The Future of Crop Yields and Cropped Area

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Introduction

Between 1961 and 2000, average world crop yields grew rapidly, much more quickly than they had in the preceding millennia that humans have been growing domesticated crops. The rapid growth was a result of the *Green Revolution*, a concerted international effort to exploit advances that had been made in crop breeding, fertilizers and herbicides.

On the basis of the Green Revolution experience, there is a wide range of expectations of future crop yields. Two broad viewpoints bracket the range of expectations of the future. First, a group that might be called *Technological Optimists* assume that the 1961-2000 period is merely the first few years of a permanent (or very long-term) change from past experience. In this view, agriculture changed fundamentally around the mid-20th Century. Second, a group that might be called *Technological Pessimists* assume that the 1961-2000 period is, if not unique, at least extremely difficult to replicate, and unlikely to be replicated any time soon. Moreover, they view the steady decline in percent yield increases that can be seen in longer-term data as a sign that yields will eventually saturate, and view possible signs of decline in yield growth in the most recent data as indicating that yields may saturate soon – perhaps within the first quarter of the 21st Century. People of both persuasions can draw on evidence – both direct and indirect – that their view is the correct one.

For this case study, the Technological Pessimist viewpoint is represented by the paper of Jonathan Harris (Harris, 2001). The Technological Optimist viewpoint is represented by two distinct views. First, there is the belief that yields will grow exponentially, although perhaps at a slightly lower rate than has been seen over the 1961-2000 period. This view is represented by Paul Waggoner and Jesse Ausubel (2001). Second, there is the view that historical yield growth is linear, rather than exponential, and that the linear growth seen over the 1961-2000 period is likely to continue for at least the next two to three decades. Tim Dyson is a major proponent of this view (Dyson, 1998).

In this case study, the available evidence on crop yields is surveyed, and a set of scenarios is presented that includes examples from both versions of Technological Optimism and a version of the Technological Pessimist view. The scenarios were implemented in the IPAT-S scripting language. The full script is included as an appendix to this case study, and it can also be downloaded from the IPAT-S web site. Readers who are interested in exploring and modifying the scenarios can download the script and the free IPAT-S software from http://www.kb-creative.net/IPAT_S.

Different Lessons from the Green Revolution

The Green Revolution strategy emerged from a surprising confluence of different lines of agricultural research (Evans, 1998) – the development of cheap nitrogenous fertilizers, of dwarf varieties of major cereals, and of effective weed control. Nitrogenous fertilizers increase crop production substantially, but make plants top-heavy, causing them to fall over. The development of dwarf varieties solves this problem, but at the cost of making plants highly susceptible to weeds, which grow higher than the dwarf plants, depriving them of light. The development of effective herbicides removed this problem. Further Green Revolution development focused on crop breeding to increase the harvest index – the ratio of the mass of grain to total above-ground biomass.

The Green Revolution strategies, while outstandingly effective, are limited. The harvest index can only be increased so far, and photosynthesis sets a limit to total biomass production. While these limits are theoretically extremely high, and very high yields have been recorded in field trials and competitions, Harris (2001) argues that it is unlikely that national or global average yields will ever approach these levels, because record yields are reached under optimal conditions, which are met by only a small fraction of global cropland.

Unmentioned by Harris, but also significant, is that it is rarely in the interest of working farmers to reach maximum yields. There are at least two reasons for this. First, for a given crop variety, it can be expected that profit will be maximized at some level below the yield optimum, as marginal increases in yields decline with increasing inputs. Second, working farmers must hedge their bets. If a growing season is expected to be drier than usual, a farmer may plant most of his or her fields with a drought-tolerant variety, but a forecast of dry weather is not a certainty, and in order not to lose an entire year's crop if the forecast is wrong, he or she is likely to plant a wet-tolerant variety as well. Whether the forecast is borne out or not, the yield will be sub-optimal. Additionally, in some cases there may be a third reason: where crop residues are important as livestock feed, farmers may resist increasing the harvest index of their crops, as that would reduce the mass of the residue compared to that of the grain (Humphreys, 1991). Together, these arguments suggest an important, but often-neglected point: that optimal farmer decisions result in sub-optimal yields, making it highly unlikely that the highest recorded yields will ever be seen in average yield data.

Because the Green Revolution period is historically unusual and the Green Revolution strategies have clear limits, it cannot be simply claimed that historical trends are likely to persist. Additional arguments must be put forward. Indeed, the Technological Optimists do put forward other arguments. Essentially, there are two. First, the Green Revolution strategy is far from being fully exploited, and we will see further gains as the benefits continue to unfold. Second, even when the Green Revolution strategies have been fully exploited, further strategies will be developed, allowing yields to continue growing at historically rapid rates. Recent developments in genetically engineered crops and livestock indicate that further advances may indeed be within reach.

Different Lessons from the Historical Data

Waggoner and Ausubel (2001) look at FAO yield data from the 1961-2000 period and conclude that yields are growing exponentially. However, others have looked at the FAO data and have seen either a linear growth (Dyson, 1998) or evidence for saturation (Harris, 2001). The reason why the data can support such a variety of interpretations is that the thirty years for which FAO data are available is a very short time. In comparison to all of agricultural history, the period covered by the FAO data is insufficient to clearly reveal the direction of the long-term trend. Moreover, oddities in the land-use statistics from 1981 to 2000 (such as the correction of Chinese land-use statistics and the reclassification of marginal cropland under the Conservation Reserve Program in the U.S.) as well as real events (such as the collapse of agricultural production in the former Soviet Union) are reflected in the yield data. The net effect is to make yield growth appear to slow and then accelerate, returning to the long-term trend by around 2000.

Both exponential and linear functional forms are excellent fits to the 1961-2000 data. However, an "s-shaped" logistic curve, which saturates over the long run, cannot be ruled out. Indeed, it begins to look like a much more likely candidate when pre-Green Revolution years are added in. Data before 1961 are scanty, so long-term trends in crop yields must be pieced together from incomplete information.

Consider first the example of (unhulled) rice yields in Japan. Plucknett (1991), in the course of an essay on the contribution of agricultural research to food security, provides a summary history of rice yields in Japan from 900 AD to 1954. His figures are rough. Nevertheless, when presented along with FAO data from 1961 to 2001, they match reasonably well, and give an idea of the historical trend. Plucknett's figures, with three-year averages of FAO data, are shown in Figure 1. It is clear from the figure that for rice, at least, recent yield growth rates are quite unusual.

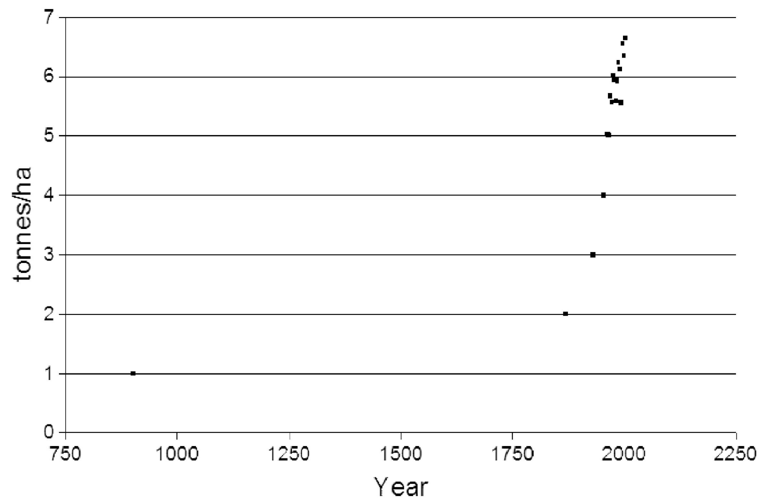

Figure 1: Historical unhulled rice yields in Japan

Looking at a more general category of crops (but over a shorter time period) Evans (1998) suggests that between 1935 and 1960, yields for several important cereals increased by about 10%. In Figure 2, estimated historical yields from FAOSTAT data are shown, as well as a data point for 1935. The data are normalized to equal 100 in 1961, and the 1935 data point is set to 100/110%, or 90.9. The 1935 figure is clearly rough, but if the growth in yields from 1935 to 1961 are anywhere near 10% then it is clear from the figure that the recent linear or exponential-type growth is an historical aberration.

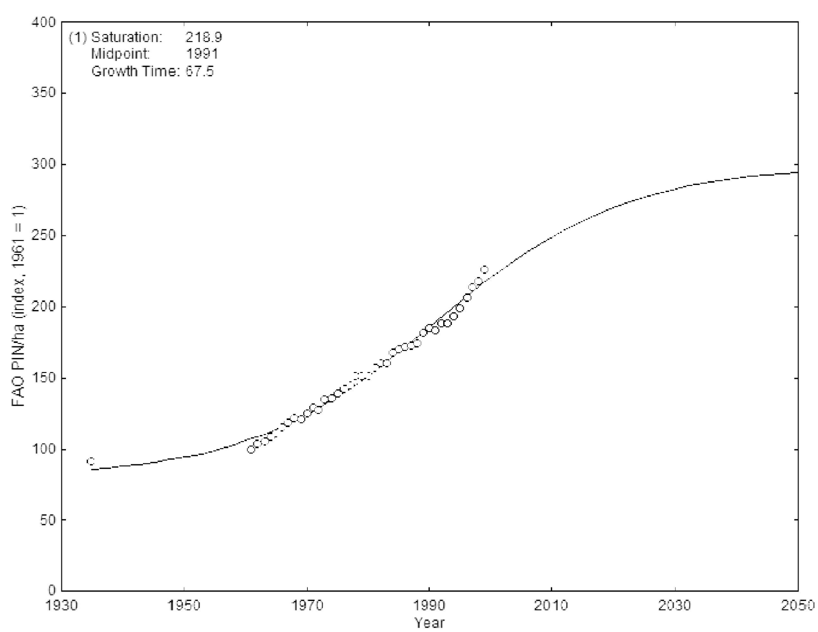

Figure 2: Historical cereal yields, 1935 (est.) and 1961-2000, with logistic fit

Indeed, it begins to look more s-shaped, suggesting that a logistic curve may be a reasonable fit to the historical data. Figure 2 shows the fit to a logistic curve that asymptotically approaches a minimum of 80 in the distant past and a maximum of around 300 in the distant future. (The logistic curve was fit using the Loglet software of Rockefeller University's Program for the Human Environment.) At the least, the fit does not look unreasonable, making it difficult to rule out a saturated, logistic curve. Moreover, the curve in Figure 2 saturates alarmingly soon. With a characteristic time span of 67.5 years (the time it takes to go from 10% to 90% of the saturation level) and a midpoint of 1991, the boom period stretches from around 1957 to 2025.

Note that small changes in relevant parameters (asymptotic value in the distant past, number of logistic curves in the fit) can lead to large differences in the saturation point. The point of the logistic exercise is not to say that yields *will* saturate in the next two to three decades, but that it is impossible to rule that possibility out on the basis of the historical data alone.

Scenario Framework

The scenario framework used in this case study is the one presented in Waggoner and Ausubel (2001). In that paper, changes in cropped area are decomposed into a product of factors, using a modified IPAT identity:

$$L = P \times A \times C \times R_n \times y^{-1},$$

where L is cropland area, P is population, A is "affluence" (gross world product per capita), C is consumption (food expenditure as a fraction of total income), R_n is the "non-food ratio" (the ratio of non-food crop production to food crop production), and y is the yield. The same framework is used in this paper. Trends in all factors are the same as in Waggoner and Ausubel (2001) except for population and yield. For population, the 2002 revision of the United Nations medium fertility variant is used (Waggoner and Ausubel also used the UN medium fertility variant, but for the 1998 revision). For the yield, four different scenarios are presented, of which Waggoner and Ausubel's Reference scenario is one.

The scenarios for this paper were developed using the IPAT-S scripting language. The IPAT-S interpreter can be downloaded at no charge, and the IPAT-S script used for these scenarios is printed in its entirety in the appendix. Readers are encouraged to investigate their own yield assumptions by downloading the IPAT-S software, entering the script and modifying it as they desire.

In the IPAT-S script, Wagggoner and Ausubel's formula is implemented using IPAT-S syntax as:

```
:: Population >> Income * Appetite * NonFood / Yield -> Cropland
```

This expression states that changes in *Cropland* (corresponding to L in Waggoner and Ausubel's formulation) are driven by changes in *Population* (corresponding to P), but modified by changes in *Income*, *Appetite*, the *NonFood* ratio and *Yield* (corresponding to A, C, R_n and y, respectively).

The four scenarios are *Tech Optimist Linear*, *Tech Optimist Exponential*, *Tech Pessimist* and *Intermediate*. The Tech Optimist Linear and Tech Optimist Exponential assumptions are drawn directly from Waggoner and Dyson (1999) and Ausubel (2001), respectively. The Tech Pessimist assumptions are drawn from logistic fit to cereal yield data as presented in the previous section. The Intermediate View is a modification of the Tech Pessimist view, in which successive waves of innovation lead to further yield increases, but with diminishing effectiveness. (For details, please see the IPAT-S script in the appendix.) Yield assumptions for the different scenarios are shown in Figure 3.

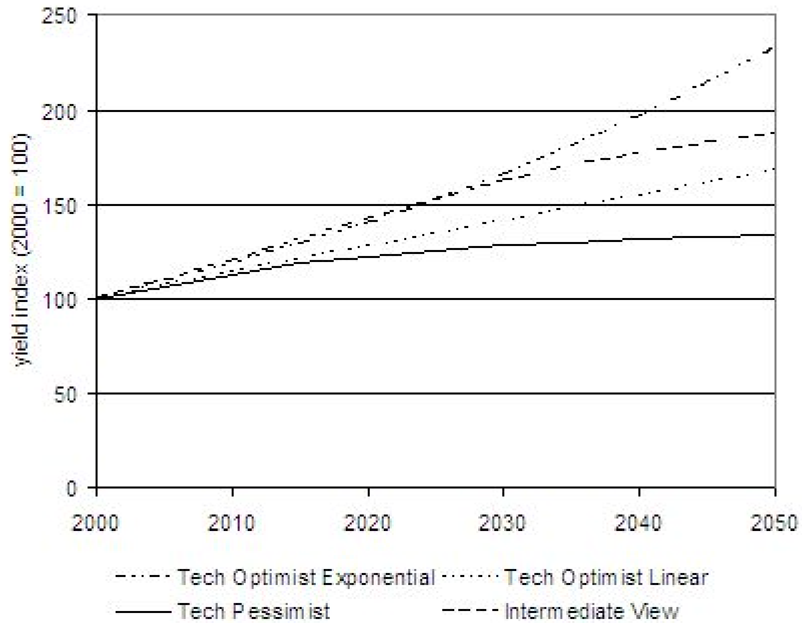

Figure 3: Yield assumptions in the four scenarios

Scenario Results

The main output of the scenario calculations is the change in global cropland area. The results are shown in Figure 4. As can be seen in the figure, even within the Technological Optimist viewpoint there is a wide range of possible outcomes. In fact, the linear and exponential growth assumptions give qualitatively different outcomes: either a net reduction or a net expansion of global cropland.

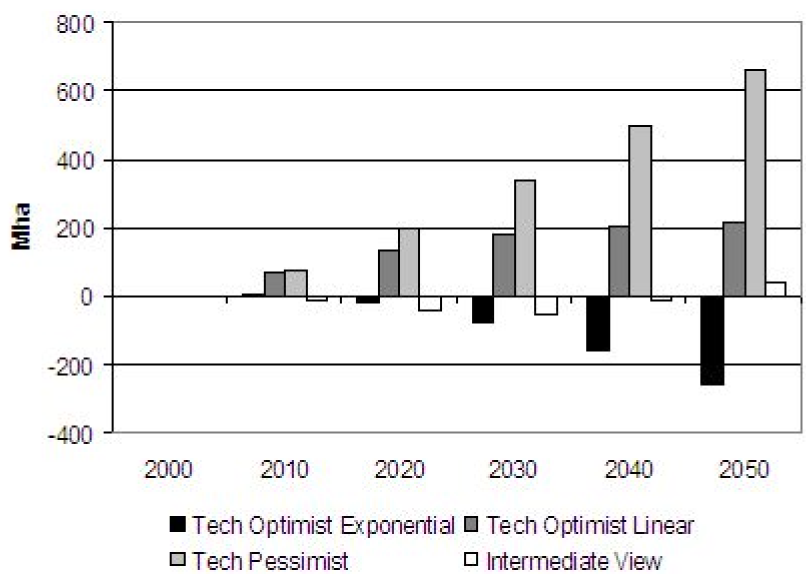

Figure 4: Change in global cropland area in the four scenarios

The Technological Pessimist outlook (as modeled in the IPAT-S script shown in the appendix) suggests the depressing possibility of a 600 Mha expansion of cropped area, a roughly 44% increase over the scenario period.

The Intermediate View scenario looks surprisingly similar to the Tech Optimist Exponential scenario in the first three decades. However, beyond that point the trajectories begin to diverge. The new technologies that appear in the Intermediate View scenario reach their limits and, following the assumptions in the IPAT-S script given in the appendix, after about 2040, no new technologies are forthcoming, leading to an initial saving of global cropland, with a modest net expansion by 2050.

Conclusion

There is considerable uncertainty about the future of global crop yields. The large range of plausible outcomes leads to a similarly large range of outcomes for future changes in crop area. The debates between technological optimists and pessimists rages today, and are likely to continue to rage in coming decades, because the implications of the different positions will not become clear for some time. In the face of uncertainty, scenario exercises are a useful way to look at the range of possibilities. The two Technological Optimist variants lead to either a shrinkage of global cropland by 260 million ha between 2000 and 2050 or a growth 215 million ha – a 475 million ha difference, or nearly one-third of total cropland area in 2000.

With such a large range of possible outcomes even within the technological optimist camp, we would do well to remain alert. Given the nature of agricultural production in much of the world today and the challenges facing agriculturally-based economies, we cannot be sanguine about the prospects for agricultural productivity, the availability of cropland, or for the environment.

References

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Appendix: IPAT-S Script

```
base year 2000
scenario years 2010 to 2050 by 10

dimension scenario 'Tech Optimist Exponential' 'Tech Optimist Linear' \
                   'Tech Pessimist' 'Intermediate View'

load _Loglet from 'IPATS_standard' as Logistic

##
## World population, UN medium variant, 2002 revision (millions)
##
summvar Population = 6070.581, 6830.283, 7540.237, \
                     8130.149, 8593.591, 8918.724

##
## Economic growth, change in food consumption
##
ratio Income = gr(1.80%)
ratio Appetite = 1/Income^0.7
ratio NonFood = gr(0.0%)

##
## Yield changes & land use
##
var Yield{scenario}, Cropland{scenario}

Yield.0 = 100          # index
Cropland.0 = 1500      # million ha (approximate)

##
## Yield scenarios
##

##### Waggoner and Ausubel: Tech Optimist Exponential's exponential yield increase #####
:: >> gr(1.70%) -> Yield{scenario = 'Tech Optimist Exponential'}

##### Dyson: Tech Optimist Linear's linear yield increase #####
:: 2.711 + 0.0426 * (y - 1990) >>-> Yield{scenario = 'Tech Optimist Linear'}

##### Saturated yields #####
# Follow a logistic path of increasing, then saturating yields
var tempYld

# Single logistic:
#   midpoint at 1990
#   saturate at 220 (so max yield index is 220 + 80 = 300% of 1961 level)
#   characteristic duration of 68 years (so from roughly 1956 to 2024)
call Logistic using tempYld \
                  218.9 67.5 1991
# Logistic starts from base of 80, not from 0, so add 80 to drive total yield
:: 80 + tempYld >>-> Yield{scenario = 'Tech Pessimist'}

##### Intermediate View #####
# Like "Tech Pessimist," but add two further logistics for
# future advances
# Use:
#   midpoint of 2020 and 2050
#   additional yield increase equal to one-half, then one-quarter the
#       first logistic
#   characteristic duration one-half as long as first logistic
call Logistic using tempYld \
                  218.9 67.5 1991 \
                 <110   35   2020> \
                 <55    35   2050>

# Logistic starts from base of 80, not from 0, so add 80 to drive total yield
:: 80 + tempYld >>-> Yield{scenario = 'Intermediate View'}
```

```
##
## Changes in cropland use
##
:: Population >> Income * Appetite * NonFood / Yield -> Cropland

##
## Report results
##
report Yield as "Yield (2000 = 100)"
report 100 * Cropland/Cropland.0 as "Cropland (2000 = 100)"
report Cropland - Cropland.0 as "Change in cropland (Mha)"
```