How Do You Spot a Trend?
An Examination of Recent Phosphate Rock Production

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Abstract

This work examines recent historical phosphate rock production and determines possible identifiable trends. The difficulties of identifying trends from short time-series are described. Statistical analysis alone cannot be definitive in identifying a trend. These results, however, can be supported by information about sources of increasing global demand. A bilinear model was developed that indicates global per-capita phosphate rock production was essentially steady from 1993 to 2006 at an average annual 22.58 kilograms per capita. Since 2007 there has been strong growth at an average annual rate of 5.1 percent per year. This, combined with a population growth rate of 1.14 percent per year, yields a growth rate in the total phosphate rock production of 6.3 percent per year. Even if further growth in per-capita production is linear at current rates and not exponential, total global phosphate rock production would have to increase by a factor of 3.6 to satisfy the demand by the year 2050. Whether such an increase would be expected to continue to this extent or not, this increase should provide motivation to begin the implementation of significant conservation measures. Underlying drivers of per-capita demand suggest that strong growth is likely to continue.

Key words: forecast, per capita, phosphorus, production, trends

1. Introduction and Data

Over the five-year period from 2006 to 2011 the world production of phosphate rock (PR) increased at an average annual rate of 6.3%, according to USGS data (U.S. Geological Survey, 2014). This is a higher rate than has been observed since 1968. Does this constitute a trend? What do the data tell us about how fast phosphate rock production is currently increasing? Does the increase represent a trend, or is it a spurious result? A close examination of past trends will be useful for estimating future trends. We will base this examination on the USGS PR production data for the years 1900 through 2012 (U.S. Geological Survey, 2014) and global population estimates from the U.S. Census (2014) (Fig. 1). The PR production data for 2013 are available. They are shown in the figures, but not considered in the analysis, since the last year of annual production data are preliminary, and typically show considerable revision in the following year's USGS report.

An understanding of the trend could help to address three questions: first, how fast PR production is increasing now; second, how production driven by demand will change in the future; and third, how long PR reserves will last. This paper will focus on the first question in detail. The answer to that question provides a starting point for discussion of the others.

The concern for potential future scarcity of phosphorus resources rests primarily on two kinds of information: available or potentially available phosphorus reserves, and trends in phosphorus production and consumption. The reserves are based on presumably fixed mineral resources that can be mined. The fraction of resources that may ultimately be claimed as reserves depends upon many factors related to the cost of recovering them. These include the grade of the ore, its purity and physical factors controlling its recovery such as depth or location of the mineral formation. The effect of these factors can be modified by economic and technological developments. There is considerable uncertainty and debate about the ultimately quantity of recoverable resources. By the latest USGS figures, Morocco controls about 75% of the world's reserves (Jasinski, 2014), but Morocco does not publicize details about the availability of those resources. The production of PR, on the other hand, is more reliably known.

Figure 1 shows how the PR production rate (P) has varied since the year 1900. How long will production continue to increase? Subsequently, will it level off or will it commence a decline? Several investigators have fitted these data to a bell-shaped curve (either Gaussian or logistic-based) in order to extrapolate a peak year of production (Déry & Anderson, 2007). In this context the relationship is called a Hubbert curve. Cordell *et al.*

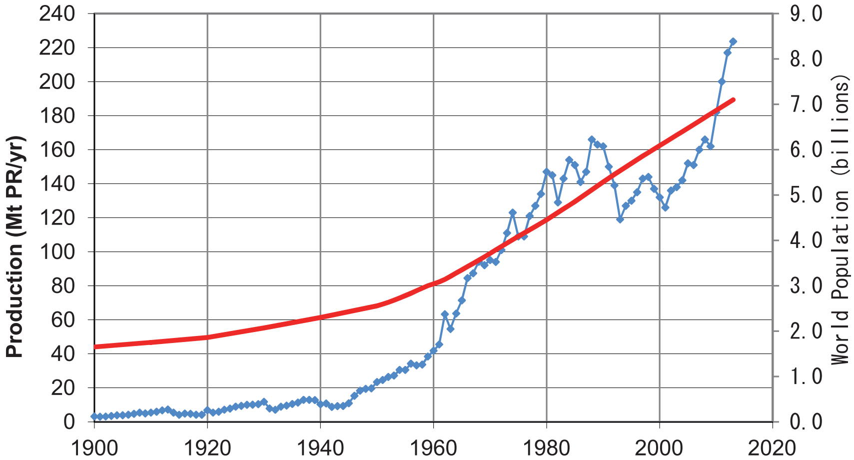

Fig. 1 Global PR (phosphate rock) production (U.S. Geological Survey, 2014) (solid diamonds) and world population (U.S. Census, 2014) (red line).

(2009) improved on the Hubbert curve procedure by utilizing information on known reserves in the fitting procedure. They predict that phosphorus production could peak by 2033 at 28 Mt/yr (about 214 Mt PR/yr). Since then this value has already been exceeded. Vaccari and Strigul (2011) have shown that Hubbert curve fits are highly susceptible to the stage of production. In the case of data on U.S. production, which has already passed its peak, the fitting procedure produces reliable fits only after the peak has already occurred. This then makes the results susceptible to the uncertainty in that information. Nevertheless, Hubbert-curve analysis may be useful for when we compare various methods of forecasting, all of which are subject to considerable uncertainties.

2. Methods

The rate of increase can vary widely from year to year. The rates can be smoothed by computing an annual average rate of increase over multiple years so trends can be more easily seen. The compound annual rate of increase from year i to year j (r_{ij}) can be computed by equation (1):

$$r_{ij} = \left(\frac{P_j}{P_i}\right)^{\frac{1}{j-i}} - 1 \qquad (1)$$

P_j is the global PR production for year j.

Several factors can account for changes in production/demand, including population increase, changes in dietary consumption and diversion of crops for non-food use (primarily for energy). Of these, population is the factor most easily accounted for, and likely the most significant "master variable" for growth in phosphorus demand. Thus, the data will first be normalized by population, and the resulting data examined for trends, yielding the per-capita phosphate rock production, P_C (kg PR/cap/yr) from P and world population, N:

$$P_C = P/N \qquad (2)$$

The relationship between the overall rate of increase (as computed from equ. 1) of PR production (r_P), the rate of population increase (r_N) and the rate of increase in per-capita PR production (r_C) is:

$$(r_P + 1) = (r_N + 1) \cdot (r_C + 1) \qquad (3)$$

Thus we can compute the per-capita PR production rate of increase from the rates for total PR production and population increase:

$$r_C = \frac{r_P - r_N}{r_N + 1} \qquad (4)$$

The average rate of increase can be very sensitive to the averaging period. Over the two years leading to 2012, the rate of increase in per-capita consumption averaged 8.0% per year; for the five years ending in 2012, the rate averaged 9.0%; and over ten years the average is 3.56%. Which value best reflects the current trend? The approach that will be taken here will be to examine trends for various periods. Several measures of goodness-of-fit will be compared. The results of that analysis will suggest that a bilinear model would be appropriate. In a bilinear model the data are divided into two contiguous sets, and a linear model fit to each using least-squares regression.

3. Results

Figure 2 shows the annual rate of increase in global PR production compounded over ten-year periods ending at the indicated year. (The one-year rates varied much more, ranging from –33% to 66%.) The fastest decade of increase was during the post WWII period from 1944 to 1954, averaging 12.6% per year. Another peak decade occurred from 1958 to 1968, with production increasing an average of 10.8% per year. This period corresponds with the "green revolution," in which high yield grains were developed and put into production. These high yields did not come for free, but required increased inputs in the form of fertilizer and irrigation. The long subsequent period of declining rates of increase indicates a possible saturation effect, as further increases in yield may have required expansion of the cultivated area and increased dissemination of modern agricultural techniques.

From 1989 to 1993, PR production decreased sharply, by 28% overall, a compound average of 6.4% per year. This has been attributed to two factors (Smil, 2002): First, the collapse of the Soviet Union resulted in marginal agricultural lands being taken out of production. Second, agricultural scientists realized that the amount of phosphorus applied per hectare that had been recommended for many years was significantly more than required to maintain optimal crop yield, and began to adopt more conservative fertilization practices. Note that the large fluctuations prior to 1940 reflect the very low production compared to more recent levels, and are therefore less meaningful in today's context.

Since 1993 the annual increase in PR production has generally resumed. After several ups-and-downs, the years since 2006 have shown a steady and apparently increasing rate of increase, culminating in a 2012 level about 31% higher than the highest value before 2010, which occurred in 1988. However, as of 2013 the per-capita production has yet to exceed the 1988 value.

Figure 1 also shows global population since the year 1900 (U.S. Census, 2014). The annual global population growth rate during this period decreased steadily from a post-WWII peak of 2.06% in 1969 to 1.10% in 2012.

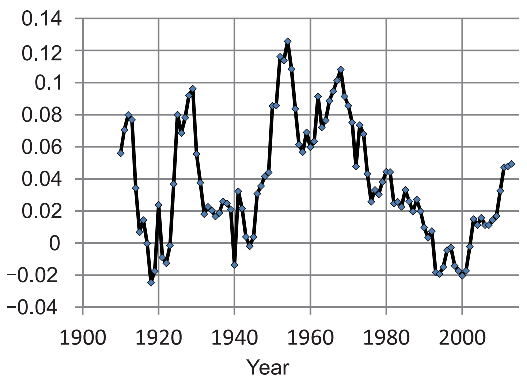

Fig. 2 Ten-year moving average annual rate of increase in global PR production.

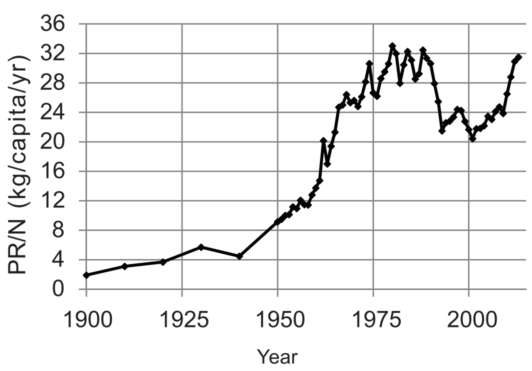

Fig. 3 Global per capita phosphate rock production.

Although the rate of decrease is dropping, the total number added to the population each year over that period (ΔN) has been fairly stable, averaging 78.6 million per year, and ranging from 71.1M to 87.5M. In 2012 the figure is 77.3M. Thus the decrease in the population growth rate is due to an increase in the denominator value. However, the forecast for 2050 is for ΔN as well as r_N to decrease to 43.2M and 0.46%, respectively.

Figure 3 shows the per-capita PR production (P_C), since 1900. The value of P_C increased steadily during this period up to the mid-1970s, almost quadrupling from 1950 to its peak of 33 kg/capita/yr in 1980. Thereupon it stabilized for about a decade, until it began the precipitous decline from 1988 to 1993. The overall increase is likely due to increased use of fertilizer throughout the world, driven by the demand for improved dietary quality. In the past 40 years, however, malnutrition as measured by the percentage of undernourished persons has been cut almost in half without a net increase in per-capita PR production. The percentage of undernourished persons in the world has decreased steadily from 26% in 1969–1971 to 21% in 1990–1992, and 14% in 2005–2007 (FAO, 2011).

The major factors that contributed to the high P_C up to 1988 are no longer operational. Accordingly, if we are interested in current trends, we should examine the period from 1993 to the present. The data for these years are shown in Fig. 4. Thus the original question posed above of how fast PR production is increasing now will be examined in light of these data.

In making estimates of future phosphorus production, Mohr and Evans (2013) assumed that per capita phosphorus consumption would stabilize at 3.5 kg P/cap/year. This is equivalent to 26.7 kg PR/cap/yr at a PR grade of 30% P_2O_5. It may also be compared to the Recommended Dietary Allowance (RDA) for P of 0.70 g P/day for adults (Calvo & Uribarri, 2013), which is 0.26 kg P/yr. The large difference is due to losses between the mine and the fork, including mining waste, agricultural losses such as erosion and harvest losses, loss of animal waste and food waste in processing and preparation, and because the actual dietary intake may be much more than the RDA (about 1.1 g/d for adult women in the U.S.A., and 1.5 g/d for adult men).

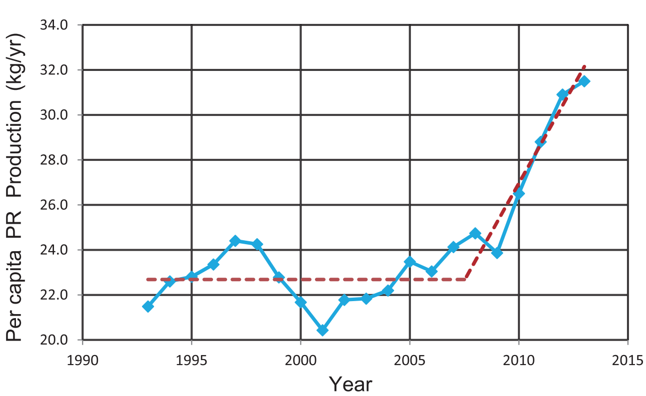

Fig. 4 Global per capita production of phosphate rock from 1993 to 2013, with a bilinear model (dotted line).

Per capita PR consumption, however, has been increasing fairly steadily for thirteen years, and has exceeded the Mohr and Evans value of 26.7 kg PR/cap/yr for the past three. In just the three years from 2009 to 2012, the per capita production rate increased an average of 9.0% *each year*, an overall increase of 30%. The 2013 value of P_C is the highest in 25 years at 31.5 kg PR/cap/yr. Is this significant? What does this suggest about the possibility of future changes?

Clearly, results from just a few years should be viewed cautiously. The five years of consecutive increase in P_C from 1993 to 1997 were followed by four consecutive years of decline. Interestingly, the USGS reported in 2000 that industry analysts predicted a 2.3% per year increase in demand for phosphate fertilizer for the decade to follow (Jasinski, 2000). The actual average rate of increase from 2001 to 2010 was 3.3% per year for total PR production, and 2.0% per year on a per-capita basis.

The declining P_C from 1998 to 2001 has been attributed to a variety of factors, including four consecutive years of reduced planted acreage in the U.S., mostly of corn, poor spring weather in some regions of the U.S. causing missed fertilizer applications, quotas imposed on phosphorus imports by China, and lower usage in numerous parts of the world due to high fertilizer prices, poor weather and reduction in cultivated areas (Jasinski, 2001).

What trend in the data does Fig. 4 show? One approach to examining the trends is to compute the goodness-of-fit of the linear regression models for various periods. Here we compare models for each of the periods starting in 1993 and ending in different years from 2001 to 2012, *i.e.*, the models for the years 1993 to 2001, 1993 to 2002, etc. The fits were computed using the Linest function in Microsoft Excel (Microsoft, 2007). The Linest function computes the coefficients of the fitted linear equation plus a variety of statistics, including the coefficient of determination (R^2), the sum of the square of the errors (SSE), the degrees of freedom of the fit (n_f), the sum of squares of the regression (SSR) and the F-statistic for overall goodness of fit. The probability that the fit occurs by chance ($p(F)$) can be computed from the F-statistic using the FDIST function in Excel. If $p(F)$ exceeds a threshold value (*e.g.*, 5%) then the linear model is not statistically different from just using the average of the data, *i.e.* no linear trend is detected.

No trend was detected for all models up to the model for 1993-2010. Including the data for subsequent years produced strongly significant trends ($p(F) < 1\%$). Clearly the P_C was increasing significantly to 2010. How should the data be modeled overall? It is suggested to use a bilinear model in which the years up to the year before a switching point are modeled using the average value (zero trend), and subsequent years are fitted to a linear equation by least squares regression. The adequacy of a linear model for the more recent years was tested in a way similar to the previous trend analysis. A series of linear regressions was computed for models of the data for the years X to 2012, with X varying from 2003 to 2010. All of these models showed strong linear correlations, with the strongest significance for the 2006–2012 model. Thus a variety of bilinear models may be suggested with various switching points.

A final test was made by computing the bilinear models for switching points from 2000 to 2010, and comparing the resulting sum of squares of the errors (SSE). The models with switching points from 2005 to 2008 produced similarly low SSE values, with 2006 giving the smallest:

$$P_{C,i} = \begin{bmatrix} 22.58; & 1993 < i < 2006 \\ 1.392 \cdot i - 2771; & 2007 < i < 2012 \end{bmatrix} \tag{5}$$

Thus the best bilinear model assumes a constant P_C for 1993 to 2006 and a linear model for subsequent years. This model is shown as the dotted line in Figure 4. The average P_C for 1993 to 2007 was 22.58 (+/– 0.56) kg/cap/yr, and the subsequent annual rate of increase was 1.392 (+/– 0.84) kg/cap/year. (The ranges are computed using 95% confidence intervals.) The R^2 value corresponding to this model is 87%. At the 2012 level of P_C, the predicted rate of increase is 4.5% per year. As the denominator increases each year, the rate as a percentage decreases.

Having used the bilinear model to identify the switching point, one could also examine the average annual growth rate for the years since. The average annual increase in per-capita production from 2007 to 2012 was 5.1% (6.3% for total PR production). This may be the best way to express the current trend looking backwards. But to extrapolate this rate implies exponential growth.

Another model likely to give a good fit would be a sigmoidal (logistic) curve. Such a model would predict an asymptotic maximum P_C value that the world would be trending to. But such a prediction might be too tempting, since such a fit would be subject to similar uncertainty as Hubbert curve modeling (Vaccari & Strigul, 2011). A logistic model was fit to the 2008-2012 data:

$$P_{C,i} = \frac{K}{1 + b \cdot \exp\left(-k(t - t_0)\right)}; \quad b = \frac{K - P_{C,0}}{P_{C,0}} \tag{6}$$

The resulting fit was K = 315 kg/cap/yr, k = 0.063, t_0 = 2006, and $P_{C,0}$ = 21.5 kg/cap/yr. The value of K is the asymptotic per-capita production rate. Thus this model predicts that P_C will eventually reach ten times the current rate. Again, such a prediction is subject to considerable uncertainty and should not be relied on at all.

The medium-term prediction of each of these three models, however, might be of interest. The exponential growth at the current 6.3% rate of increase suggests that in 2050 P_C would reach 256 kg/cap/yr – more than eight times the 2012 value. The logistic model predicts 169 kg/cap/yr – 5.6 times current rates.

The linear model predicts 82.9 kg/cap/yr for 2050 – 2.7 times the 2012 value. When combined with the 33% increase in population predicted by the U.S. Census, total

PR production would be predicted to increase by a factor of 3.6, to 777 Mt/yr. Thus even the most conservative of these models suggests an alarming increase. This strongly suggests that current trends are unsustainable.

These results illuminate what information can be gleaned from the data. By themselves they cannot tell us whether to accept a zero trend, as in the first 14 years since 1993, or the strong trend indicated for the period from 2008 to the present. This requires a judgment that depends on our knowledge of the real-world factors affecting the demand for and production of phosphate rock. However, the results show a reasonable and parsimonious way to describe the data.

There are market factors that could explain, and therefore support, the trend since 2008. This period corresponds to a period of explosive growth in the economy of China, the world's largest producer of phosphate rock. This period was also a time in which there was a large increase in the production of crops for use in fuel production.

Although it is clear that per capita production, and therefore consumption, has been accelerating over that past five or more years, there is no guarantee that this trend will continue. It is possible that the curve could level off relatively soon, or even show a correction and decline. We might be optimistic and expect that the driving forces will be self-limited. In any case it appears that the current trends are unsustainable. Whether they limit themselves or not is somewhat speculative either way. Therefore it would seem to be prudent to respond to the state of our knowledge as it is, and at least begin to implement conservation measures.

In the end, only time can validate whatever judgment is made. As was said by the Scottish economist Alec Cairncross (quotationsbook.com, accessed April 2011):

> A trend is a trend is a trend.
> But the question is, will it bend?
> Will it alter its course through some unforeseen force
> and come to a premature end?

An examination of the drivers of these changes could help clarify the question. Such drivers would include trends in dietary changes or their economic determinants and in agricultural practices at regional or smaller scales.

4. Conclusions and Recommendations

A bilinear model indicates that global per-capita phosphate rock production was essentially steady from 1993 to 2006 at an average of 22.58 kg/cap/yr. Since 2007 there has been strong growth at an average annual rate of 5.1% per year. This, combined with a population growth rate of 1.14% per year, yields a growth rate in the total phosphate rock production of 6.3% per year.

Even if further growth in per-capita production is linear at current rates and not exponential, total global phosphate rock production would have to increase by a factor of 3.6 to satisfy the demand by the year 2050. Whether such an increase would be expected to continue to this extent or not, this should provide motivation to begin the implementation of significant conservation measures.

Underlying drivers of per-capita demand suggest that strong growth is likely to continue. Medium-term prediction of future trends should take into account the effects of these drivers at the regional- or country-level of detail.

The analysis suggests that the current growth rate is unsustainable. It is acknowledged that extrapolation of trends is risky. Nevertheless, trends should not be ignored. The presence of such a strong current trend should motivate government and industry to examine their practices and begin planning and implementation of measures to reduce waste of the resource. This kind of analysis needs to be strengthened by a closer examination of the factors that drive these trends. These include trends in dietary consumption, use of crops for fuel, changes in agricultural practices, and in fertilizer costs. These, in turn, should be resolved at regional or even country-level scales. That kind of detail would also be useful in informing future policy choices.

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