November 2000 **No. 3 — 2000**

Phosphorus Feeding Strategies for Dairy: Effects on Manure P and P Cycles[1]

J. Mark Powell[2] and John Peters[3]

Most dairies in the U.S. continue to be land-based, that is, they produce most of their feed and use their land to recycle manure nutrients through crops. To remain economically viable, many dairies are increasing herd size and importing more feed. In these systems, the expanded importation of feed and fertilizer P has resulted in large positive P balances (Tunney, 1990; Bundy, 1998; Satter and Wu, 1999). In many areas of intensive livestock production, amounts of P produced in manure often exceed local crop requirements (Sharpley et al., 1993; Kingery et al., 1994). This can lead to the build-up of soil test P to levels much above what are needed for optimal crop yields. For example, repeated application of manure and fertilizer has increased the level of soil test P (Bray-1 P extraction) in Wisconsin from an average of 34 ppm in the 1968-73 period to 52 ppm in 1995-99 (Combs and Peters, 2000). A level of 25-35 ppm is considered more than adequate in all but sandy soils for alfalfa, corn and soybean production based on University of Wisconsin soil test recommendations. Clearly, alternative feed, fertilizer, manure and land management strategies are needed that reduce nutrient accumulation and loss from dairy farms.

Excessive soil nutrient accumulation, transport of nutrients by surface and subsurface runoff, and subsequent pollution are pressing environmental challenges facing the livestock industry (USDA-USEPA, 1999). While much remains to be learned about the relationship between soil P levels and the potential threat to surface water quality, it is fair to say that higher levels of soil P in excess of plant requirement increase the risk of environmental damage (Sharpley, 1996). Although both nitrogen (N) and P are associated with accelerated surface water eutrophication, greater attention is given to P because of the difficulty in controlling the exchange of N between the atmosphere and a water body, and the inputs of N via atmospheric N fixation by blue-green algae (Krogstad and Lovstad, 1991). Thus, control of P inputs is of prime importance in reducing eutrophication of our lakes and streams (Sharpley et al., 1994).

---

[1] Adapted from Powell, J.M., Z. Wu, and L.D. Satter. 2000. Dairy diet effects on phosphorus cycles of cropland. J. Soil Water Conserv. 0:000-000. (In press).

[2] USDA-Agricultural Research Service, Dairy Forage Research Center, Univ. of Wisconsin, 1925 Linden Drive West, Madison WI 53706

[3] Director, Soil and Forage Analysis Lab, Department of Soil Science, Univ. of Wisconsin-Madison.

Agricultural P management options are targeted at minimizing P imports onto the farm while controlling runoff and erosion (Sharpley and Withers, 1994). On soils excessively high in plant-available P, recommended fertilizer and manure rates are low to supply P equal to, or less than, crop requirement so that soil test P may be lowered slowly in the long-term. Better recycling of manure P may be achieved by timely spreading of manure over larger crop areas rather than on small areas around the barns. Land management practices, such as conservation tillage, pastures or perennial forage crops on sloping soils, are being promoted to reduce the amount of P in runoff and erosion.

The long-term solution, however, is to balance nutrient inputs and outputs through proper feed, fer-tilizer and manure management. To achieve nutrient balance, dairy farms need to consider (1) num-ber of animals, (2) nutrient excretion in manure, (3) nutrients recovered during manure handling, storage, land application and recycled through crops, and (4) contingency plans to export nutrients off-farm if there is an excess of critical manure nutrients relative to on-farm crop production needs (Van Horn, 1998). At present, our knowledge base remains incomplete with respect to the environ-mental implications of important nutrient management options, such as optimal feeding of nutrients, proper handling, storage and land application of manure, and cropping patterns that minimize nutrient buildup and losses.

Research is needed to reduce P content in feed or to enhance P utilization in animals while maintaining animal health and production. In this way, P imports in animal feed, P excretion, and amount of P having to be recycled can be reduced. Recent research has shown that dietary P can be reduced by 25 to 30%, which reduces manure P by an even greater percentage, without sacrificing milk production or quality (Van Horn, 1998; Satter and Wu, 1999).

This paper examines how reductions in dietary P affect the amount and forms of P excreted in manure, the land required for recycling manure P through crops, and the ability of a farm land base to recycle manure P in view of new federal and state guidelines that limit the land application of manure based on crop P requirements.

RELATIONSHIP BETWEEN DIETARY P AND MANURE P EXCRETION

The National Research Council (NRC) recommends that the typical dairy cow diet contain between 0.34 and 0.42% P, and early lactation diets (0-3 weeks) should contain 0.49% P (NRC, 1988). To minimize perceived risks of P deficiency, many dairy nutritionists recommend dietary P levels that exceed current NRC recommendations, and it is common to see dietary P levels between 0.5 and 0.6% for high producing herds (Howard and Shaver, 1992; Keuning et al., 1999). Such levels of dietary P are clearly excessive and can be reduced by 30 to 40% without sacrificing milk production and quality (Satter and Wu, 1999).

In 1999, a survey of 98 Wisconsin dairy farms was conducted to evaluate feeding practices (Jackson-Smith and Powell, 2000). Results indicated that 72% of the farmers surveyed used forage-testing technology and 80% usually added supplemental P to their milk cow rations. Another 12% were not sure if supplemental P was being added to their feed. In addition, 71% were not sure what percent P is usually included in a typical dairy cow ration, and for those who reported a value it averaged 0.52%.

After feeding, dairy cows secrete P in milk and excrete P in feces. Little P is found in urine, because the kidney is not a major route of P excretion (McDowell, 1992). Addition of excess inor-ganic P to dairy diets results simply in a greater excretion of total P (Table 1) and water-soluble P in feces (Fig. 1). The annual 42 to 77 lb fecal P cow^{-1} range found in this study (Table 1) corresponds closely to the 39 to 71 lb cow^{-1} range calculated by Van Horn et al. (1994) for lactating cows fed diets ranging from 0.4 to 0.6% P. Other studies have found that supplemental P increases the P content of feces (Morse et al., 1992; Khorasani et al., 1997), and that as total P in feces increases, so does the proportion of inorganic, plant available P (Bromfield, 1960). Our study shows that water-soluble inorganic P accounts for approximately 30 to 35% of the total P in dairy feces (Fig. 1). Water-soluble P (Sims, 1993) consists of inorganic orthophosphate that is readily available for algae uptake, and therefore, is linked to eutrophication (Krogstad and Lovstad, 1991).

Table 1. Annual P fed and excreted in feces by a lactating cow.†

Dietary P level	Supplemental P	Fecal P
%	--------------- lb cow^{-1}year^{-1}	--------------
0.35 ‡	0	41.7
0.38 §	5.5	47.2
0.48	23.4	65.3
0.55	36.2	77.8

† Assumptions: Cow is producing 20,065 lb of milk per 305 day, and consuming 49.6 lb dry matter per day, or 15,133 lb per 305 day; milk contains 0.09% P; no net change in body P content of the cow.

‡ May be marginally deficient in P for very high producing cows based on a typical diet containing corn grain, alfalfa, corn silage, and soy-bean meal.

§ Recommended level of dietary P (Satter and Wu, 1999).

SHIFTING LAND APPLICATION OF MANURE TO A P-BASED STRATEGY

The Natural Resources Conservation Service (NRCS) of the USDA has recently laid out new manure management guidelines that target excessive land applications of manure P (NRCS, 1999). When animal manure is land-applied, either of two guidelines apply:

(1) When soil specific P threshold (TH) data are available that identify the soil P level at which losses of soluble P in runoff become significant, the P application may be based upon the following guidance:

Soil test P level	Allowed P application rates
< ¾ TH value	Nitrogen based application
$ ¾ TH <1 ½ TH	Crop removal
$1 ½ TH < 2 TH	½ Crop removal
$2 TH	No application

(2) When soil specific P threshold data are not available, the P application shall be based upon the following guidance:

Soil test P level	Allowed P application rates
Low	Nitrogen based application
Medium	Nitrogen based application
High	1.5 times crop removal
Very high	Crop removal
Excessive	No application

Various other policy options are being discussed to enhance an efficient utilization of manure. These include manure applications based on a field's P risk index (Lemunyon and Gilbert, 1993), N leaching potential, linking the number of animals to the area of land and cropping system available for manure utilization, etc. (Bannon and Klausner, 1996). Phosphorus risk index is the most sophisticated approach, but requires information on soil erosion and runoff, distance to a water body, soil test P, and amounts and method of fertilizer and manure application. Therefore, strategies for reducing nutrient losses from manure must be site specific. The growing general consensus is that land application of manure will become increasingly regulated based on soil test P level and a field's risk to contribute P to surface water.

DIET EFFECTS ON LAND REQUIREMENT FOR MANURE APPLICATION

A shift from an N to a P-based strategy for land application of manure may profoundly affect nutrient management on dairy farms. In Wisconsin, many dairy farms already have fields that test "high" or "excessive" in available P (Proost, 1999; Combs and Peters, 2000). Manure applications to these fields will have to be reduced or eliminated as producers are regulated to shift from manure N to P-based strategies. If the amount of manure applied to cropland is restricted to crop P removal, supplementation of the dairy diet with inorganic P can increase dramatically the land requirement for recycling manure P (Table 2). For the purpose of this study, we restrict our analysis to lactating cows. The non-lactating cows and growing and replacement heifers generally do not receive dietary P supplements. Therefore, the cropland required for recycling manure P for this part of the herd would remain constant unless herd size changes.

Of the total cultivated area in Wisconsin, approximately 42% is alfalfa, 33% is corn grain, 8% is soybean and 6% is corn silage (Bundy, 1998). The average harvested dry matter of these crops is 5.0, 3.3, 1.3, and 7.7 tons/acre, respectively (Kelling et al., 1998). The average annual P uptake of this cropping pattern is approximately 27 lb/acre, calculated as the combined proportional P uptake of each crop when soil test P is at optimum levels (Kelling et al., 1998). We used this cropping pattern and its P uptake, and guidelines that limit manure applications to the amount of crop P removal, in the following analysis of how dietary P affects the amount of cropland needed for recycling manure P through crops. A shift in cropping pattern, for example growing more corn silage to remove more P, would obviously affect the land requirement for manure P recycling.

Approximately 1.75 acres of the mixed alfalfa, corn, soybean cropping system (27 lb/acre P crop removal) is required to recycle manure P excreted by a lactating cow (20,065 lb milk over 305 d) fed a diet containing 0.38% P. Raising dietary P from 0.38 to 0.48% for a single lactating cow requires an additional 17.9 lb of supplemental P annually (Table 1) and increases the cropland area needed for recycling manure P by 0.69 acres per cow, or 44% (Table 2). Bannon and Klausner

Table 2. Land requirement for recycling fecal P excreted by a cow fed various dietary P levels.

Dietary P level	Land area needed to recycle fecal P	Change in land area due to diet P supplementation
%	acre †	%
0.35	1.6	0
0.38	1.8	13
0.48	2.4	57
0.55	2.9	87

† Annual cropping system comprised of 47% alfalfa, 37% corn grain, 9% soybean, and 7% corn silage having harvested dry matter of 5.0, 3.3, 1.3, and 7.7 ton/acre, respectively, and an area-weighted P removal of 27 lb/acre.

(1996) estimated that 1.04 to 1.90 acres cow^{-1} would be required to recycle manure P through of a corn-legume rotation on dairy farms in New York state. Our higher estimated range of 1.56 to 2.92 acres cow^{-1} (Table 2) reflects the great potential impact of dietary P level on land requirements for recycling manure P through crops.

DIET EFFECTS ON SOIL TEST P

Our analysis has examined the effect of dietary P supplementation on manure P output and the additional land required to recycle manure P through crops given new regulations that limit the land application of manure to a crop P demand. If the land base was fixed (i.e., a producer does not have additional land on which to apply manure), dietary P supplementation could profoundly affect soil test P levels. For example, if a producer has 1.75 acres of cropland available for spreading the manure for each lactating cow, land application of manure from cows fed a diet providing no excess of P (0.38%) would be just sufficient to meet the crops' P demands, and soil test P levels would not increase (Table 3). However, at this one cow: 1.75 acres ratio, any amount of supplemental P in excess of the cow's requirement would result in manure P that, when applied to cropland, would increase soil test P levels.

Recycling manure nutrients through crops is the linchpin of manure management on most dairy farms. However, effective recycling of manure nutrients through crops presents many challenges. For example, manure of ruminant livestock typically has an average N:P ratio of 4, whereas the N:P requirement of major grain and hay crops is 8 (White and Collins, 1982). Typical dairy diets exacerbate the difference in N:P ratios between crops and manure (Fig. 2). When manure from cows fed excessively high P diets is applied to cropland to meet a crop N demand, soil test P will increase much quicker than if dietary P is adequate, but not excessive. Reducing dietary P will not only reduce manure P concentrations but will also improve the N:P ratio. The N:P ratio of manure also can be improved by reducing volatile N losses from manure (Van Horn, 1998).

Table 3. Theoretical changes in soil Bray-1 P levels due to application of dairy manure derived from a cow fed various levels of dietary P.

Dietary P level	Manure P in excess of crop P demands †	Change in Bray-1 P ‡
%	lb/acre/year	ppm/year
0.35	– 3.0	– 0.4
0.38	– 0.1	0
0.48	10.4	1.3
0.55	17.6	2.2

Another way to consider the effect on a fixed land base of adding excessive supplemental P to the diet is to examine a farm's ability to "absorb" additional soil P until all fields have soil test P levels in excess of crop P demands. According to NRCS guidelines (NRCS, 1999), it is at this point that manure may no longer be applied. If a farmer has no other land available for manure spreading, one can consider the farm as a "sink," having a certain ability to receive P until the sink is full. A recent survey of 96 dairy operations in Wisconsin showed a tremendous variability in soil test P levels among farms and among fields within a farm (Proost, 1999). That study showed that the farm weighted averages for soil test P were in excess of most crop needs. All of these farms have fields that contain excessive levels of soil test P, and all fields of some farms contained excessive levels of soil test P.

To illustrate the effect of diet P supplementation on a farm's ability to recycle P, we used a dairy farm (Proost, 1999) that typifies the field distribution of soil test P (Fig. 3). This farm has two fields (23.5 acres) that have excessive Bray-1 P, and fifteen fields (170 acres) that test below excess soil P levels. The 170 acres have the capacity to store an additional 1590 lb of Bray-1 P (0-15 cm soil depth) until all fields reach excessive Bray-1 P levels. It takes approximately 7.8 lb/acre of P (18 lb P_2O_5 /acre) addition/removal to increase/decrease Bray-1 P by 1 ppm (Kelling et al., 1998).
Therefore, the 170 acres of this farm could receive a net additional 14,000 lb of manure P before all fields reach excessive Bray-1 P levels.

Assuming good manure management, the farmer's decision on how much supplemental P to feed will profoundly affect how many cows and for how long the farm could support milk production before all fields attain excessive levels of soil test P (Table 4). By supplementing only minimal amounts of P to meet the cow's requirement (0.38%), and eliminating fertilizer P altogether, the farm depicted in Fig. 3 can continue to support 90 lactating cows on 170 acres indefinitely. The addition of dietary P supplements in excess of the cow's requirement results in manure P in excess of crop P requirements, and reduces the number of cows the farm can support and/or the number of years before all fields reach excessive soil test P levels. For example, annual addition of 17.9 lb P per cow to increase dietary P from 0.38 to 0.48% for a 90 cow herd would create excessive soil test P levels in 11 years.

Table 4. Effect of dairy P supplementation on a farm's ability to store soil P. †

Dietary P level	Fecal P	Years to attain excessive Bray-1 P in all fields
%	lb/cow/year	
0.35	41.7	Indefinite
0.38	47.2	Indefinite
0.48	65.3	11
0.55	77.8	6

† Example of a 193-acre dairy farm depicted in Fig. 3 that has 170 acres that can receive up to 14,000 lb before all fields attain excess Bray-1 P levels. Assumes a stocking rate of 90 lactating cows and an annual crop P removal of 27 lb/acre.

In this analysis, we have assumed an equal distribution of manure across all fields, but not all fields are equally accessible on most farms. Manure is applied often to the most accessible fields (those closest to the barn, closest to roads, etc.) resulting in soil nutrient buildup (Fig. 3). Repeated application of manure in amounts that exceed crop P requirements accelerates the buildup of soil test P and increases environmental risk, especially on sloping land close to waterways.

Considerable time is required for depletion of excessive soil test P. McCollum (1991) esti-mated that, without further P addition, 16 to 18 years of corn or soybean cropping would be needed to deplete soil available P (Mehlich-3) in a sandy soil from 100 ppmP to a desired level of 20 ppm P. In our present analysis, the corn, alfalfa, and soybean cropping system would decrease Bray-1 P by 3.4 ppm annually if manure and fertilizer P were not applied. It would take, therefore, approxi-mately 24 years to draw down soil available P levels in the highest testing fields (100 ppm P, Fig. 3) to 20 ppm P. In the mean time, the farmer must find other fields to receive manure.

DIET EFFECTS ON P BALANCE

A strategy of reducing dietary P supplements would benefit dairy producers, because both feed costs and the amount of manure P that has to be recycled would be reduced. A 0.1% reduction in dietary P level would result in 30% less manure P, or 213,000 tons of P in manure from confined dairy operations nationally (Van Horn, 1998). Satter and Wu (1999) estimated that excessive P supplementation costs the U.S. dairy industry an unnecessary $100 million annually.

Reduction in dietary P supplementation can improve the P balance on a dairy farm (Table 5), thereby reducing environmental risks. The import of P onto dairy farms consists of protein supple-ment, mineral supplement, and starter fertilizer for corn grain and silage. If the dietary P level is reduced to 0.38% (a level that does not decrease milk production; Satter and Wu, 1999), the import of supplemental P could be greatly reduced, thereby stopping the accumulation of P on a whole farm basis (however, uneven distribution of manure may result in accumulation of soil test P in some fields). Dairy operations that purchase all of their protein supplement and part of their grain can achieve P balance only if they reduce dietary P supplementation to meet the animal's requirement and eliminate P fertilizer. Dairy operations importing all of their protein supplement and grain will have to find additional land for manure application.

Table 5. Annual P balance for a 100-cow dairy (adapted from Satter and Wu). †

P import to farm		P export from farm	
	lb		lb
Protein supplement	1219	Milk	1806
Dicalcium phosphate ‡	1627	Cull cows and calves	300
Grain	0	Surplus feed	0
Forage	0	Manure	0
Fertilizer	1181	Runoff	201
Total	4027	Total	2307

† Cows average annual milk production of 20,065 lb. Balance includes lactating and dry cows, 80 heifer replacements. In this example, the farm produces all of the grain and forage, and purchases only protein (soybean) and mineral/vitamin supplements.

‡ Assumes dicalcium phosphate is used to raise dietary P from 0.35 to 0.48%.

CONCLUSIONS

Modifying nutrient management recommendations and practices present many challenges. Most programs aimed at improving nutrient management on dairy farms target either the feed, fertilizer, and/or manure nutrient components. For example, the newly approved USDA/EPA Unified Strategy for Animal Feeding Operations (USDA/USEPA, 1999) recognizes that feed management can be an important tool for achieving a preferred balance of nutrient in manure, but the strategy does not propose any adjustments to feed practices. The Field Office Technical Guide of NRCS, which is the primary technical reference for development of comprehensive nutrient management plans for animal feeding operations, does not consider feed management.

There is clearly a need for more integrated approaches to improving nutrient management on dairy farms. Luxurious use of dietary P supplements increases dramatically the land required for recycling manure P and reduces the number of years a farm can support dairy production before all fields attain excessive soil test P levels. We should seek a more holistic understanding of how nutrient management in one production component (e.g., feed) affects nutrient cycling in other production components (e.g., soils and crops).

REFERENCES

Bannon, C.D., and S. Klausner. 1996. Land requirements for the land application of animal manure. p. 194-204. In Animal agriculture and the environment: Nutrients, pathogens, and community relations. Proc. Animal Agriculture and the Environment, Ithaca, NY.

Bromfield, S.M. 1960. Sheep feces in relation to the phosphorus cycle under pasture. Aust. J. Agric. Res. 12:111-123.

Bundy, L.G. 1998. A phosphorus budget for Wisconsin cropland. Report submitted to Wis. Dept. of Natural Resources and Wis. Dept. of Agriculture, Trade & Consumer Protection. Univ. of Wisconsin-Madison.

Combs, S.M., and J.B. Peters. 2000. Wisconsin soil test summary. Fertilizer Dealer Mtg. Univ. of Wisconsin-Cooperative Extension Programs, Madison, WI. (Handout).

Howard, W.T., and R.D. Shaver. 1992. Use of high producing herd diet evaluation in dairy extension programming. J. Dairy Sci. 75 (1):186.

Jackson-Smith, D., and J.M. Powell. 2000. How Wisconsin dairy farmers feed their cows: Results of the 1999 Wisconsin Dairy Herd Feeding Study. Wis. Farm Research Summary no. 5, July 2000.

Kelling, K.A., L.G. Bundy, S.M. Combs, and J.B. Peters. 1998. Soil test recommendations for field, vegetable and fruit crops. Publ. no. A2809, Univ. of Wisconsin-Extension, Madison, WI.

Keuning, J.L., S.L. Gunderson, and R.D. Shaver. 1999. Survey and management practices on six high producing Wisconsin dairy herds. J. Dairy Sci. 82 (4):844.

Khorasani, G.R., R.A. Janzen, W.B. McGill, and J.J. Kenelly. 1997. Site and extent of mineral absorption in lactating cows fed whole-crop cereal grain silage or alfalfa silage. J. Animal Sci. 75:239-248.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23:139-147.

Krogstad, T., and O. Lovstad. 1991. Available soil phosphorus for planktonic blue-green algae in eutrophic lake water samples. Arch. Hydrobiol. 122:117-128.

Lemunyon, J.L., and R.G. Gilbert. 1993. Concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483-486.

McCollum, R.E. 1991. Buildup and decline in soil phosphorus: 30-year trends on a Typic Umpra-buult. Agron. J. 83: 77-85.

McDowell, L.R. 1992. Minerals in animal and human nutrition. Academic Press, Inc. San Diego, CA.

Morse, D., H.H. Head, C.J. Wilcox, H.H. Van Horn, C.D. Hissem, and B. Harris, Jr. 1992. Effects of concentration of dietary phosphorus on amount and route of excretion. J. Dairy Sci. 75: 3039-3049.

National Research Council (NRC). 1988. Nutrient requirements of dairy cattle. Natl. Academy Press. Washington, DC.

Natural Resources Conservation Service (NRCS). 1999. Conservation practice standard, nutrient management. CODE 590, Part 402. USDA-NRCS, Washington, DC.

Proost, R.T. 1999. Variability of P and K soils test levels on Wisconsin farms. In Proc. 1999 Fertilizer, Aglime and Pest Mgmt. Conf. 38:278-282, Madison, WI.

Satter, L.D., and Z. Wu. 1999. Reducing manure phosphorus by dairy diet manipulation. In Proc. 1999 Fertilizer, Aglime and Pest Mgmt. Conf. 38:183-192, Madison, WI.

Sharpley, A.N. 1996. Myths about phosphorus. p. 60-75. In Animal agriculture and the environment. Proc. Animal Agriculture and the Environment Conf. 11-13 Dec. 1996, Rochester, NY.

Sharpley, A.N., T.C. Daniel, and D.R. Edwards. 1993. Phosphorus movement in the landscape. J. Prod. Agric. 6:453-500.

Sharpley, A.N., and P.J.A. Withers. 1994. The environmentally sound management of agricultural phosphorus. Fert. Res. 39:133-146.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437-451.

Sims, J.T. 1993. Environmental soil testing for phosphorus. J. Prod. Agric. 6:501-507.

Tunney, H. 1990. A note on a balance sheet approach to estimating the phosphorus fertilizer needs of agriculture. Irish J. Agric. Res. 29:149-154.

U.S. Department of Agriculture and U.S. Environmental Protection Agency (USDA/USEPA). 1999. Unified national strategy for animal feeding operations. USDA/USEPA, Washington, DC.

Van Horn, H.H. 1998. Factors affecting manure quantity, quality and use. Mid-South Ruminant Nutrition Conf. 7-8 May 1998, Dallas-Fort Worth, TX.

Van Horn, H.H., A.C. Wilkie, W.J. Powers, and R.A. Nordstedt. 1994. Components of a dairy manure management system. J. Dairy Sci. 77:2008-2030.

White, W.C., and D.N. Collins (ed.). 1982. The fertilizer handbook. The Fertilizer Institute, Washington, DC.