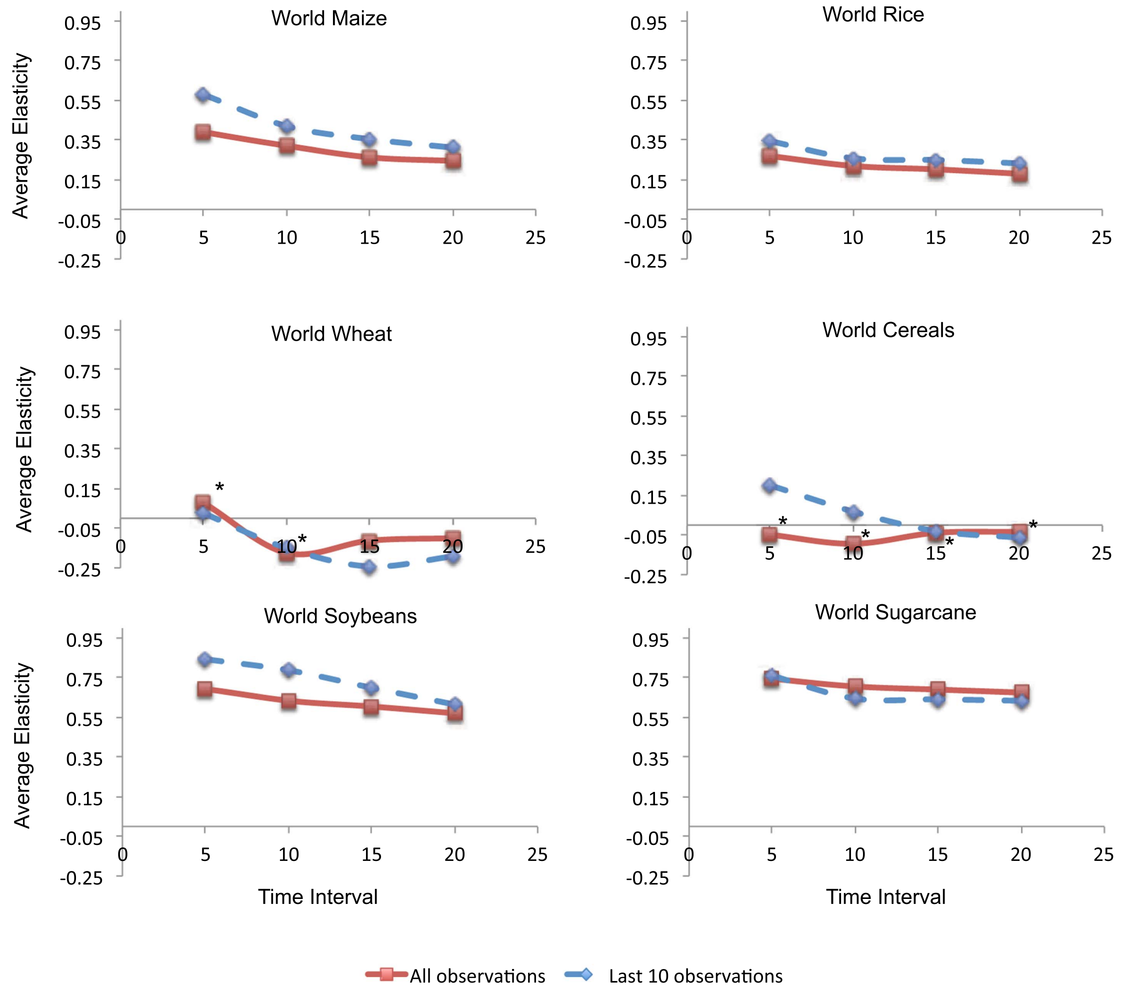

Figure 4. Plot of the mean elasticity at each of the four time intervals of 5,10,15 and 20 years for the five crops and the cereals aggregate at the global level. For each crop it shows the average across all observed elasticities from 1961 to 2013 at a fixed time interval (solid red line) as well as the average of the just last ten observed elasticities for a given time interval (dashed blue line). For example, the mean elasticity across all observed elasticities at the 5 year interval for world maize is computed as the average of the elasticity for 1961–1966, 1962–1967,… 2007–2013. The average over the last 10 observed elasticities at the 5 year interval is computed as the average of the elasticity for 1999–2004, 2000–2001,...2008–2013. Each of the values plotted was found to be significantly different from zero at a 5% confidence level, the exceptions being marked with an asterisk. The exceptions are wheat at the 5 year and 10 year intervals (both across all observations and for just the last 10 observations) and the cereals aggregate, which is not significantly different from zero at 10, 15 and 20 year intervals (both across all observation and last 10 observations).

as shown in equation (3).

$$\overline{\eta}^k = \frac{1}{T_2 - T_1 - k + 1}\sum_{t=T_1}^{t=T_2-k}\frac{Q_t}{A_t} * \frac{\Delta A_t^{t+k}}{\Delta Q_t^{t+k}}. \quad (3)$$

Figure 4 shows that as the time interval widens the average elasticity declines, which means that achieving a given increase in output is associated with a smaller increase in cropland as the time interval expands i.e., the time over which the give increase in output is realized. This is simply capturing the cumulative effect of rising average crop yield over time. The figure also shows that average elasticity is positive (statistically significant at the 5% confidence level) for maize, rice, soybeans and sugarcane at each of the four time intervals. In contrast, elasticity for wheat varies from significantly positive to significantly negative to not different from zero. Notably, cereals exhibit a significantly positive average elasticity when only the last 10 observations at the 5 and 10 year intervals, spanning the periods 2004–2013 and 1999–2013 respectively, are considered. In other words, more recent trends in average elasticity of cereals suggest that the increase in global output of cereals has entailed an increase in the total area under cereal crops.

As a robustness test of elasticity trends, for each of the four different fixed time intervals, the average elasticity was compared for the full time span of {1961–2013} vis-a-vis the time span {1961–2000}. The results, which are in table A2 in the appendix, also show that recent developments are contributing to an increase in the elasticity of cropland with respect to output, the exception being wheat on a 15 and 20 year time frame.

Table 1. Proportion of occurrences when global area under a crop declined while its global output increased i.e., $\Delta A < 0$, $\Delta Q > 0$, $\eta < 0$. The columns denote the different fixed time intervals over which changes in crop area and output are measured.

Crop	5 year	10 year	15 year	20 year
Maize	8%	0%	0%	0%
Rice	15%	2%	0%	0%
Wheat	35%	35%	58%	61%
Cereals	35%	44%	47%	55%
Soybeans	0%	0%	0%	0%
Sugarcane	0%	0%	0%	0%

Table 2. The co-efficient on a linear time trend fitted to the last 10 observations of the elasticity at each different fixed time interval. Trends that are significant at a 5% level are denoted with an asterisk. A positive (negative) co-efficient implies that the mean elasticity is increasing (decreasing). If the mean the elasticity is positive, then the positive (negative) time trend means that increasingly larger (smaller) expansion in cropland is required to increase output.

Crop	5 year	10 year	15 year	20 year
Maize	0.056*	0.0421*	0.0336*	0.0188*
Rice	0.0178	0.0195	0.0161*	0.013*
Wheat	−0.0209	0.0922	0.0499	0.0161
Cereals	−0.0079	0.0531*	0.0373*	0.0263*
Soybeans	0.0167	0.0009	0.0206	0.0061
Sugarcane	0.0542	0.0316*	0.0168	0.0069*

A simple average of the elasticity between different pairs of years could mask any systematic variability such as with respect to the change in output or with respect to percentage change in output. For instance, larger increases in output could be associated with smaller elasticity, say, due to diffusion of a major productivity enhancing breakthrough. To control for such types of associations, a change-in-output-weighted mean elasticity, $\overline{\eta}_{\Delta Q}^{k}$, and a percentage-change-in-output-weighted mean elasticity, $\overline{\eta}_{\Delta Q/Q}^{k}$, were also computed as shown in the equations (4) and (5).

$$\overline{\eta}_{\Delta Q}^{k} = \sum_{t=T1}^{t=T2-k}\left(\frac{\Delta Q_t^{t+k}}{\sum_{t=T1}^{t=T2-k}\Delta Q_t^{t+k}}\right)\eta_t^{t+k}, \qquad (4)$$

$$\overline{\eta}_{\Delta Q/Q}^{k} = \sum_{t=T1}^{t=T2-k}\left(\frac{\Delta Q_t^{t+k}/Q_t}{\sum_{t=T1}^{t=T2-k}(\Delta Q_t^{t+k}/Q_t)}\right)\eta_t^{t+k}, \qquad (5)$$

where, η_t^{t+k} is computed as shown in equation (2).

The results for the two sets of weighted elasticities are shown in table A1 in the appendix alongside the results for unweighted elasticities. Weighted elasticities differ slightly from unweighted elasticities and there does not appear to be any systematic difference between the weighted and unweighted elasticities. Wheat is again an exception, with weighting having a larger effect on the mean elasticity when compared to the effect of weighting on the other crops. This reflects the trends in the 1980s and 1990s when wheat experienced much faster rate of yield growth. For any fixed time interval, the change in output between any two pairs of years that intersect with these two decades would be higher relative to pairs of years that did not intersect with these two decades. The rest of the analysis does not involve any weighting.

In addition to examining trends in elasticity, it is worth also examining the frequency with which cropland has contracted at the same time as output has expanded. If such episodes are observed to occur relatively frequently then it is plausible to imagine a future in which a greater future demand for food using less cropland in absolute relative to the present area of global cropland. To this end, a simple arithmetic count of each of the four possible different combinations of directional change in area and change in output was carried for each of the four different fixed time intervals for the different crops. These combinations are: (i) $\Delta A > 0$ and $\Delta Q > 0$ such that $\eta > 0$; (ii) $\Delta A > 0$ and $\Delta Q < 0$ such that $\eta < 0$; (iii) $\Delta A < 0$ and $\Delta Q > 0$ such that $\eta < 0$; and (iv) $\Delta A < 0$ and $\Delta Q < 0$ such that $\eta > 0$. For the sake of brevity, the discussion is confined to instances when cropland decreased while output increased (i.e., $\Delta A < 0$, $\Delta Q > 0$ such that $\eta < 0$), which is the most desirable outcome if the goal is shrinkage of cropland.

Table 1 shows that for maize, rice, soybeans and sugarcane such episodes are infrequent on a 5 year span and non-existent at higher time intervals. This suggests that area has not declined when output has increased on any 10 years or longer time interval. However, wheat exhibit a different pattern with relatively frequent episodes during which area declined while production increased, which in turn drives the patterns observed for cereals. Figures A3 and A4 in the appendix depict the trends for wheat and cereals aggregate respectively. A further analysis reveals that for wheat, and therefore, the cereals aggregate, the trends reflect two decades of decline in the global wheat area during the 1980s and 1990s. However, since the turn of the century the area planted with wheat is growing. This coupled with the expansion of global area under maize and rice has resulted in global cereals area reaching 720 million hectares in 2013, which now almost equals the peak of 726 million hectares which was recorded in 1981.

The third and final statistic is the time trend of elasticity. Trends in average crop yield might cause elasticity to exhibit a trend. For instance, diffusion of new technologies raises average crop yield, which, while holding all else fixed, would weaken the correlation between change in cropland and change in output. This would cause the elasticity to decline. On the other hand, rapid growth in demand could cause expansion of agriculture into marginal areas with lower average crop yield relative to existing cropland, thus strengthening the correlation between change in cropland and output. This would cause the elasticity to increase.

Table 2 shows the linear time trend coefficients estimated from a regression of the last 10 observations of the elasticity at each time interval against a linear time trend and a constant. To be clear, by analyzing a fixed number of observations at the 5,10,15 and 20 year intervals, we are analyzing data between different starting years but all ending in 2013. Trends that are significant at a 5% level are denoted with an asterisk. It suggests that mean elasticity is either increasing (i.e., a positive time trend) or stable (no time trend). Interestingly, a significant negative time trend is not to be found. If the mean the elasticity is positive, then the positive (negative) time trend means that increasingly larger (smaller) expansion in cropland is required to increase output.

One plausible explanation of a positive time trend of elasticity is expansion of cropland into marginal areas lands with lower average crop yield per acre. There is evidence that Maize cultivation is expanding on parcels that used to enrolled the US Federal Conservation Reserve Program that targets marginal areas, and is expanding into areas of hay production and grazing lands [15, 16]. For wheat which had negative mean elasticity, the time trend is positive at higher time intervals albeit insignificant. Interestingly, for cereals, based on the last 10 observations, the time trend is significant at the 10, 15 and 20 year intervals suggesting that mean elasticity is increasing. These might be on account of a faster rate of increase in wheat demand which is causing wheat area to decline at a slower rate as well as due to growth in demand maize.

3. Conclusion

Forecasting global land use is a daunting exercise. Technology, climate, population, affluence, consumer preferences, and public policies are just a few important drivers of land use that are uncertain. This analysis simply interprets historical trends in annual global cropland and crop production using a new correlation called the elasticity of cropland with respect to crop production. The salience of using this elasticity measure as opposed to crop yield is that it captures trends in both changes on the gross margin as well as changes to the mean. The three descriptive statistics of elasticity—mean elasticity, the frequency with which output increased while crop area declined, and the time trend of elasticity—each measured at different but fixed, arbitrarily chosen time intervals, consistently point to an expansion in cropland if global consumption is to grow as well. In addition to corroborating the general conclusion from earlier studies that focus simply on trends in average crop yield, the elasticity analysis sheds new light on the data. It shows that over longer time horizons of 10 years or more, whenever production has increased, cropland has expanded, the only exception being wheat. And, even for wheat the time trend of elasticity points to an expansion in cropland if its global output is to grow. This provides a strong support to hypothesize that peak cropland might not be at hand.

It is worth reiterating that these findings apply to harvested area and not arable land (please refer back to the introduction for a discussion of this distinction). A question whose importance cannot be overstated is how much of the future expansion in global cropland might be accommodated on existing agricultural land (say, by expanding area under some crops while contracting area cultivated with other crops), and how much of the expansion might entail encroachment, either directly or indirectly, into non-agricultural lands (say, by bring currently 'set-aside' or retired farm land back into production, by expanding into pasture land or through clearing forest land). There is growing evidence pointing to each of these types of changes occurring in different specific regions of the world (see [15–17]). It is also argued that the mechanism by which average crop yield is raised (specifically, whether it is a technology-driven or market-driven improvement or both) and the locations where it is realized (specifically, whether it is close to or far away from the agricultural frontier in a region) will determine whether cropland expands into or contracts from the agricultural frontier in those locations [18]. An elasticity-based analysis can be brought to bear on trends in land use activities at the agricultural frontier in specific ecologically-sensitive areas of the world. Lastly, the elasticity measure could also be used to shed light on questions concerning peaks in the consumption of other scarce natural resources including different types of fossils fuels, water, or other minerals as well as peaks in the release of different types of pollutants.

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Appendix

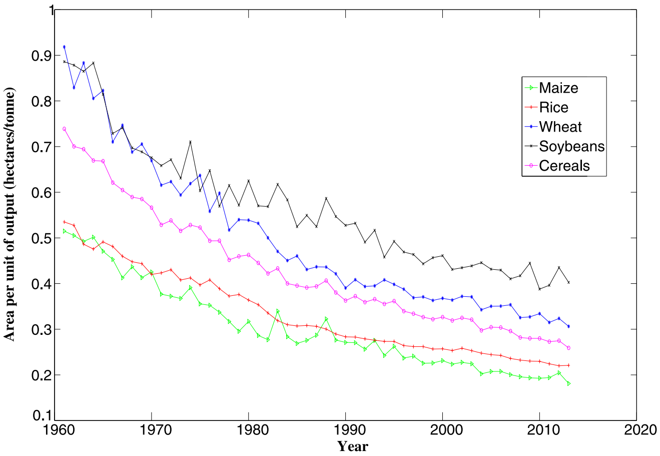

Figure A1. Time trend in the amount of land (in hectares) required for producing 1 metric ton (or tonne) of output for four major crops and a cereal crop aggregate on a global average basis since 1961 through 2013. While less and less land is now required to produce these crops, the rate at which land intensity is declining is also falling, which is evident from the flattening of the trend for each crop. Data from FAOStat database

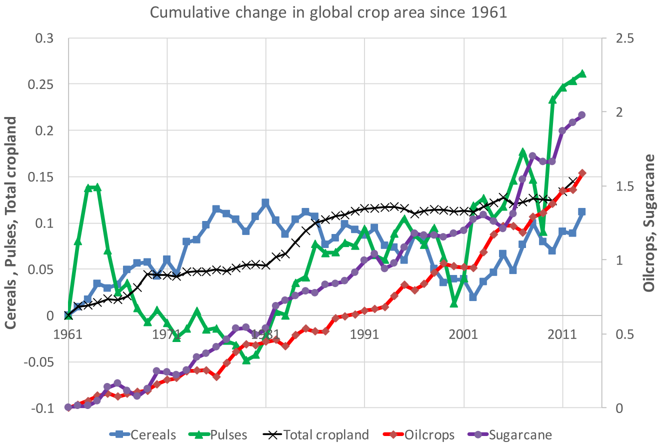

Figure A2. Trends in cumulative change in global area since 1961 for select different categories of crops and total cropland (excluding pasture and meadows). Cereals, pulses and total are plotted on the left axis while oil crops and sugarcane are plotted on the right axis. The total cropland are all higher relative to 1961 levels and each appears to be expanding more rapidly since 2000.

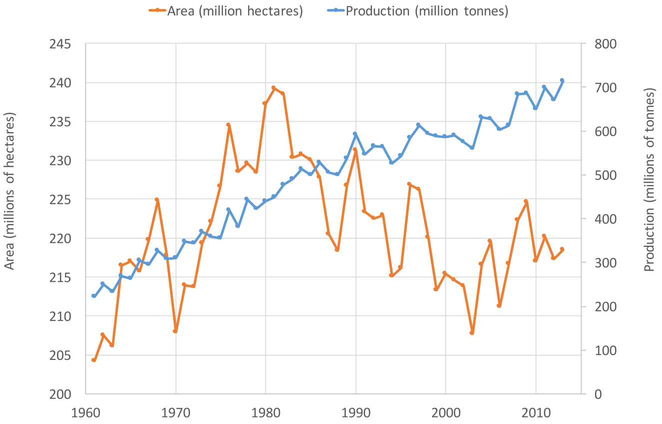

Figure A3. Trends for global wheat area and production.

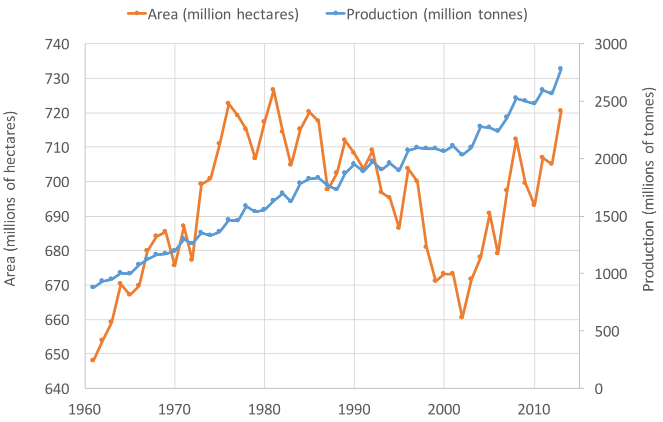

Figure A4. Trends for global cereals area and production.

Table A1. Comparing unweighted average elasticity ($\overline{\eta}_U$) to change in output-weighted average elasticity ($\overline{\eta}_{\Delta Q}$) and percentage change in output-weighted average elasticity ($\overline{\eta}_{\Delta Q/Q}$) for each of the five different time intervals over which elasticity is analyzed—[5, 10, 15, 20].

Time span	5			10			15			20		
Crop	$\overline{\eta}_U^5$	$\overline{\eta}_{\Delta Q}^5$	$\overline{\eta}_{\Delta Q/Q}^5$	$\overline{\eta}_U^{10}$	$\overline{\eta}_{\Delta Q}^{10}$	$\overline{\eta}_{\Delta Q/Q}^{10}$	$\overline{\eta}_U^{15}$	$\overline{\eta}_{\Delta Q}^{15}$	$\overline{\eta}_{\Delta Q/Q}^{15}$	$\overline{\eta}_U^{20}$	$\overline{\eta}_{\Delta Q}^{20}$	$\overline{\eta}_{\Delta Q/Q}^{20}$
Maize	0.39	0.37	0.32	0.32	0.32	0.28	0.26	0.28	0.26	0.24	0.26	0.24
Rice	0.27	0.26	0.26	0.22	0.22	0.23	0.20	0.20	0.20	0.18	0.18	0.18
Wheat	0.08	0.02	0.05	−0.17	0.02	0.03	−0.11	−0.03	0.01	−0.10	−0.04	−0.01
Cereals	−0.05	0.05	0.07	−0.09	0.03	0.05	−0.04	0.00	0.02	−0.03	−0.01	0.01
Soybeans	0.70	0.68	0.63	0.63	0.66	0.63	0.61	0.62	0.60	0.57	0.57	0.56
Sugarcane	0.74	0.73	0.73	0.71	0.70	0.71	0.69	0.69	0.69	0.68	0.67	0.68

Table A2. Average elasticity at the four different fixed time intervals for the entire time span from 1961–2013 against those for years before 2000. The purpose of this exercise is to understand how the changes occurring since the year 2000 are affecting the average. The asterisk symbol denotes that it the average is statistically positive at the 5% significance level.

	1961–2013				1961–2000			
	5	10	15	20	5	10	15	20
Maize	0.3871^*	0.3206^*	0.2624^*	0.2445^*	0.3708^*	0.3048^*	0.2367^*	0.2091^*
Rice	0.2692^*	0.219^*	0.2019^*	0.1799^*	0.2441^*	0.2154^*	0.1894^*	0.1632^*
Wheat	0.081	−0.1746	-0.1128^*	-0.1002^*	0.0481	−0.0968	−0.0291	0.0065
Cereals	−0.0492	−0.0943	−0.039	−0.0341	−0.0009	−0.0567	−0.0081	0.0148
Soybeans	0.6962^*	0.6344^*	0.6051^*	0.5711^*	0.6477^*	0.5848^*	0.5734^*	0.5577^*
Sugarcane	0.7426^*	0.7058^*	0.69^*	0.6752^*	0.7506^*	0.7372^*	0.7115^*	0.6914^*

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