Phosphate Rock Demand into the Next Century: Impact on World Food Supply

James R. Herring[1] and Richard J. Fantel[2]

[1]U.S. Geological Survey, MS 939, Box 25046, Denver, Colorado 80225, USA, and [2]U.S. Bureau of Mines, Minerals Availability Field Office, Bldg. 20, Denver Federal Center, Denver, Colorado 80225, USA

A vital and indisputable link exists between phosphate rock and world food supply. Phosphate rock is the source of phosphorus used to make phosphatic fertilizers, essential for growing the food needed by humans in the world today and in the future. We modeled the depletion of the known reserves and reserve base (which includes reserves) of phosphate rock based on various scenarios for increasing population and future demand for phosphate. Using these scenarios, the presently known reserves will be depleted within about 50 years, and the remainder of the reserve base will be depleted within the next 100 years. For this model, we used rates of growth of demand for phosphate rock of between 1 and 1.7 percent annually. We also examined demand rates that decrease over time toward demand stasis. Growth-rate scenarios that stabilize demand at the year 2100 are little different from unconstrained growth. Demand stabilization by 2025 extends the reserve base by only about 50 years. Additional considerations could affect these depletion scenarios, causing them to be substantially too high or too low. Nonetheless, the ineluctable conclusion in a world of continuing phosphate demand is that society, to extend phosphate rock reserves and reserve base beyond the approximate 100 year depletion date, must find additional reserves and/or reduce the rate of growth of phosphate demand in the future. Society must: (1) increase the efficiency of use of known resources of easily minable phosphate rock; (2) discover new, economically-minable resources; or (3) develop the technology to economically mine the vast but currently uneconomic resources of phosphate rock that exist in the world. Otherwise, the future availability of present-cost phosphate, and the cost or availability of world food will be compromised, perhaps substantially.

Key words:

Phosphate rock resources
Phosphate rock reserves
Phosphate rock depletion
Resource depletion models
Phosphate rock demand

> A warning about the future should not be taken as a prediction of doom, but rather as a mandate to follow a different path.
>
> —paraphrased from Meadows and others (1992)

Introduction

Requirement for Phosphate and Its Principal Use

For a growing human population, there is an incontrovertible and ubiquitous requirement for increasing amounts of phosphatic fertilizer used to produce food: Nutrient phosphorus is necessary for all life and must be supplied naturally or through nutrient supplementation using fertilizer. Other elements, for example, nitrogen, potassium, sulfur, carbon, oxygen, and a variety of trace elements, also are necessary for life. Nonetheless, the requirement for phosphorus is universal and profound for all organisms. Without phosphorus, no animal or plant can survive; moreover, no element can substitute for the biological role of phosphorus. For humans, the phosphorus necessary for life is obtained from food that, in turn, obtained its necessary phosphorus ultimately from natural soil levels or from phosphorus added to the soil as fertilizer. Continual growth and removal of crops removes phosphorus from the soil; consequently, it must be resupplied for subsequent crop growth. Complete phosphorus removal from the soil by crop growth can occur in a few growing seasons; for example, Shacklette (1977) estimated, for a case in the United States, that wheat cropping plus natural losses would deplete the soil of phosphorus within the plow zone in 2 years.

Present food production does not accommodate need. The world population today, even with its extensive use of fertilizers, is marginally able to feed itself; 14 percent of the present population is malnourished (Schmidheiny, 1992). This situation could degenerate. Future production of fertilizers may be inadequate in amount or distribution to sustain an increasing crop demand. For many third-world countries, the amount of phosphate fertilizer available continually lags behind that needed to provide food for their population. Worse, the amount of fertilizer available for many of these countries risks becoming a progressively smaller fraction of that needed by their growing populations. The world's growing human population will require additional production of phosphate fertilizers to maintain or to increase food yield. Consequently, the present and increased future demand for phosphate to assure adequate food production in a world of increasing population is unequivocal. Yet, the ability of the world to meet this need may be limited. Increasing environmental and legislative controls on phosphate rock mining and manufacture, especially in the developed countries, may limit even present production rates. Thus, the world's need for phosphatic fertilizer will increase, but fertilizer availability, even if increased, could still fall short of need.

The purpose of the research reported herein was to investigate scenarios for future demand for phosphatic fertilizer and the ability of the known and potential phosphate rock resources to satisfy that demand. We do not consider aspects of market response to future demand for phosphate rock; these concepts are discussed by others, for example, Harre and Isherwood (1980). Also, we do not examine direct economic linkages between phosphate rock availability and food cost. The latter considerations have been addressed in a recent study that suggested, in a scenario without fertilizer and crop protection chemicals in the United States, domestic food costs would increase by 45 percent, U.S. agricultural competitiveness would be destroyed, and there would be an increase in world hunger, particularly in developing nations (Urbanchuk, 1990).

Phosphate Rock Deposits, Mining, and Fertilizer Manufacture

Several background factors about phosphate rock deposits and their mining and manufacture into fertilizer are important to the consideration of future availability of phosphate rock resources for the world. Aspects of occurrence, mining, and manufacture, each in their own way, affect economic considerations that, in turn, may determine future availability of phosphate rock. For summaries of phosphate rock occurrence, production, and use, see, for example, Emigh (1983), Cathcart and others (1984), Russell (1987), Fantel and others (1988), Harben and Bates (1990), Stowasser (1990, 1991), or Herring (in press). These aspects are considered in brief here and in detail separately (R. J. Fantel and J. R. Herring, unpub. data, 1993). As a point of clarification, phosphate rock varies widely in its P_2O_5 content, to a maximum of about 42 percent (18 percent phosphorus); however, most economically minable phosphate rock ranges from 21 to 38 percent P_2O_5. The most recent world average is 30.8 percent P_2O_5, with 69 percent of the mined rock ranging from 30.4 to 32.3 percent P_2O_5.

Phosphorus is ubiquitous in crustal rocks with an average concentration of 0.2 percent; however, it generally occurs in fine-grained, apatitic minerals that are relatively insoluble. Two principal types of phosphate rocks are mined as phosphatic ore throughout the world: igneous deposits and phosphorites. The latter are occurrences of phosphatic minerals in sedimentary rocks, primarily marine. Worldwide, phosphorites account for about 90 percent of the demonstrated phosphate rock resources and

Table 1. Materials deleterious to phosphoric acid production.

Deleterious material	Result	Approximate problem level for U.S. phosphoric acid manufacture
MgO	Viscous sludge forms during phosphoric acid production, which lowers productivity and increases energy requirements; Mg also precipitates fluorine in the reactor stage and plugs gypsum filters	>1%
Fe plus Al (also called I + A content)	Forms viscous sludge and makes the phosphoric acid sticky	Combined oxide content >2.5% to 3%
Ca	If too high, excess sulfuric acid is required	$CaO/P_2O_5 > 1.6$
Cl	Causes excessive corrosion in processing equipment	Cl > 0.2%
F	Excessive F causes air pollution problems in U.S.	Depends on emission controls
Organic matter	Causes foaming in phosphoric acid production	>4% to 5% CO_2

Source: Fantel and others, 1984.

most of present mining (Fantel and others, 1988). In the United States, all present production, as well as that for the foreseeable future, occurs from extensive deposits of phosphorite. Enormous phosphorite deposits also exist in a few other parts of the world, especially in the former Soviet republics, China, and various countries in North and West Africa and the Middle East.

Over three-quarters of the phosphate rock produced in market-economy countries today is recovered by surface mining. The remainder of the ore is recovered by underground mining, predominantly in Morocco and Tunisia. Several elements or compounds, if present in sufficient quantities in the ore, can compromise the production of phosphoric acid and can create greater manufacturing cost or produce inferior products (table 1). These impurities can decrease the profitability of acid manufacture by increasing costs, and the presence of these undesirable components in sufficient quantities can preclude mining because of loss of profitability or because of technical obstacles to the processing of phosphate rock into acid. Most of the run-of-mine phosphate ore is beneficiated by some combination of sizing, washing, flotation, or calcining.

At least 85 percent of the phosphate rock produced in the United States and the rest of the world is used to manufacture fertilizer products that are used by the agriculture industry. Some phosphate rock is left unprocessed and is applied as fertilizer directly to soil; however, this accounts for only a few percent of world phosphatic fertilizer use. Most phosphate rock mined throughout the world is manufactured into phosphoric acid. This acid may be exported or used in domestic markets to make products that also, as in the case of the United States, can then be used domestically and/or exported. The major products made from phosphoric acid are ammonium phosphates and triple superphosphate for fertilizers, but they also include monobasic and dibasic calcium phosphates for animal feed supplements, polyphosphates for detergent additives, and phosphates for industrial compounds. Domestic processing of phosphate rock that is not used to produce phosphoric acid is instead used to produce elemental phosphorus from which a variety of industrial chemicals are made.

Most phosphoric acid in the world is produced directly from phosphate rock ore using a wet chemical acidulation, shown descriptively in equation 1. Sulfuric acid is the common reactant that is used because it is relatively inexpensive. However, in Europe some phosphoric acid production processes use nitric acid as the reactant. The most common phosphate mineral used in this process is francolite, a carbonate-bearing fluorapatite, but the reaction is illustrated here using the more simplified formula for fluorapatite. The reaction products, gypsum and phosphoric acid, are separated by filtration and centrifugation. For this reaction, about 3 tons of phosphate rock are consumed to produce 1 ton of phosphoric acid (100-percent basis), 5 to 6 tons of product gypsum, and about 85 kg of fluorine:

$$\begin{aligned}&\underset{\text{fluorapatite}}{Ca_5(PO_4)_3F} + \underset{\text{sulfuric acid}}{5H_2SO_4} + 10H_2O \\ &\rightarrow \underset{\text{gypsum}}{5CaSO_4 \cdot 2H_2O} + \underset{\text{phosphoric acid}}{3H_3PO_4} + \underset{\substack{\text{hydrogen}\\ \text{fluoride gas}}}{HF\uparrow}.\end{aligned} \quad (1)$$

Most phosphoric acid is used to produce a variety of fertilizer products. Diammonium and monoammonium phosphate fertilizer are made by reacting the phosphoric acid with ammonia. If the phosphate rock is reacted with phosphoric rather than sulfuric acid, triple superphosphate is produced. If the wet-process phosphoric acid is evaporated and then reacted with ammonia, a liquid am-

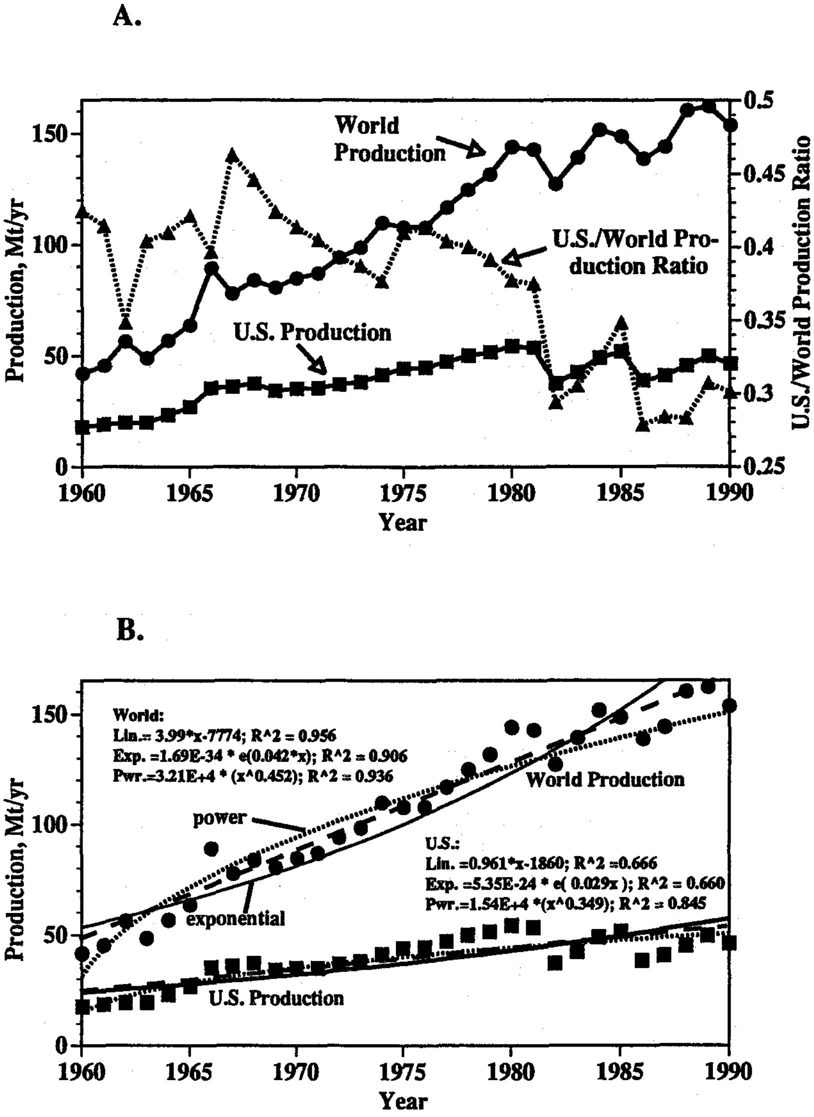

Figure 1. *A,* United States and world historical production of phosphate rock from 1960 to 1990. *B,* Various types of trends fit to the data: linear, exponential, and power (geometric). Equations for the various fits and their regression coefficients (R∧2) are given. The equations for the power fit use production in kilotons and a 30-year interval beginning with year 1. Source of production data: Stowasser (1991).

monium phosphate fertilizer results. Phosphate animal feed supplements are made from the defluorination of either phosphate rock or phosphoric acid. Production of these nutritional feed supplements also uses phosphate rock in an application directly relevant to world food supply. Other agricultural chemicals, such as insecticides and herbicides, also are produced from phosphate rock. However, they account for only a few percent of the demand for phosphate rock, and they also may have other chemicals that can substitute for them. In the United States, 6 percent of phosphate rock consumed is used to manufacture phosphatic industrial chemicals. These latter chemicals should not be considered in the forecast of the agricultural use of phosphate rock.

Production and Demand

U.S. Production

By 1960, annual U.S. production of phosphate rock reached about 18 megatons (Mt), and it continued to increase until about 1980; it has ranged from 40 to 55 Mt annually during the past decade. In 1990, the United States produced 46 Mt with an average P_2O_5 content of 30.6 percent. Current U.S. production supplies virtually all domestic need, which includes domestic end use and exported products. These exported products include phosphate rock and value-added phosphate products, for example, fertilizer, that are derived from phosphate rock. The U.S. Government neither stockpiles nor recycles phosphate. At present, the United States is the world's largest producer of phosphate rock. U.S. production over the past 30 years has accounted for an average of 38 percent of world production. However, in the past 8 years, the U.S. share of world production has dropped to an average of 30 percent. Historical U.S. production of phosphate rock is shown in figure 1. Note that the trend is better fitted with a linear rate of increase of about 1 Mt annually, rather than with an exponentially increasing rate. Although the United States at present is the world's largest producer of phosphate rock, domestic production will decline in 15 to 20 years unless new sources are developed. This production decline will occur because the low-cost, high-grade resources in the southeastern United States are nearing depletion during the next few decades. A number of older mines will close in Florida and Idaho during remaining years of this decade, but several new mines are planned that may sustain the supply of phosphate rock through the early years of the next century. Based on mining company plans, U.S. planned and potential production of phosphate rock could decrease to less than one-half its present level as soon as 2015 and remain that low or lower for at least the following 15 years (Herring and Stowasser, 1991; Stowasser, 1991).

World Production

The world has an abundance of phosphate deposits, mostly in marine sedimentary rocks; however, the distribution of minable deposits throughout the world is uneven. Countries with major phosphate rock deposits, including both igneous and sedimentary types, that presently are being mined or are under development are the former Soviet republics, the United States, Morocco, China, Jordan, and Tunisia. The first three account for about two-thirds of present world production; all six account for 85 percent of present production. World production of phosphate rock concentrate for 1990, according to the U.S. Bureau of Mines (USBM), was 154 Mt with an average grade of 30.8 percent P_2O_5. World production for the past 30 years is shown in figure 1. The exponential rate of annual growth of production is 4.2 percent. However, the regression coefficient (R^2) of the exponential fit is only 0.906, whereas that of the linear fit to the historical production is 0.956. This linear fit indicates an annual addition of 3.99 Mt. A geometric (power <1) fit to the historical data also has a higher regression coefficient, $R^2 = 0.936$, than that of the exponential fit. This latter type of trend implies that the rate of demand increase (slope) becomes smaller through time than in the exponential relationship, in which the rate continually increases.

Demand

The most important use of phosphatic fertilizer presently is and will remain for food crops. A report prepared for the USBM by the Wharton Econometric Forecasting Associates (WEFA) (Wharton Econometric Forecasting Associates, 1988, 1992) analyzes the components of world fertilizer demand into the next decade. Most of our conclusions in this report concerning future demand for fertilizers are based on their expectations of continued growth in world grain production and trade. World trade of grain in the 1990's should be stronger than the weak scenario experienced in the 1980's, but not as strong as the 1970's. The strongest growth in grain imports will be seen in Asia and the Middle East, whereas the former Soviet republics will become a less important import market. China will remain a strong wheat importer, and by the end of the decade will also be a grain importer. The United States and Canada will likely increase grain exports, whereas production and exports from the European Community are expected to decline. Eastern Europe is expected to expand grain output and consequently should enter the export market by the end of the decade. Based on these and various other factors, WEFA projects a slower rate of growth in world fertilizer consumption in the 1990's than occurred in the 1980's (Wharton Econometric Forecasting Associates, 1992). Fertilizer prices are expected to be weak (actually continuing to decline when adjusted for inflation), and the associated costs of production are expected to rise, increasing prices, decreasing crop-production profitability, and slowing the rate of growth in fertilizer application rates. Growing environmental concerns, particularly in North America and Western Europe, will also cause a reduction in application rates and in the amount of acreage fertilized. However, phosphatic fertilizer use also is tied to economic crops besides those used for food. As various countries, especially the lesser-developed countries (LDC's), try to improve their balance of payments using exports of nonfood crops, additional demand for fertilizers could be realized. For example, China has announced plans to substantially increase planting of cotton in the upcoming decade in an attempt to secure additional export revenue.

The WEFA estimate for annual increase in phosphate rock production from the present (1992) through 2005 ranges from a low of 0.6 percent to a high of 1.3 percent; the average is 1.1 percent. WEFA also estimates the annual demand increase for phosphate fertilizer over this same interval; this ranges from 0.4 percent to 1.4 percent with an average of 1.1 percent. The actual forecast interval of the study is from 1991 to 2005, and over this interval, the average annual rate of increase for phosphate rock production and phosphate fertilizer demand are 1.04 and 1.02 percent, respectively. Over this same interval, population growth is estimated at 1.50 percent annually. The WEFA study assumes that the rate of growth of phosphate rock production and phosphate fertilizer demand can be smaller than population growth because of economic factors and improved efficiency of applied fertilizers.

There are other possible demand scenarios, however, and most of these other estimates for world demand of phosphatic fertilizer or phosphate rock are higher. In 1990, the U.S. Chemical Industries Association forecast world demand for fertilizers and other agrochemicals to grow at least directly proportional to world population growth. Under the assumption that demand will at least accompany population increase, we have used, among our demand projections, one that increases at the present rate of population growth of 1.7 percent annually. This rate of population growth is forecast to decrease gradually to a stable population of 11.2 billion in 2100, producing an average rate of growth between 1990 and 2100 of 0.68 percent (World Resources Institute, 1992). The U.S. Department of Agriculture forecasts a 2 percent annual growth in world demand of phosphate rock through 2040 (Stowasser, 1991). Fantel and others (1988) consider, among others, a world demand of phosphate rock that grows at 3 percent annually. Because there are other studies, mentioned previously, that use higher demand scenarios than the WEFA study, we also have examined some of these higher demand scenarios in our study. We have examined various unconstrained (unchanging) exponential growth scenarios and assume a highest case of 3 percent annual growth in phosphate fertilizer demand. The present population growth rate in most of the LDC's is near, at, or, in several countries, well above this value. Forecasts of higher rates also exist. For example, the forecasts by Wells (1975) extensively use an empirically derived rate of 2.7 percent increase in fertilizer application to obtain a 1 percent increase in crop yield. Using the modern rate of population growth, 1.7 percent, and assuming parallel demand for food production, the fertilizer demand in this case would increase by 4.6 percent annually.

Projection of these rates of demand growth beyond the end of the millennium are tenuous. Even the current rate of population growth could be considerably altered in the immediate future by shifting developments in the world. Greater awareness of limited availability of resources in the world could lead to a decrease in population and, consequently, of phosphate rock demand. Alternatively, if high growth rates are maintained in LDC's, where most of the growth occurs at present, then the average global rate of population growth and, we assume, fertilizer demand, could increase. This growth scenario could result especially if present birth rates are maintained and there are medical advances that lengthen the life span (decrease the death rate) in the LDC's. Most of the world population increase in the past three decades has resulted from substantially decreased death rate rather than increased birth rate; the latter, in fact, has decreased over this time (Meadows and others, 1992).

Resources and Reserves

Definitions and Explanations

For our study, resources refers to known or indicated certainty of the existence of phosphatic material, regardless of grade, tonnage, or mining conditions. Reserves and reserve base, on the other hand, refer to those resources that could be economically extracted or produced at the time of assessment, or to that portion of the resources that meets certain minimum economic criteria related to current mining and production practices, respectively. The U.S. Geological Survey (USGS) is responsible for determination of phosphate rock resources, whereas the USBM determines reserves and reserve base by applying economic criteria to those resources (U.S. Bureau of Mines and U.S. Geological Survey, 1980).

The USBM has defined reserves as the phosphate rock that can be mined profitably at present for less than $40 per ton (1992 dollars), including capital, operating expenses, taxes, royalties, miscellaneous costs, and a 15 percent rate of return on investment, whereas reserve base (which includes reserves) is the phosphate rock that can be mined for less than $100 per ton with the same cost considerations as for reserves. Fantel and others (1988) list the domestic and international reserves and reserve base of phosphate rock as determined by the USBM. For the various scenarios of the model in this work, reserves have been subtracted from reserve base, and the remainder of the reserve base is termed modified reserve base (MRB). It is important to note that the reserve base, because of higher production costs and other factors, will cost more to mine in terms of constant dollars than the present cost to mine reserves. In other words, the depletion of world reserve base (or MRB) that we consider here already requires a higher mining cost in terms of constant dollars than the cost for mining reserves and, consequently, an increase in future food production costs compared to present. For example, mining the U.S. reserve base of phosphate rock of about 16 gigatons (Gt) (Stowasser, 1991) would cost on average 2.8 times more per ton in 1989 costs than the reserves that were mined that year at a cost of $19.50 per ton.

World Amounts

The USBM, in 1992, reported world demonstrated reserves of phosphate rock to be 12.0 Gt and the demonstrated reserve base (which includes reserves) to be 37.8 Gt. Nearly one-half of these reserves are in Morocco and the Western Sahara, whereas only 10 percent are in the United States. In terms of worldwide reserve base, Morocco and the Western Sahara contain nearly two-thirds, and the United States, 13 percent.

The total phosphate resources of the world are immense, but most of these resources are not currently economically recoverable. For example, the onshore resources for the Atlantic Coastal Plain of the United States are inventoried to be 22 Gt. Ongoing work by the USGS indicates that the southeastern U.S. phosphate deposits offshore have vast lateral extents from peninsular Florida to possibly as far north as the Grand Banks (Manheim and others, 1991). For example, upwards of 200 Gt of phosphate concentrate may occur in the Miocene sediments of the Continental Shelf offshore Georgia (Herring, Manheim and others, 1991; Herring, Popenoe and others, 1991). In the western states, Cathcart (1991) estimates the amount of phosphate rock that could be surface mined and that is less than 300 meters below surface entry level to be 25 Gt, whereas the resources deeper than 300 meters are about 500 Gt. The latter number represents identified phosphate rock that is not considered to be a demonstrated resource because it occurs at depths that are too great for mining in the foreseeable future.

In another study, Fantel and others (1988) list 35.1 Gt as the demonstrated resources of phosphate rock that are potentially recoverable in the market-economy countries. Also, Fantel and others (1984) suggest that, of the world demonstrated phosphate resources of 106 Gt with a weighted average grade of 17.5 percent P_2O_5, 35.7 Gt are recoverable with a weighted average grade of 32.0 percent P_2O_5. To compare with presently mined phosphate rock and to obtain the rock tonnages that we use in the depletion model, we converted the tonnages of the recoverable and the remaining resources to an assumed grade of 30.8 percent P_2O_5, which is the average of world phosphate rock mined in 1990. The recoverable and remaining resources of phosphate rock then become 37.1 and 23.3 Gt, respectively. However, it is presumptuous to consider that the remaining demonstrated resources represent economically minable resources within the immediate future because their weighted average grade would be 10.4 percent P_2O_5, which is about one-third of the average grade of phosphate rock presently mined worldwide. Krauss and others (1984) estimate world phosphate resources to be 29 Gt of rock that are known and economically minable and 91 Gt of rock that are presently known and subeconomic extensions of known, economic deposits; both their amounts have been recalculated to a single tonnage with an assumed, averaged P_2O_5 content of 30.8 percent. Extensions of known but subeconomic deposits are estimated, using the data of Krauss and others (1984), as 34 Gt of rock at this same P_2O_5 content; however, this ignores omitted economic data from many of the centrally planned economies at the time. In another study, Cathcart (1980) lists reserves of phosphate rock that contain at least 30 percent P_2O_5 as 20 Gt and presently uneconomic resources as an additional 90 Gt. Depletion models similar to the ones in our work have been considered by Emigh (1972) using an extremely large resource base of 1,300 Gt, which he refers to as estimated reserves. However, Emigh's study does not address the economic minability of these estimated resources of phosphate rock.

Depletion Model and Results

Our model is based on anticipating the future demand of phosphate rock, then depleting the known reserves and reserve base according to that demand. Similar types of phosphate depletion models have been used in the past, for example, by Wells (1975); however, our model differs in that we use substantially revised estimates of phosphate rock resources, defined here, for depletion. More importantly, we deplete specific subsets of those resources, the reserves and reserve base, that consider the global economics of mining (Fantel and others, 1988), rather than simply forecasting depletion of resources without regard to economic considerations.

For the model, we assume production to be equal to demand; this becomes more valid over time because producers try to minimize unsold stock. Another consideration in the model is the boundary conditions, which for typical growth models, require an initial value. In the case of phosphate rock, there is some fluctuation in the production trend through time as use responds to production as well as to stock on hand (fig. 1). Growth models sensitively depend on initial values; consequently, the world production value listed for 1990 in our model, 160 Mt, is the production average from 1989 to 1991. We think that this average better reflects the production trend and eliminates some of the variance in year-to-year production (fig. 1). Actual production for 1990 was 157 Mt.

For our input of future phosphate rock demand, we have used several scenarios of unconstrained growth in phosphate rock demand, scenarios A through I in table 2. The rates of phosphate rock demand growth are based in part on world historical production over the past 30 years (fig. 1). Scenario A uses a linear increase in world demand with an annual addition of 3.99 Mt. We justify the inclusion of the linear increase in demand because the historical increase of phosphate rock production has a higher linear regression coefficient, 0.956, than either the exponential or power increases, which are 0.906 and 0.936, respectively. Scenarios B through G use varying degrees of exponential increase in demand. Scenario B uses the demand growth rate that is projected by the WEFA study through the year 2005, 1.04 percent annual growth. Next, we use a modification of the WEFA forecast, which assumes that this rate forecast by WEFA continues until 2005, the end of their forecast period, and then is followed by a rate of 1.5 percent (scenario C). We use this latter rate because it is closer to the present rate of population growth. In addition, we have used exponential, annual increases of 1.5, 1.7, 2, and 3 percent, scenarios D through G, respectively. For the final scenarios, H and I, we have projected future demand using Napierian logarithmic and power functions because of their relatively high regression coefficients of fit to the historical data compared to the exponential increase. These latter two functions require that the rate of increase in demand lessen through time, which, if population growth remains geometric and phosphate demand follows growth, is unrealistic.

Figure 2 shows the depletion over time of world phosphate reserves and MRB for the various unconstrained growth scenarios of demand increase previously mentioned. In our model, world population growth and phosphate rock demand (assumed equal to production) are normalized relative to their 1990 values: 5.3 billion people (= 1) and 160 Mt of phosphate rock (= 1). Reserves and MRB figures are normalized to their values at the beginning of 1990 (= 1) of 12.6 Gt and 21.7 Gt (after subtracting reserves), respectively (Stowasser, 1990; U.S. Bureau of Mines, 1991, 1992). As an example of the model calculations, scenario E projects phosphate demand to increase at 1.7 percent annually, which is equivalent to the present rate of population growth. Known world reserves are depleted in 49 years and MRB in 90 years from 1990. In our model, reserves have been depleted first against anticipated demand, then the remaining MRB is depleted. As the reserve base is used to satisfy demand, its higher production costs will directly increase the cost of fertilizer and, consequently, of food. We use years to depletion (YTD) to show the effect of various scenarios. Table 2 lists the YTD, relative to the base year of 1990, until the world reserves and MRB are depleted according to the various scenarios. Also included in the model is the ratio of demand (production) to population, where population is forecast to increase at its present rate, 1.7 percent annually (figs. 2 and 3). This ratio suggests a measure of the stability of the forecast if phosphate demand is, indeed, directly dependent on population and if population continues to increase at its present rate. Significant departures of this ratio from one indicate an imbalance between projected population (growing at present rate) and projected phosphate demand. The model is described in detail by J.R. Herring (unpub. data, 1993) and includes a listing of the parameters necessary to generate the various depletion scenarios discussed in this study.

Table 2. Unconstrained phosphate rock demand growth from base year = 1990.

Scenario	Demand growth	Years to depletion (from 1990)	
		Reserves	Modified reserve base
A	Linear	47	95
B	Exp—1.04%	56	112
C	Exp—1.04% & 1.5%	53	99
D	Exp—1.5%	50	96
E	Exp—1.7%	49	90
F	Exp—2%	46	83
G	Exp—3%	40	67
H	Log (Napierian)	47	96
I	Power	59	135

The results of these scenarios of unconstrained growth with no future additions to either reserves or MRB are that reserves are depleted within about 50 years from 1990, and MRB is depleted within about another 50 years (table 2). A linear increase in phosphate rock demand produces a slightly higher rate of growth than the 1.7 percent annual increase in demand until approximately the year 2008. At 2037, the demands become equal, and subsequently the exponential rate of demand growth exceeds the linear demand. The most delayed depletion of the exponential growths results from the WEFA forecast rate of 1.04 percent. The log projection rock demand closely matches the 1.04 percent annual increase. The power projection has the most delayed depletion of reserves and MRB for all unconstrained growth scenarios.

Discussion

Modifications That Will Influence the Model Results

In our modeling, we have examined scenarios where phosphate rock demand was tied to world population. We assumed that the sole use of phosphate rock is for bioessential nutrient replacement in food and feed crops. In the United States, 95 percent of mined phosphate rock consumed is used to produce fertilizers; worldwide, at least 85 percent of phosphate rock production is used for fertilizers and fertilizer products. The remaining use of phosphate rock is for the production of phosphatic industrial chemicals, some of which include feed supplements and other agricultural chemicals. Demand for these industrial chemicals may not be directly linked to population, principally because technological changes can alter demand or because other, nonphosphatic chemicals may substitute for them. In other words, the demand for phosphate rock as it relates to food supply should consider only the bioessential agricultural use of phosphate and not consider phosphatic industrial chemical use. A reduced or absent future demand for these industrial

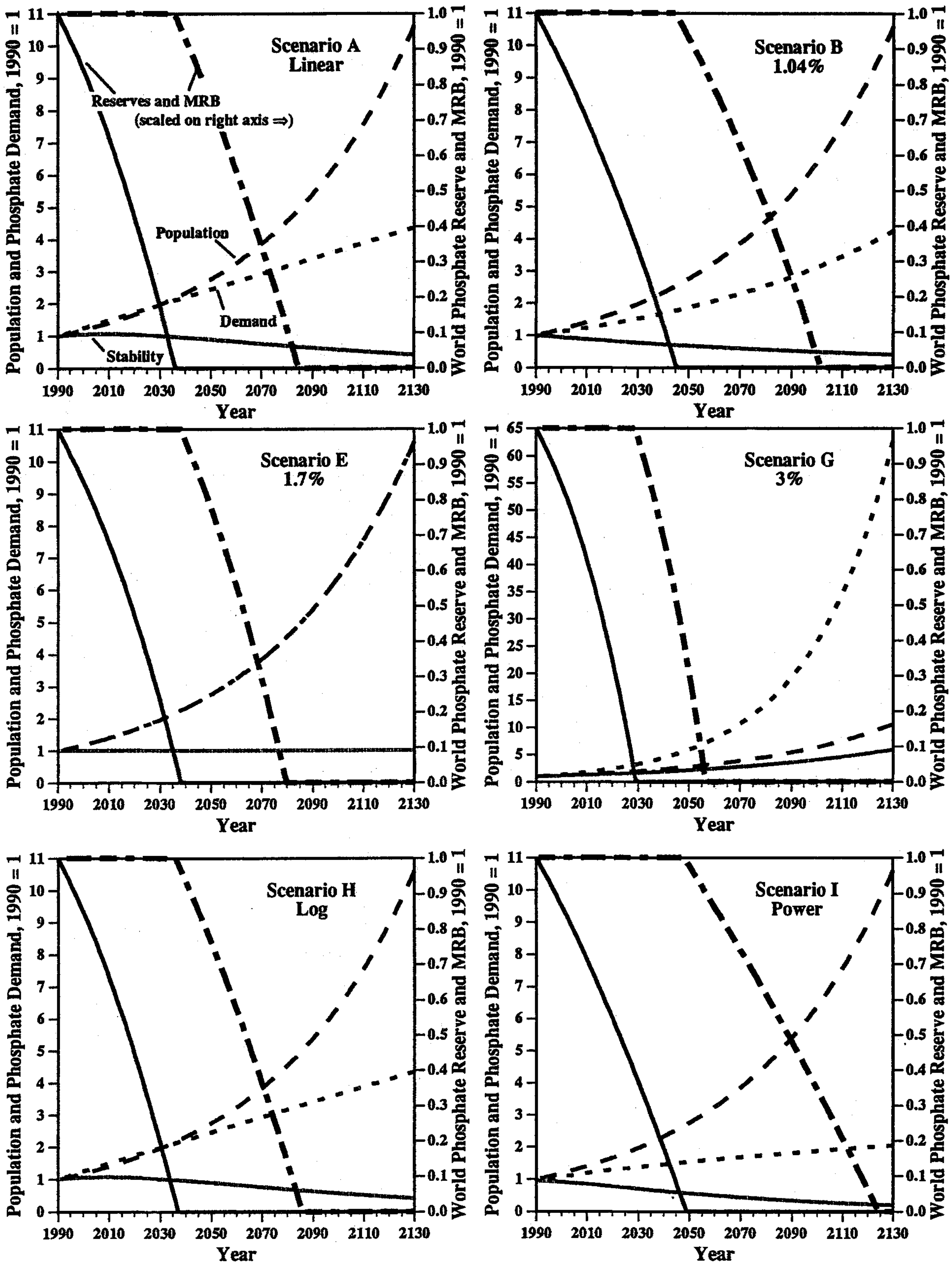

Figure 2. Scenarios for depletion of world phosphate reserves and modified reserve base (MRB, which is equal to reserve base less reserves) for unconstrained growth in phosphate rock demand. Reserves and MRB figures are scaled on the right axis and normalized to their 1990 values (= 1) of 12.6 Gt and 21.7 Gt (after subtracting reserves), respectively. World population growth and phosphate rock demand (assumed equal to production) are scaled on the left axis and shown relative to their 1990 values: 5.3 billion people (= 1) and 160 Mt of phosphate rock (= 1). Reserves are depleted first against anticipated demand, then the remaining

chemicals produces only a small extension of the YTD of phosphate rock reserves and MRB. For example, using scenario E (table 2) with unchecked annual demand growth of 1.7 percent but reducing the initial demand (production) to 85 percent of the 1990 amount produces a maximum extension in YTD of the MRB from 90 to 98 years. This is a maximum increase that could occur in YTD because the 85 percent value for fertilizers is minimal, and the actual depletion value would lie somewhere between 91 and 98 years. Also, demand for phosphate chemicals, some of which are directly tied to agricultural use and the production of food, also could remain a static percentage of use or could grow through time. Consequently, demand for these chemicals could contribute to depletion of phosphate rock reserves and could compete for the phosphate available to supply agricultural needs. In summary, we conclude that the phosphatic industrial chemicals will have an inconsequential effect on phosphate rock resource depletion.

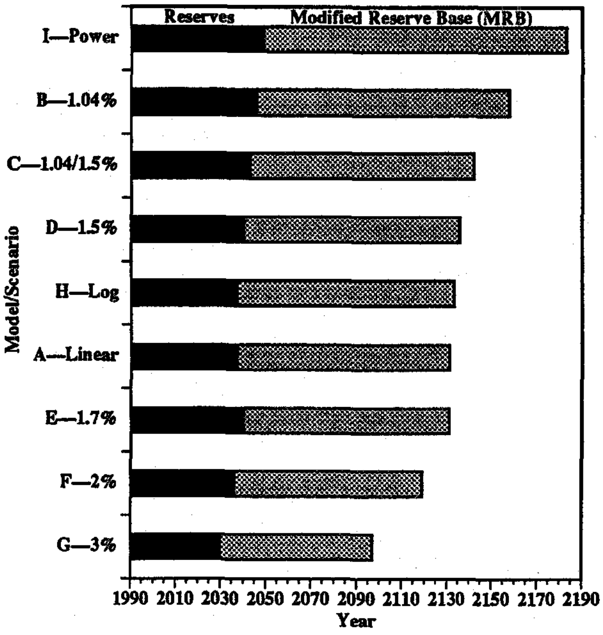

Figure 3. Summary bar chart of the depletion dates of the reserves (on left) and modified reserve base (on right) for the various scenarios in figure 2.

The greatest uncertainty in our modeling lies in forecasting future demand of phosphate rock. The WEFA forecast for rate of growth in demand is admitted, by its authors, to be intentionally conservative. Compelling evidence suggests that demand could grow at a higher rate. For example, if the present rate of population growth of 1.7 percent is maintained, then, to provide the identical amount of food per capital, phosphate fertilizer demand presumably will be forced to grow at least at the same rate or even at a higher rate if natural soil levels of phosphorus become depleted. Historical production of phosphate rock for the past three decades has grown at an annual rate of 4.2 percent. Finally, most arable land that can be used for crops has been developed. Thus, future food growth will depend on greater crop yields from this existing cropland—something that can be achieved only with the additional use of fertilizers.

There are scenarios wherein the future population would stabilize, but the demand for resources would continue to increase (Meadows and others, 1992). This could happen, for example, if the stabilized population demanded increasing per capita industrial output with increased amounts of goods and services and an increasing quality of life. We suggest in this case, however, that there would not be commensurate increase in the demand for phosphate resources, because the demand for food would remain roughly proportional to the population. Alternatively, a higher per capita industrial output could become more pollutive, which would reduce agricultural yields and require additional fertilizer simply to maintain a static level of food production. Finally, it is possible for a stabilized population to increase or decrease its demand for phosphate based on changes in diet preferences and the phosphate necessary to support that food production.

Demand Stabilization. Several changes could affect our modeled parameters and lengthen or shorten the various estimates of YTD. The first consideration that could lengthen YTD estimates is that population and phosphate demand growth rates could be estimated too high or they could decrease, tending, hopefully, toward stasis. This could include a change in dietary habits requiring less phosphorus per capita in the food web to support human food needs. To test this effect, we examined a set of scenarios where the rate of growth of demand slowly decreases toward stability, presumably in response to a

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MRB is depleted. The stability index (see text) is scaled on the left axis and suggests the degree of imbalance (greater departures from 1) between projected population (growing at present rate) and projected phosphate demand. Among the exponentially increasing demand curves, only the smallest (1.04 percent), intermediate (1.7 percent), and highest (3 percent) cases are shown; other exponential cases will be intermediate to these. For the 1.7% annual increase demand growth scenario, the demand and population curves are superimposed, and the stability index is 1. Reserves and reserve base figures are from the U.S. Bureau of Mines and population data are from U.S. Bureau of the Census.

Table 3. Constrained growth decrease beginning in the year 2000.

Scenario	Demand growth	Years to depletion (from 1990)	
		Reserves	Modified reserve base
Stable at 2025:			
A	Linear	51	137
B	Exp—1.04%	62	169
C	Exp—1.04% & 1.5%	61	165
D	Exp—1.5%	58	155
E	Exp—1.7%	56	149
F	Exp—2%	53	140
G	Exp—3%	46	115
Stable at 2050:			
A	Linear	48	120
B	Exp—1.04%	59	153
C	Exp—1.04% & 1.5%	57	143
D	Exp—1.5%	54	134
E	Exp—1.7%	52	127
F	Exp—2%	49	117
G	Exp—3%	42	90
Stable at 2100:			
A	Linear	48	105
B	Exp—1.04%	57	132
C	Exp—1.04% & 1.5%	55	118
D	Exp—1.5%	52	112
E	Exp—1.7%	50	105
F	Exp—2%	48	95
G	Exp—3%	41	75

similar trend in population growth. We assume that the earliest date that there could be some global realization to limit population growth and fertilizer demand is 2000. Hence, the various demand scenarios listed in table 2, except H and I, have been left to increase as before until 2000, then they are decreased over intervals of 25, 50, or 100 years and subsequently remain constant. The rate of decrease over the interval leading to stasis is linear for simplification, and the various stabilization scenarios all presume the current values for demonstrated reserves and reserve base.

The results are given in table 3 and shown in figures 4 and 5. These results are considered to be conservative forecasts of demand because these scenarios assume realization of and implementation of sustainability only a very few years from now. In the case of the linear increase in phosphate rock demand, most of the effect is produced in the YTD of the MRB. The decreases in demand over intervals of 25, 50, and 100 years are insufficient to appreciably change the YTD for reserves because the decreases in rate of demand generally take effect after most reserves have been depleted. The effect on MRB is an extension of YTD by 42 years for the most rapid attainment of stabilization, by the year 2025, but only an extension of 10 years for stability occurring at 2100. In all cases, the most rapid attainment of stabilization of demand (demand stability by 2025) has the greatest effect in extending YTD, whereas attainment on the order of a century after the base year produces little difference in extension of YTD over nonconstrained demand scenarios.

The other principal effect occurs in the constrained scenarios that have exponential growth of demand and is tied to the exponential rate. The most extended YTD for MRB is 169 years, which is for the 1.04 percent growth rate of phosphate demand that becomes stabilized at 2025, and the shortest YTD is 75 years for 3 percent demand stabilized at 2100 (table 3). If phosphate demand growth is as small as suggested in the WEFA study, then YTD for MRB could range from 132 to 169 years for the 25- through 100-year stabilization scenarios. However, if demand growth is 3 percent, then YTD for MRB could range from 115 to as short as 75 years from 1990, with the latter figure occurring in response to the longest time for demand stabilization.

New Resource Discoveries. Another major modification in the results of the model would occur if YTD estimates were extended by discovery of new phosphate rock resources that became economically minable or by conversion of known phosphate rock resources to reserves or MRB status. This latter condition could occur, for example, if there were improvements in the technology or processing of certain types of phosphate rock ore that at present are not economic to mine and process or if there were different economic considerations. As an illustration, if economical processing of phosphate rock with greater than about 1 percent MgO became possible, 2 Mt of MgO-rich phosphate rock in the southern extension of the Florida phosphate field potentially could become minable (Fantel and others, 1983). To examine this modification, we consider two scenarios of additions to MRB to test the sensitivity on YTD estimates.

The results are given in table 4 and shown in figures 6 and 7. These increases are assumed to occur as pulse additions in the year 2000; this date is considered to be the soonest that quantification or production of newly discovered or newly processable reserves could occur. The first amount, 20 Gt, is equal to inferred world resources of phosphate rock, not including the resources of China and the former Soviet republics (Fantel and others, 1983; Fantel and others, 1988). The second addition, 24.3 Gt, is equal to the hypothetical resources in the United States (Fantel and others, 1983) and is combined with the inferred resources for a total increase of MRB to 44.3 Gt. The effects on YTD of the MRB estimates are listed in table 4. The first addition of 20 Gt extends the YTD by 14 to 34 years, whereas the second addition of 44.3 Gt extends MRB by 26 to 67 years. For both additions, the largest extensions of YTD occur in the smallest of the exponential, in the log, and in the linear demand increase scenarios. The 3 percent annual demand growth produces the shortest extension. The power fit to the demand curve is considered separately because its rapid, progressive flattening produces a near static demand. This is perhaps unrealistic for most considerations of increasing demand; alternatively, it does stimulate a near leveling of demand with time, which would occur with a stabilizing population and demand. The power-fit additions scenarios, which are not included in the table, extend YTD to 2183 for 20 Gt and 2245 for 44.3 Gt.

In all the additions scenarios, the depletion times for the reserves remain identical to the data in table 2 because, in our model, we deplete reserves prior to MRB, into which the additions have been made. Finally, the additions are made only to the unconstrained demand growth scenarios. Obviously, if additions are made to reserves or reserve base and demand growth becomes constrained as discussed previously, there will be a cumulative effect in extending YTD estimates.

Other Considerations. There are additional scenarios for extending YTD that we mention here only qualitatively. For example, perhaps less fertilizer could be applied to some crops. Also, the phosphate used for food growth could in part be recycled. Substantial recycling efficiencies produce considerable extension of YTD; for example, 80 percent reuse of phosphate extends YTD by a factor of 5. Finally, more efficient food crops, requiring less fertilizer per unit harvest but still supplying the necessary dietary phosphate for human needs, could be developed.

Alternatively, other conditions could shorten the estimates of YTD. Of principal concern is the underestimation of phosphate demand and population growth. We note that much higher rates of population growth than the present average, 1.7 percent, already exist throughout much of the world, especially in the LDC's where much of the world's population growth occurs. In many of these countries, annual population growth rates exceeding 1.7 percent and up to 5 percent are not uncommon (World Resources Institute, 1990, 1992). Furthermore, it is also possible that assuming phosphate demand to be directly proportional to population growth is insufficient. This might occur, for example, because world arable land seems to have become maximized and presently is declining (Meadows and others, 1992). Consequently, increasing amounts of food will have to be produced from constant or decreasing areas of arable land—a result that can only be accomplished with additional input of fertilizer. Worse, the continued forcing of larger crop yields from the same amount of arable land eventually may exceed a linear increase in fertilizer application to produce a given increase in crop yield.

Table 4. Additions to modified reserve base for unconstrained growth—years to depletion (YTD) from 1990.

Scenario	Demand growth	20 Gt (= World inferred resources)	Additional 24.3 Gt (= U.S. hypothetical resources); Total 44.3 Gt
		Modified reserve base—years to depeletion	Modified reserve base—years to depletion
A	Linear	128	161
B	Exp—1.04%	145	174
C	Exp—1.04% & 1.5%	124	146
D	Exp—1.5%	120	142
E	Exp—1.7%	113	132
F	Exp—2%	103	119
G	Exp—3%	81	93
H	Log (Napierian)	130	162

YTD estimates would be lowered if some fraction of the presently known reserves or reserve base were removed, as could happen, for example, if environmental restrictions to mining were imposed on some potentially minable sites. Also, even at decreasing or stabilized population growth rates, there could be a change toward dietary habits or preferences that tend to be more phosphate-intensive per capita. This is occurring presently in some parts of the world, especially the Orient, where, since 1950, meat production has tripled (Schmidheiny, 1992), while over the same time population has only increased by a factor of 2.3. Finally, there could be additional demand for phosphate other than for food and industrial chemical need. For example, biomass energy is suggested as a possible future amelioration of the world's energy crisis, and this energy source would be particularly useful in the developing countries. Unless the biomass is processed to recycle bioessential nutrients back into the soil, the continued harvesting of crops for biomass energy will place additional, perhaps considerable, requirements on phosphate demand.

Environmental Considerations of Mining and Manufacturing

Environmental considerations play a substantial and ever-increasing role in the cost and mining of phosphate rock worldwide. Mining costs are in part a consequence of environmental attitudes, determined by citizenry and government; however, not all countries share the same attitude toward reclamation. In the United States, rec-

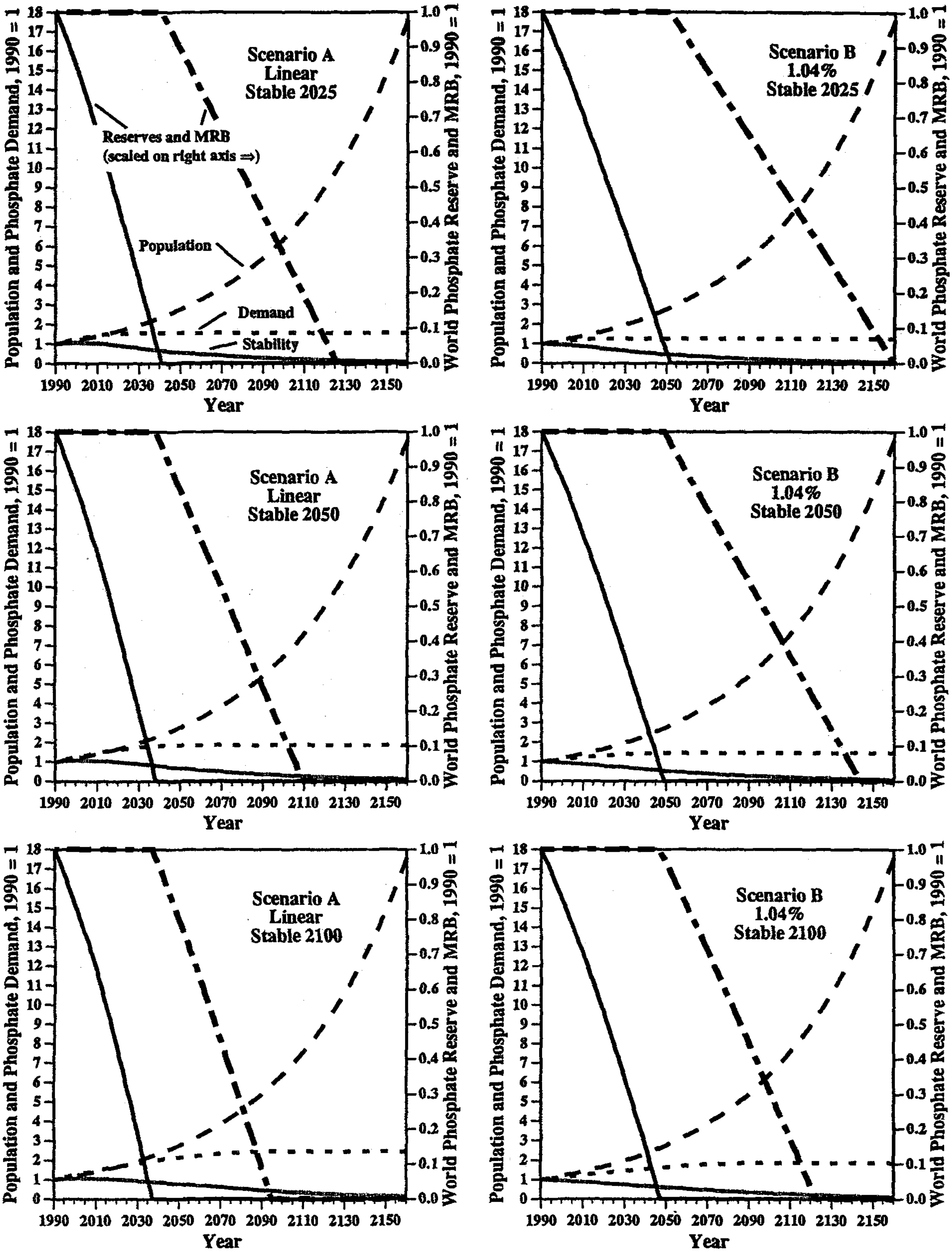
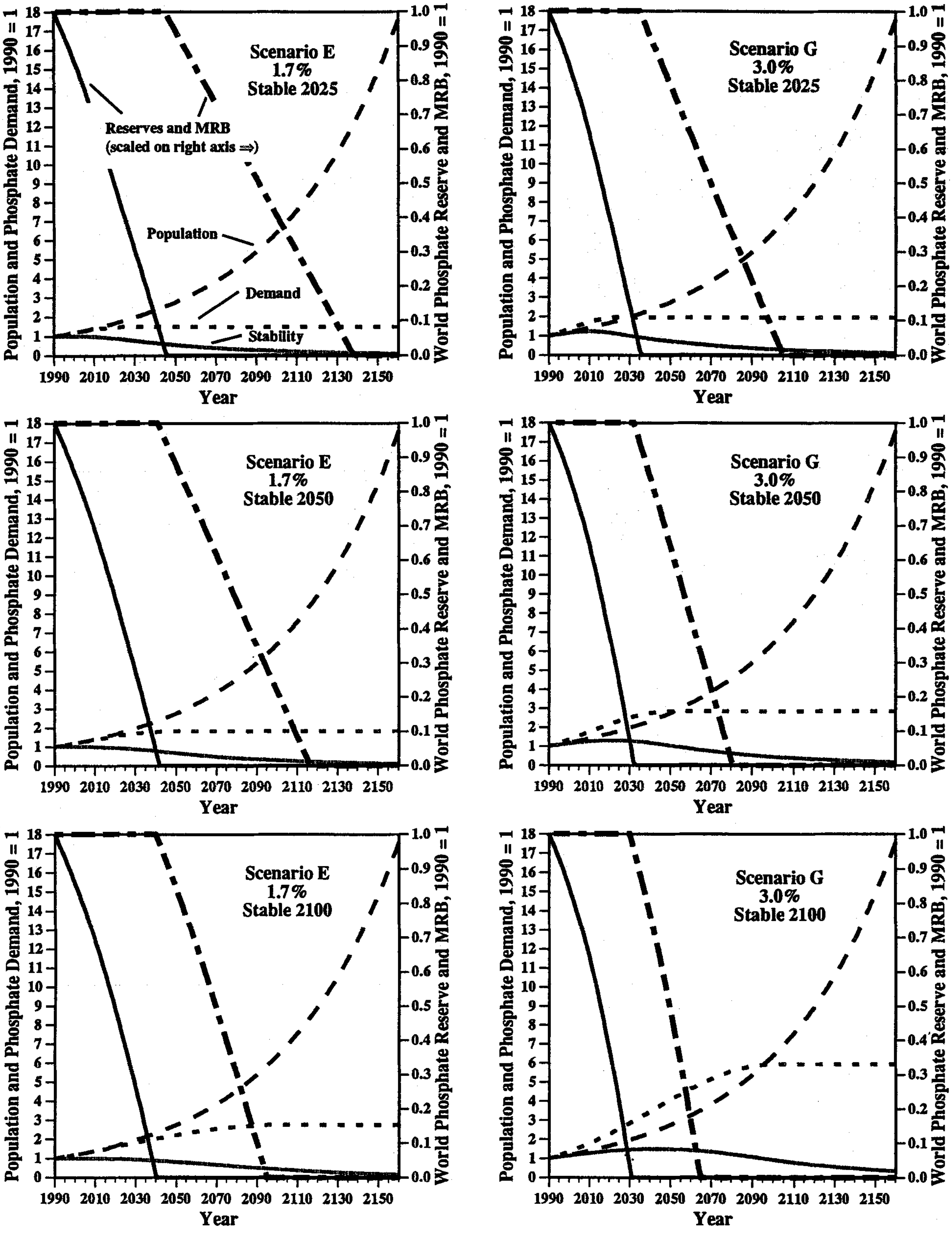


Figure 4. Scenarios for depletion of world phosphate reserves and modified reserve base (MRB, which is equal to reserve base less reserves) that tend toward demand stability. Values are scaled as in figure 2. Demand increases at various rates until 2000, then a linear decrease in demand occurs, reaching a stabilized value in 2025, 2050, or 2100. Individual scenarios are read from top to



bottom in increasing times to demand stability. Among the exponentially increasing demand curves, only the smallest (1.04 percent), intermediate (1.7 percent), and highest (3 percent) cases are shown; other exponential cases will be intermediate to these.

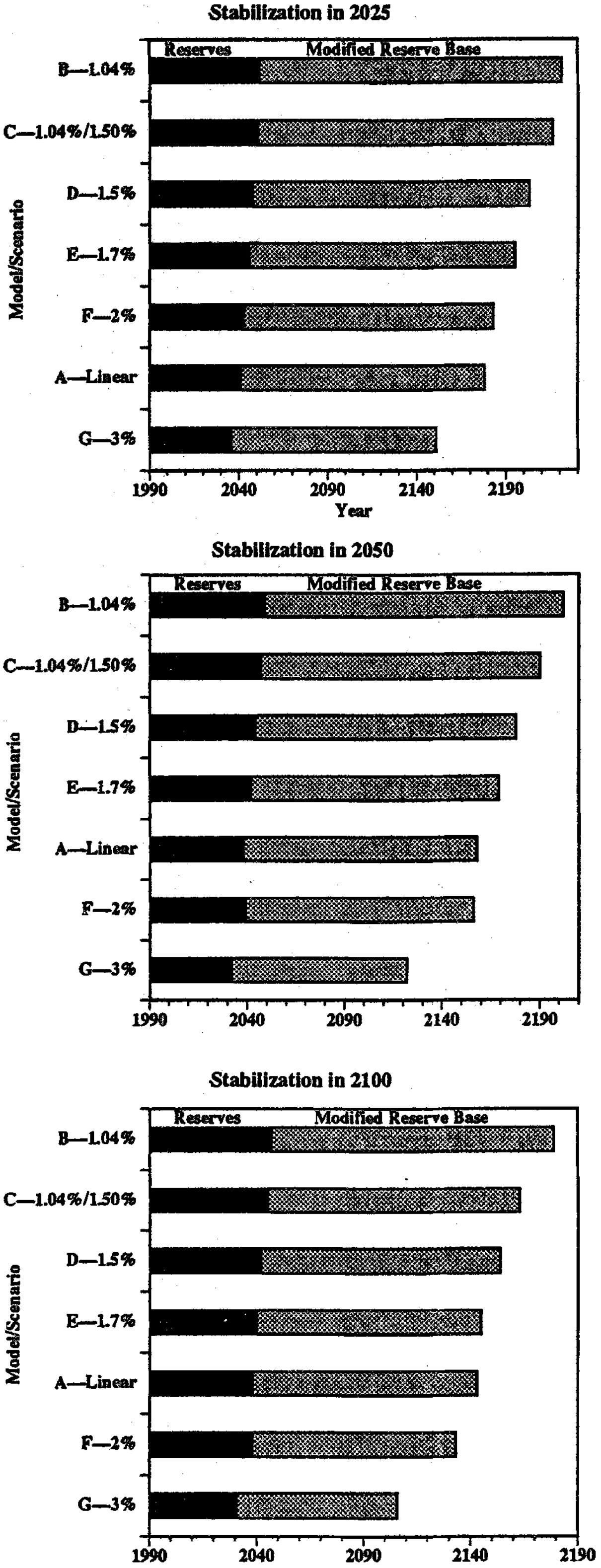


Figure 5. Summary bar chart of the depletion dates of the reserves (on left) and modified reserve base (on right) for the various scenarios in figure 4.

lamation issues are important, and mining plans must address the influence on topography, surface and ground water quality, dust, aesthetic considerations, climate, erosion, soil disturbance or loss, soil productivity loss, and desert creep in arid regions. These issues occur in part because phosphate mining early in the century led to negative feelings toward the phosphate industry, as huge pits and piles of spoil often were abandoned without reclamation. Hence, it has become the legislative stance in this country to find ways to mine and process phosphate without permanent damage to the environment and to ensure that areas can actually be improved through reclamation practices following mining. Modern permitting requires mine reclamation planning before mining occurs. Important uses of these reclaimed areas include: home sites; orchards and croplands; recreational areas, such as fishing lakes or golf courses; and wildlife sanctuaries. However, the environmental practices associated with phosphate mining vary from country to country. Several other countries that are major phosphate rock producers, for example, Morocco, take a far less supportive stance at present than the United States in reclamation practice. Some of these countries, because they spend less money on reclamation, do not need to include reclamation in the cost of their product and, hence, can well their product at cheaper prices than countries that do include reclamation in the cost of mining.

From the previous discussion of phosphate rock mining and phosphoric acid manufacturing, three striking observations with environmental consequences emerge: (1) mining removes from the ground a large volume of rock that is not entirely replaced, and the mined land cannot be restored to its original contours; (2) acidulation using the wet process generates huge amounts of gypsum; and (3) washing and screening of the ore produces immense volumes of fine-grained minerals slurried in water. In this latter case, most of the watery suspension of the fine-grained fraction is not returned to the mine pit, but is pumped to large holding areas to gradually dewater, a process that can take a few years to decades.

Each of these considerations carries its own environmental price and practice, depending on the country. All of these considerations are especially important in the United States but less so in other countries. Gypsum, because it contains a residue of phosphoric acid and entrained radioactive products of uranium decay, is presently considered by some to be hazardous. However, in May 1991, the U.S. Environmental Protection Agency ruled that gypsum is not a hazardous waste; instead, it is subject to the more flexible regulatory provisions of the Toxic Substances Control Act. Gypsum is not returned to the pit but is stored aboveground in immense piles. For example, the gypsum piles at one of the phosphoric acid plants in Florida this year will become 3 km^2 in combined area and 61 m in height. Both gypsum and the fine-grained waste fraction cause disposal problems. Current research programs in industry and the USBM are attempting to find solutions to both problems. In the case of the fine-grained fraction, the emphasis of reclamation research is on rapid dewatering, whereas research on gypsum emphasizes treating the material so that it can be returned to the mine pit or used as a commercial by-product.

Future Perspective and Opportunities

The future perspective of U.S. phosphate rock mining is uncertain. In the past two decades, the United States has been a world leader in the production and export of phosphate rock and of value-added phosphate products, for example, fertilizer. The USBM estimates that the United States has approximately 6 Gt of potentially recoverable phosphate rock at the demonstrated resource level (Fantel and others, 1983, 1988). Theoretically, this should be sufficient to sustain the present rate of production for well over 100 years. However, the United States now confronts higher production costs at new or proposed mines and must contend with increasing foreign competition, especially because of recent production and processing improvements in North Africa and the Middle East. Even though U.S. resources seem sufficient to satisfy domestic demand and provide possible export revenue well into the next century, the increasing challenges of global production and marketing, as well as domestic production costs, will determine the viability of the U.S. industry. An ominous sign is the forecast decrease in U.S. phosphate rock production to about half its present amount by 2010, if no new mines are developed, and no later than 2020 based on existing plans for the opening of new mines. This could have serious consequences for the domestic phosphate rock industry and its ability to satisfy national demand, as well as to provide export revenue. Such a significant decrease in the U.S. phosphate rock production could estimate export revenue or impose a reliance on imports to satisfy internal need.

The United States and several other countries throughout the world have an abundance of demonstrated phosphate resources, but this does not ensure that phosphate rock will be mined. Phosphate mining in the United States is capital intensive and has extremely high start-up costs. A large dragline costs about 20 million dollars, unassembled, and requires 3 to 5 years to order and construct; the cost for a washer and flotation plant or an acid production plant ranges from several hundred million to nearly a billion dollars. Mine or plant closure in this country could be leveraged by foreign producers, especially were those producers to keep their export prices artificially low for a few years. Closure, sale, and scrapping of the processing plants and mining equipment in the United States could compromise the industry, as start-up costs to rebuild those processing plants and reestablish the supporting infrastructure could become enormous. Were this chain of events to occur, the United States could quickly go from a position of satisfying internal need and of being a net phosphate rock and product exporter to a position of being a net importer and relying on foreign markets.

In the world perspective of phosphate rock availability, the market-economy countries have approximately 34 Gt of potentially recoverable phosphate rock at the demonstrated resource level (reserve base, which includes reserves). Morocco and the Western Sahara account for 63 percent of this total. How much of this will be available to world production will be determined by future economics of mining and international supply versus demand. If one or a few countries were able to monopolize the availability of phosphate throughout the world, the need for this bioessential element would require that all nations somehow maintain supply phosphate even if prices were dramatically increased. A serious imbalance between supply and demand of phosphate occurred in 1973 and 1974, when demand greatly exceeded supply. Producers increased prices by a factor of 4 to 5, and, although this was tied in part to the politics of oil prices at the time, it underscores the point that the politics of food can and likely will become increasingly important to every country. Major increases in phosphate fertilizer costs will have substantial repercussions on the global food supply. Unfortunately, fertilizer cost increases to third-world countries will only exacerbate their economic plight. The majority of these lesser-developed countries, which also have most of the world's population, have no or only minor deposits of phosphate. Many of these countries cannot grow sufficient food for their population and either must rely on the donations from other countries or must use their already meager and strained economies to import food.

Several opportunities and some restrictions likely will affect the worldwide future availability of phosphate rock. The most severe restriction is that there are no known substitutes for the bioessential role of phosphorus. Consequently, we do not consider the development of nonphosphorus compounds that could replace the essential role of phosphorus as an agricultural nutrient to be a feasible alternative. However, it is possible that a small portion of present and future phosphate demand, that used for industrial chemicals, could find nonphosphorus

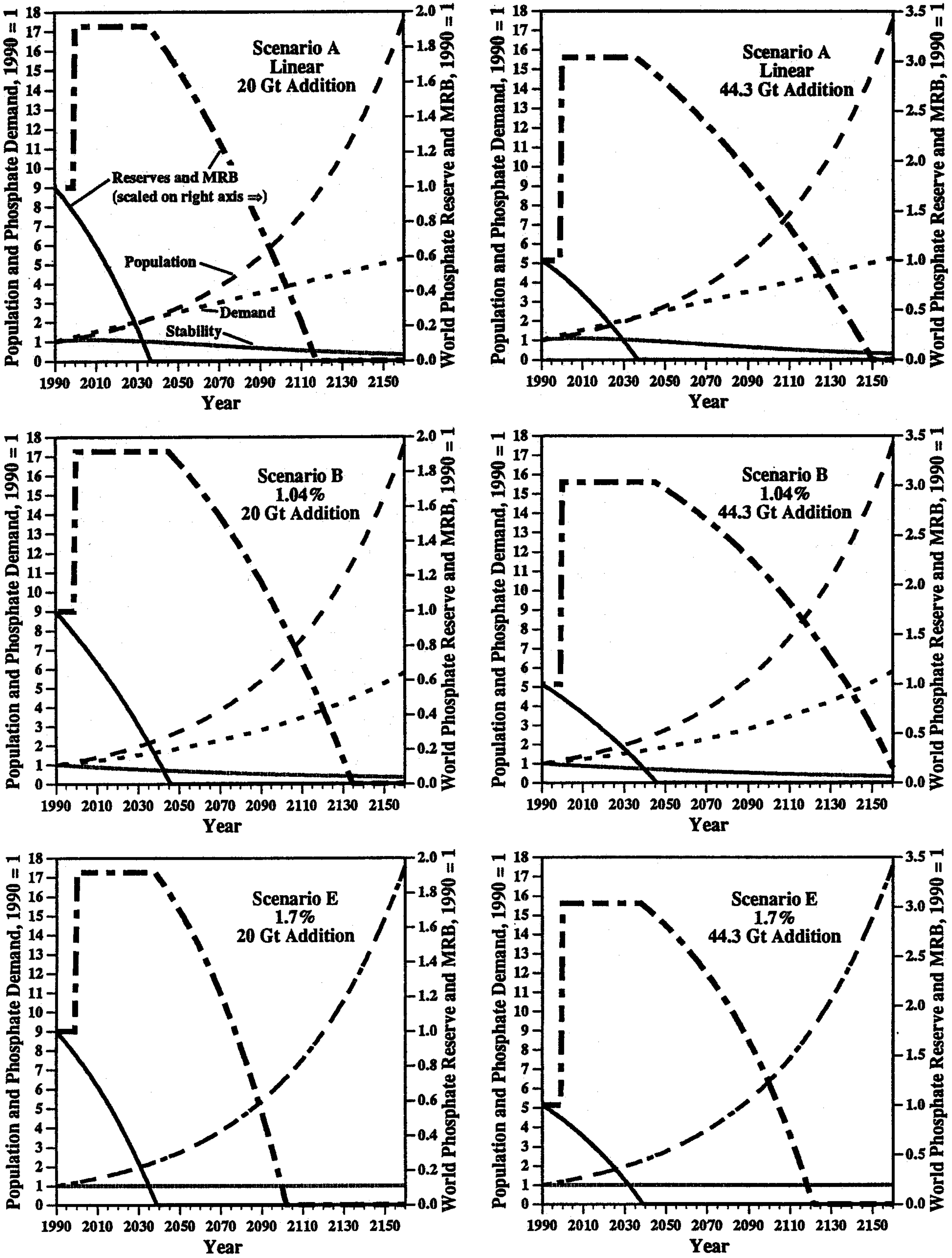
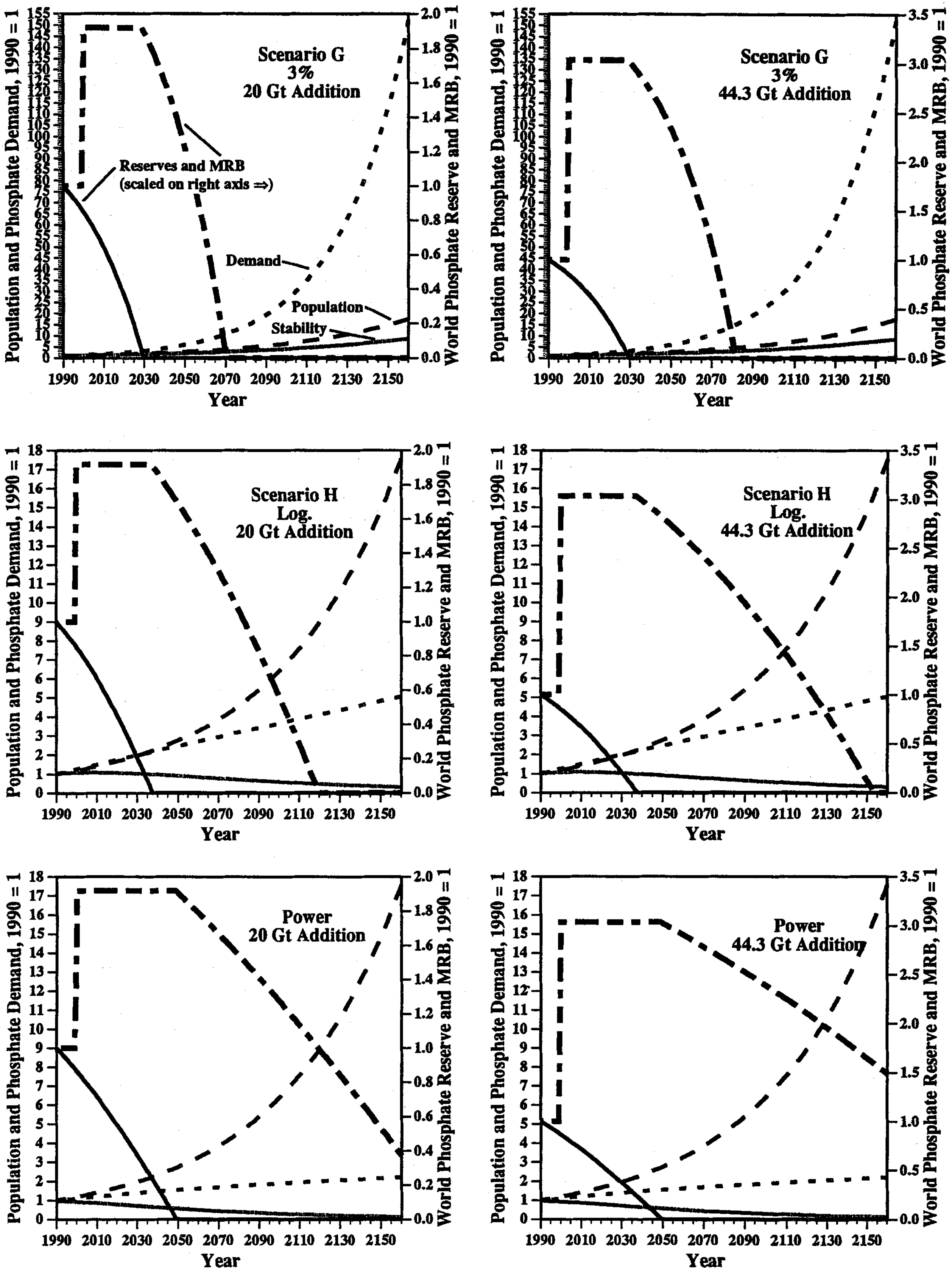


Figure 6. Scenarios for depletion of world phosphate reserves and modified reserve base (MRB, which is equal to reserve base less reserves) for assumed additions resulting from new discoveries or different economics of production. The assumed additions, which are made only to MRB and are assumed to occur in 2000, are 20 Gt (= world inferred resources) or, added to that, another 24.3 Gt (= U.S. hypothetical resources; total of 44.3 Gt). Additions are made to the unconstrained growth scenarios of figures 2



nd 3 and table 2. Values are scaled as in figure 2. Among the exponentially increasing demand curves, only the smallest (1.04 ercent), intermediate (1.7 percent), and highest (3 percent) cases are shown; other exponential cases will be intermediate to these.

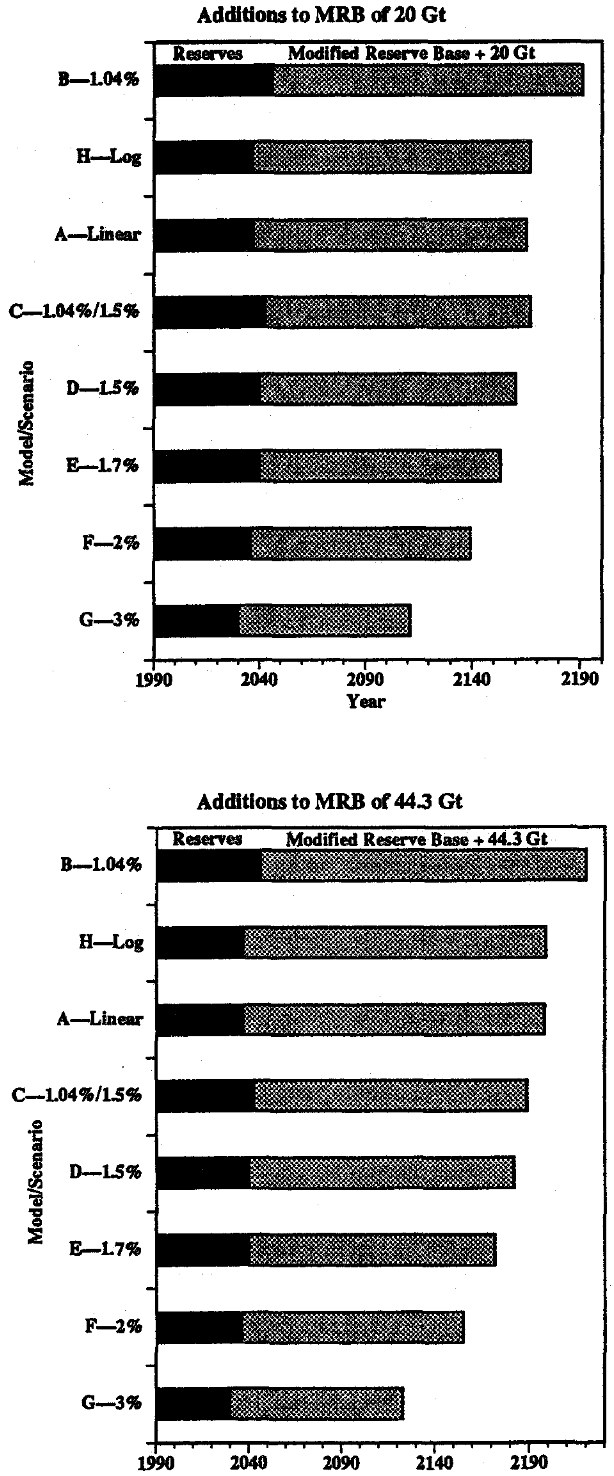


Figure 7. Summary bar chart of the depletion dates of the modified reserve base for the various scenarios in figure 6.

substitutes. Increased planting and yield or the techniques of sustainable agriculture also have been suggested as ways to increase the future availability of world food. However, increased planting, especially once natural soil levels of available phosphorus become depleted, would increase future phosphate demand. Increased crop yield might be realized with improved plant strains, wherein additional plant biomass could be obtained from the same amount of applied fertilizer. However, sufficient assimilable phosphorus to satisfy the bioessential end use must still be passed along in those crops. To this end, the techniques of sustainable agriculture may offer some modest potential for optimizing the amount of applied fertilizer necessary to produce a given crop yield.

Among the principal opportunities to increase phosphate availability in the future is the discovery of new resources of phosphate rock, including the discovery and characterization of those low-grade resources that may have future opportunity for direct application. Phosphorite deposits throughout the world have been extensively characterized during the past 15 years and, the results of these investigations should provide new, creative resource deposit models that will assist further exploration. For example, the USGS presently is characterizing grade and tonnage of the enormous phosphorite resources on the Continental Shelf of the southeastern United States.

Recycling of nutrient phosphate is the second major opportunity for increasing future availability of phosphate rock. Recycling could occur in the agriculture sector by using techniques that minimize the amount of phosphorus lost or needed to sustain yield; it also could occur in the use sector where, for example, urban effluent could be reclaimed for its nutrients. As an illustration of this potential reclamation, the measured annual effluent discharge of solid and dissolved phosphorus as orthophosphate for the southern California metropolitan area is 8 kilotons (Southern California Coastal Water Research Project, 1989). This is approximately one gram of phosphorus per person per day or the equivalent of the human minimum nutritional requirement.

The final opportunity for increasing the future availability of phosphate rock involves the development of new techniques of recovery. We expect that the areas of current industry interest that will greatly affect the future availability of minable phosphate resources worldwide include (1) processing of low-grade resources; (2) technological advances that enable high-magnesium ore to be processed; and (3) advances in new mining techniques, for example, borehole mining, that enable extraction of presently unminable deposits, especially those that are considerably deeper than can be reached by modern mining methods. Any of these factors would greatly increase the amount of minable phosphate available, particularly in the United States, for the foreseeable future.

The future of the world food supply will require sagacious and prudent use and management of phosphate resources to ensure availability for all at reasonable cost. New deposits will have to be found and new technologies developed for use. Areas of technology that will become increasingly important to addressing these needs are: application of optimum fertilizer amounts for soil and crop conditions; direct application of low-grade phosphate rock to cropland; continued, moderated release of nutrient compounds; improved processing technology to utilize lower-grade or different phosphate rock from present; and reclamation practices. Even with greater availability of phosphatic fertilizer, there may be many uncertainties that affect the availability of world food and that, in turn, may have an effect on fertilizer demand. One of the greatest uncertainties for world agriculture is the effect of the perceived global climate change in the immediate future.

Conclusions

We emphasize that the results of the model used in this study do not suggest that the world will run out of phosphate in on the order of 100 years. The phosphate resources of the world indeed are immense. Nonetheless, our data suggest that the world, well within this 100-year interval, will deplete known, low-cost reserves and much of the known, higher-cost reserve base. Moreover, if the decision is made not to mine known deposits thought at present to be minable, for example, because of restrictions imposed by mineral economics or environmental considerations, then even fewer phosphate reserves will be available in the future. The alternative is that new or recycled, economically producible resources of phosphate must be found, or the cost or availability of phosphate and consequently the availability of world food may be compromised, perhaps significantly. We suggest the following to be the most effective ways in which the future supply of phosphate may be able to accommodate demand: (1) develop techniques of recycling; (2) discover new resources; (3) develop techniques for use, including direct application, of presently known, low-grade resources; and (4) develop new, economic techniques for recovery of known, but presently uneconomic resources.

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Received August 14, 1992; revised December 14, 1992; accepted February 19, 1993.

I (JRH) thank E.D. Goldberg for planting many of the seeds that germinated in this work. Also, we acknowledge helpful reviews from Thomas Gunther, Sam Fraser, Dick McCammon Warren Finch, Donald Everhart, and an anonymous reviewer.