Chapter 16
Effects of Manure Management on Phosphorus Biotransformations and Losses During Animal Production

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16.1 Introduction

Phosphorus (P) continues to be a significant pollutant of surface waters and estuaries in the USA and around the world despite major research and education efforts, the guidelines and rules of comprehensive nutrient management given by federal and state agricultural and regulatory institutions, and the scrutiny of public interest groups (Tamminga 1992; Zhu et al. 2006; Kurz et al. 2006; Withers et al. 2007; USEPA 2008a; Trollea et al. 2008). Livestock production is a major contributor to P loading of surface- and groundwater sources in livestock production-intensive watersheds. Nutrients are imported in large quantities in animal feed, while nutrients excreted in manure accumulate locally. Environmental discharges of P include runoff from animal pens and open feedlot surfaces, seepage of effluents from manure storage areas or overflow and spills, as well as diffuse discharges from manure-treated landscapes and inadequately managed riparian zones and stream banks. An improved understanding of the composition or accurate distribution of the inorganic and organic P forms in animal manure, their respective transformations and modes of dispersal, and the receiving landscapes' vulnerability to losses of P inputs to natural terrestrial and aquatic biospheres is crucial to the success of restoring impacted aquatic ecosystems and protecting them from further impairment. In a recent analysis of the interactions between reactive surfaces of soils and manure soluble and particulate organic P forms, we have explored the multiple strategies that plants and microorganisms use to detect and obtain needed P from animal manure and the soil to meet their nutritional needs. Underlying these strategies, frequent interweaving of biophysical and biochemical processes are observed in the turnover of organic P forms (Dao 2010). In this review, particular

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attention is given to the linkages between feed inputs and the excreted P characteristics and transformations, so as to detect the relationships that exist between manure management practices and the characteristics of the waste products. This knowledge is essential for an improved understanding of management-induced biotransformations of P forms found in animal manures in order to beneficially reuse this non-renewable nutrient in plant agriculture. Shortages of the finite resource are predicted worldwide with dire consequences for global agricultural productivity (Déry and Anderson 2007; Gilbert 2009). The knowledge is also vital to the development of mitigation strategies and nutrient conservation practices to attenuate the likely losses associated with systems of manure handling, storage structures, and manure-amended agricultural fields.

16.2 Major Types of Animal Production Systems and Associated Manure Management Systems

Understanding the fate and transformations of dietary P inputs, and the choice of approach aimed at mitigating the environmental impacts of manure P lost from animal production, depend largely on the type of animal production system and particularly on the settings in which animals are raised or finished for market.

16.2.1 Extensive Production Systems on Pastures, Rangelands, and Forested Lands

In many parts of the world, small-size livestock that include sheep, goats, free-range poultry and swine can be found foraging on pastures and rangelands. Large grazing ruminants are also raised roaming freely on improved pastures, grass and woodlands in parts of North America, the pampas of South America, and the plateau of China (Heitschmidt et al. 2004; Rotolo et al. 2007). Manure management is incidental to the management of available forage and grazing intensity, and oftentimes consists of simply adjusting animal density and managing the location of drinking water sources and shade. A mixture of animal and plant production can be found in small, more intensively managed operations or subsistence farming systems where a farm has a herd of livestock, and arable lands for crop and animal feed production. Balance of P in these systems is nearly closed. The manure and bedding materials are recycled into the land used for production of crops and forages in order to improve the fertility and tilth of the soil. This type of production system is extensively used in dairy cattle production in New Zealand or Southern Australia, where production is based on a year-round pasture-based system by virtue of a temperate climate (Verkerk 2003). Similarly, a common practice in the southern Great Plains of the USA is the grazing of crop residues and the forage of winter cereals, in particular winter wheat, prior to the onset of winter dormancy or the initiation of reproductive stages of wheat. The combined economic return from winter wheat includes both that of the grain crop and that of animal products and may exceed that of the grain crop without grazing (Baumhardt et al. 2009). During the summer months, available forages include many warm-season grasses. Optimizing system performance is focused on grazing management and supplementation with dietary minerals and harvested feed during periods of low forage availability during a typical annual plant growth cycle.

16.2.2 Confined Livestock and Poultry Production Systems

Animal production has shown an increasing trend for consolidation, where annual animal concentrations of 25,000–50,000 heads of livestock or 60,000–120,000 birds per operation are becoming the norm in the southwestern USA or in the Mid-Atlantic states. Key efficiency considerations in these confined animal feeding operations are daily weight gains and feed conversion efficiency (NRC 1994, 1998, 2001). Common to all large confined feeding operations, feed is introduced from outside the farm. Decisions concerning feed uses are separated from those of production, and particularly of manure utilization on fields to produce the feed and/or cash crops. Therefore, nutrient flow in these systems is open-ended.

16.2.2.1 Ruminant Production and Dietary P Balance

In a typical system involved in the finishing of beef cattle in the USA, young calves are raised on pastures and rangelands for about 12–18 months. They are then gathered and transported to centrally located feedlots to be given a high-energy grain diet and attain a uniform marketable weight. Cattle usually stay for 4–6 months, during which time they can gain 1–1.5 kg day^{-1}. On the other hand, dairy cattle are raised in loafing barns that can accommodate 1,500–2,000 cows. The production of milk requires that the cow be in lactation, following the birth of a calf. The cycle of insemination, pregnancy, parturition, and lactation spans a period of 12–16 months. Dairy operations, therefore, include both the production of milk and the production of calves.

The P requirements for domesticated animals are well established, including those for beef cattle (NRC 2000) and dairy cattle (NRC 2001). The effects of dietary P sources and intake on P partitioning in ruminants have been evaluated in numerous studies over the last 2 decades (Wu et al. 2000; CAST 2002; Bravo et al. 2003), with more emphasis put explicitly on reducing excretion of P and on water quality impairments associated with the excess P used in animal production in the last 10 years (Morse et al. 1992; Wu et al. 2000; Erickson et al. 2002; Knowlton et al. 2001; Estermann et al. 2002; Jewell et al. 2007; Brokman et al. 2008). Dietary P requirements have been refined and lowered to values of 3.4–3.8 g kg^{-1} of dry matter for lactating dairy cows or a total P intake of 75–95 g day^{-1} (NRC 2001). Because of the high P concentration in milk (i.e., 0.95 g kg^{-1}), a continuous supply of feed P is needed to sustain a high level of milk production and animal health. However, P intake in excess of this level results in excessive blood, urine, and fecal P concentrations. For example, Wu et al. (2001) have shown that high-producing dairy cows (>55 kg milk day^{-1}) consuming 77, 97, and 115 g P day^{-1} or rations containing 3.1, 3.9, and 4.7 g kg^{-1} of dietary P, excreted 43, 66, and 88 g P day^{-1} in their feces, respectively. Fecal P concentrations increased linearly with those of dietary P intake, as shown in Fig. 16.1.

A similar relationship between P intake and excretion is found in grazing cattle (Erickson et al. 2002; Knowlton and Herbein 2002; Brokman et al. 2008). Betteridge et al. (1986) showed that steers grazing high-quality pastures excreted 10–23 g P day^{-1} or 44–74% of P intake from the grazed forage dry matter. Holstein steers grazing cool-season grass and legume mixtures excreted 39–55% of the ingested P (Brokman et al. 2008). As a matter of fact, Erickson et al. (2002) observed no change in performance and bone density of 45 feedlot steers fed rations containing 14.2–35.5 g P day^{-1} (i.e., 1.6–4.0 g kg^{-1} of dry matter). However, blood P levels increased with increased total P intake in excess of the basal daily intake of 14.2 g day^{-1} during a 204-day period. In summary, these results all showed that cattle inefficiently utilize dietary P and excrete between 40% and well over 70% of ingested P in high-P diets.

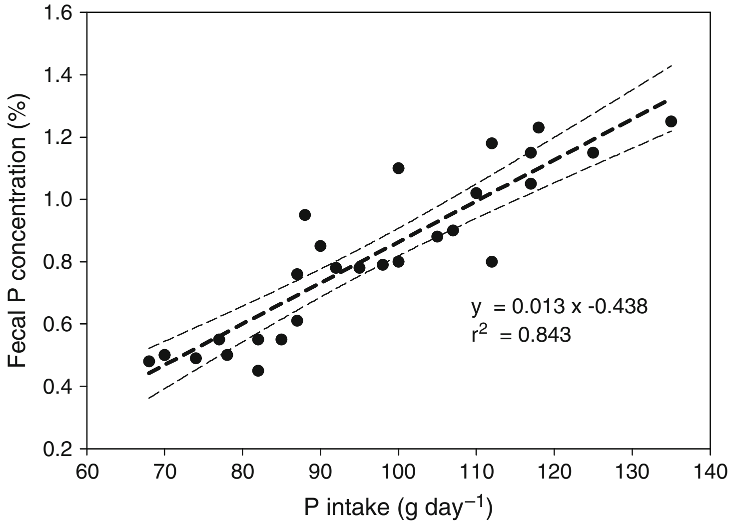

Fig. 16.1 Relationship between dietary P intake and P concentration in feces of dairy cattle fed varying levels of dietary P. *Heavy dashed line* represents the best fit and *dashed lines* on either side represent the 95% confidence intervals for predicted values (adapted from Wu et al. 2001)

16.2.2.2 Production of Monogastric Livestock and Dietary P Balance

Industrial poultry operations can involve 25,000–30,000 birds in the confined quarters of a chicken housing, and an average farm has from three to five units. Today, poultry farms produce over 900 million birds for meat and 72 billion eggs per year in the USA (NASS 2009). Feeding to requirements, growth stage or phase-feeding programs, and more recently, the use of dietary phosphohydrolases (i.e., phytases) are some of the new avenues towards reducing dietary P excretion in poultry and swine. In the latter approach, the goal is to increase feed organic P availability via the hydrolytic activity of added microbial phosphohydrolases, coupled with a decrease in inorganic P (Pi) supplementation (Kornegay et al. 1996; Bedford 2000; Boling et al. 2000; CAST 2002).

Lacking the enzymes to hydrolyze phytic acid (*myo*-inositol 1,2,3,5/4,6-hexa*kis* dihydrogenphosphate; *m*IHP), which is found in abundance in feed grains, the rations of layers and broilers are formulated on the basis of Pi content by assuming that most of the feed P is in an organically bound, indigestible *m*IHP form. For broiler chicks (<3 weeks old), Waldroup et al. (2000) observed that fecal P concentration was 12.1 g kg^{-1} when the chicks were fed at the 1994 NRC recommended dietary level of 4.5 g Pi kg^{-1} of feed dry matter. Dietary P concentrations between 3.2 and 3.4 g kg^{-1} appeared adequate for maximum bone strength (i.e., tibia) and body weight, and optimal feed conversion efficiency in broiler and egg-laying hens (Boling et al. 2000). Fecal P concentrations averaged 10.9 g kg^{-1}, and were reduced by 25% upon supplementation with phosphohydrolases (EC 3.1.3.8) at 800 units kg^{-1} of feed dry matter. Fecal P concentrations increased with increasing Pi intake, a trend similar to that observed in ruminant livestock (Fig. 16.1) (Waldroup et al. 2000). Total fecal production on a dry weight basis was about 1.3 kg per finished bird over a 48-day period (ASAE 2006). Miles et al. (2003) also found reductions in total fecal P excreted upon substitution of 1 g kg^{-1} Pi with the addition of phosphohydrolases at 600 units kg^{-1} (i.e., 9.1 g kg^{-1}, compared to 12 g kg^{-1} with a corn-based ration containing 3.5 g kg^{-1} Pi). However, water-soluble P concentration in the feces increased with enzyme supplementation and was highest (2.85 g kg^{-1}) with the supplementation treatment, compared to the NRC recommended diet of 3.5 g kg^{-1} Pi (i.e., 2.17 g kg^{-1}). Therefore, poultry were inefficient at utilizing feed P, excreting 0.48 g day^{-1} and well over 70% of feed *m*IHP even with dietary phosphohydrolases.

Swine do not produce phosphohydrolase enzymes to break down *m*IHP in the ingested feed and would excrete most of this source of P, if not for the supplementation of microbial phosphohydrolases (Cromwell et al. 1993; Powers et al. 2006). The use of exogenous phosphohydrolases can lower P excretion by about 30% (Jongbloed et al. 1992; Cromwell et al. 1993; Kemme et al. 1997; Adeola et al. 2004), limiting P excretion to between 20 and 55 g P day^{-1} (ASAE 2006). However, inclusion of dietary phosphohydrolases increased the proportion of fecal total P that was water-soluble, for example, from 55 to 59% of fecal total P (Powers et al. 2006). Thus, the practice may increase the assimilation efficiency of feed P by livestock and poultry, although it may inadvertently increase the risk of loss of water-soluble P from the site of manure application or storage stockpiles via runoff following rainfall or irrigation.

16.3 Manure P Forms and Management-Induced Biotransformations

Two major groups of manure management systems can be distinguished (1) systems to collect and store liquid manure suspensions and wastewaters and (2) systems to manage dry solid manures. Each system with their unique features adds to the complexity of the transformations of manure-borne nutrients. Similarities and differences in P transformations based on manure physical forms are discussed together to improve our understanding of the linkages between manure P speciation and potential loss pathways from major confined animal production systems.

16.3.1 Transformations of P in Semisolid and Liquid Manure Management Systems

To characterize the biotransformation processes and fate of P forms in manure, their relationship to P forms that were present in the feed must be re-examined, as well as the environment in which the manure was excreted, collected, and stored. In a small group of commercial dairy farms, Toor et al. (2005) reported that fecal samples contained on average 62% of the total P as Pi, 27% as phosphomonoesters, and 9% as phosphodiesters, where the rations contained 55% of total P as Pi, 41% as phosphomonoesters, and 5% as phosphodiesters. These chemical forms were excreted in feces, along with phosphonates that can be traced back to rumen microbes. It appears that the three farms that used high levels of dietary P (4.8–5.3 g P kg^{-1}) had cattle excreting higher fecal concentrations of *m*IHP (1.6–2.3 g P kg^{-1}) than the other three farms feeding their cattle rations containing 3.6–4.0 g P kg^{-1} (0.8–1.1 g P kg^{-1}). In excreta samples collected from distinctively different animal production systems (i.e., a confined production system, a grazing system, or a hybrid system with partial confinement and grazing for dairy cattle production), a large but variable proportion of fecal total P was present as Pi (25–68%) when Pi also made up a higher percentage of the total P in the feed (46–70%) (McDowell et al. 2008). The proportion of fecal *m*IHP declined, but decreased less in production systems feeding mixed rations with a high Pi content.

These studies and others (e.g., Knowlton et al. 2001; Dou et al. 2002) have reinforced the notion that P forms in animal manures are mostly inorganic forms, primarily because Pi is added liberally to the ration. Uncertainties in the exact composition of inorganic and organic P forms of feed ingredients, and gross generalizations used in estimating organic P availability, often caused the producer to use extra inexpensive Pi supplement in the ration as insurance against losses in animal productivity (CAST 1996, 2002; Karn 2001; Pew Commission IFAPS 2008). The supplement is highly soluble, and the excess is expelled in the animal's excreta. Thus, for all practical purposes, manure is often managed and land applied as if it contains only Pi. Widespread efforts have been expended on assessing the water-extractable Pi content of manures (Wolf et al. 2005) and in developing practices for lowering soluble P concentration in manures with P-immobilizing additives (Dao 1999; Miles et al. 2003). Land application of P-enriched manure has often been linked to temporary increases in water-extractable P (WEP) in runoff from treated fields, thus threatening to impair the water quality of nearby aquatic ecosystems (Pierson et al. 2001; Toor et al. 2003; Green et al. 2007; Dao et al. 2008). Patterns of manure P release have been quantitatively described by a log-normal distribution function, i.e., the released P concentration profile was shaped as an asymmetric peak, skewed to the left (Dao 1999; Dao and Cavigelli, 2003; Dao et al. 2008).

Manure P, however, includes many forms other than the familiar H_xPO_4, where x is 0, 1, or 2. Forms include *m*IHP and its degradation intermediates (i.e., inositol mono-, di-, tri-, tetra-, and pentaphosphates), and phosphodiesters (i.e., nucleic acids, and phospholipids) (Koopmans et al. 2003; Turner 2004; Jayasundera et al. 2005; McDowell et al. 2008; Fuentes et al. 2009). To assess conditions on the farm, Dao et al. (2006) collected 107 samples of dairy manure suspensions from storage structures on working dairy farms across five states of the northeastern USA. The manures showed a wide range of total P (i.e., 3–20 g kg^{-1}), and there were outliers that exceeded 33 g kg^{-1} in total P (Fig. 16.2). The study differed from the published literature in that water-extractable P (WEP) did not make up such a large proportion of manure suspensions, in fact, ranging only between 11 and 20% of the manure, and in that most of the manure P was associated with the colloidal (>0.1 μm) and larger particulate fraction (Dao et al. 2008). More importantly, the results showed that dairy manure contained a wide range of concentrations of enzyme-labile organic P. These forms were either derived from the feed ingredients that were not assimilated by the cattle (Dao 2003, 2004a, 2007), or were biologically synthesized during storage (Dao and Schwartz 2010).

Total P and WEP concentrations varied considerably with sampling location and reflected the high variability of management practices, manure storage conditions, and manure age between these dairy farms, as illustrated in Fig. 16.2 and Table 16.1. These two P forms were weakly correlated ($r^2 = 0.29$) (Fig. 16.3). These results suggested that the solubility of phosphates and some organic P in the manure solution phase was not exceeded in a complex manure suspension, which exhibited a wide range of electrochemical properties and suspended solid content. Solubility and speciation of P in such a complex solution phase are a function of a number of factors that include valency of the counterions for the phosphate species, chelate stability, ligand exchange, pH of medium, and dissociation equilibria, as detailed in Dao (2007). Although manure WEP content can be affected by the nature and amount of dietary Pi (as previously discussed), the solution-phase chemistry of the

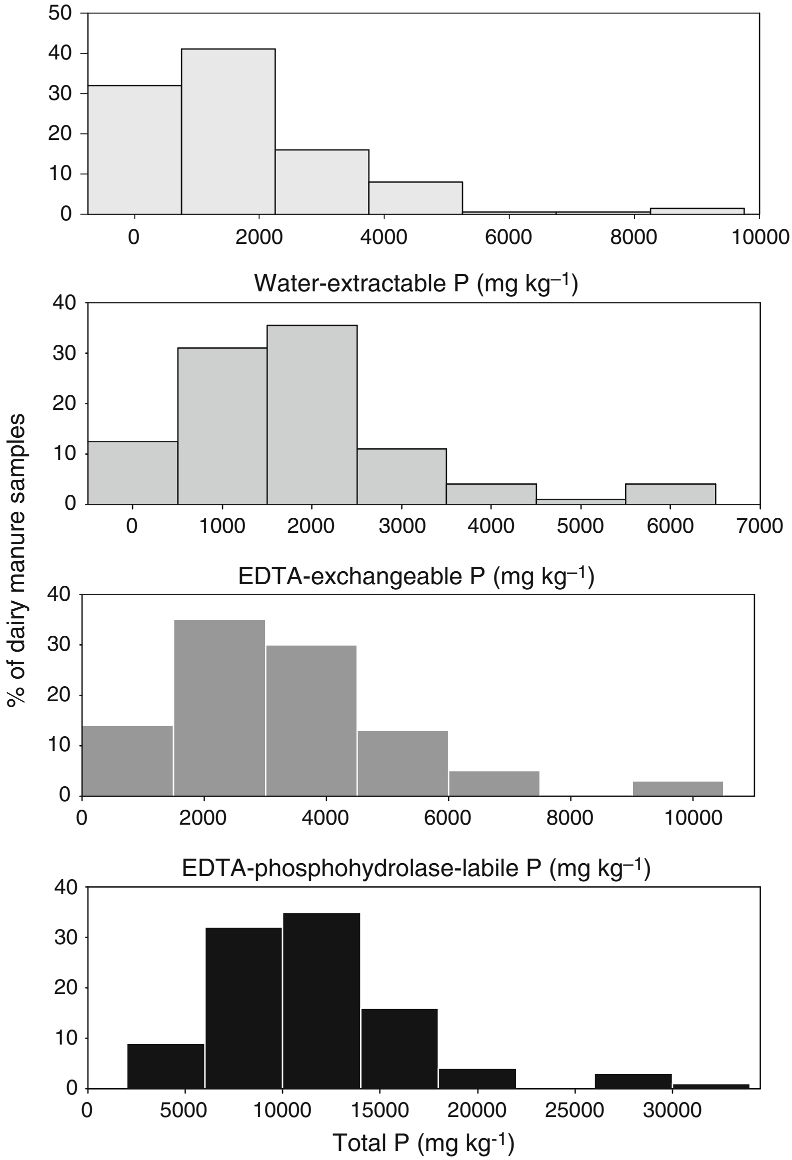

Fig. 16.2 Frequency distributions of bioactive P and total P concentrations in 107 manure suspensions collected from dairy farms across five states of the northeastern USA (adapted from Dao et al. 2006)

external environment where manure was deposited or stored (e.g., pH) appeared to be an equally important factor (Dao et al. 2006; Dao 2007, 2010).

An additional 15 (+/−8%) of manure total P was desorbable as Pi by a ligand-exchange process (shown as EDTA-exchangeable P, EEPi, in Fig. 16.2 and

Table 16.1 Mean extractability of three inorganic and enzyme-labile P fractions within groups of dairy manures varying in total P contents collected from dairy farms across five states of the northeastern USA

Manure total P range (g kg^{-1})	Number of observations	Manure P forms		
		WEP	EEPi	EDTA-PHP
		(Fraction of manure total P, g g^{-1})		
3–8	20	0.200	0.141	0.294
8–12	44	0.172	0.151	0.282
12–16	26	0.131	0.136	0.272
16–20	11	0.137	0.162	0.289
20–32	6	0.108	0.121	0.300
$LSD_{0.05}$	–	0.125	0.062	0.073

WEP water-extractable P, *EEPi* inorganic EDTA-exchangeable P, *EDTA-PHP* EDTA-exchangeable phosphohydrolase-labile P, $LSD_{0.05}$ least significant difference at $P=0.05$
Adapted from Dao et al. 2006

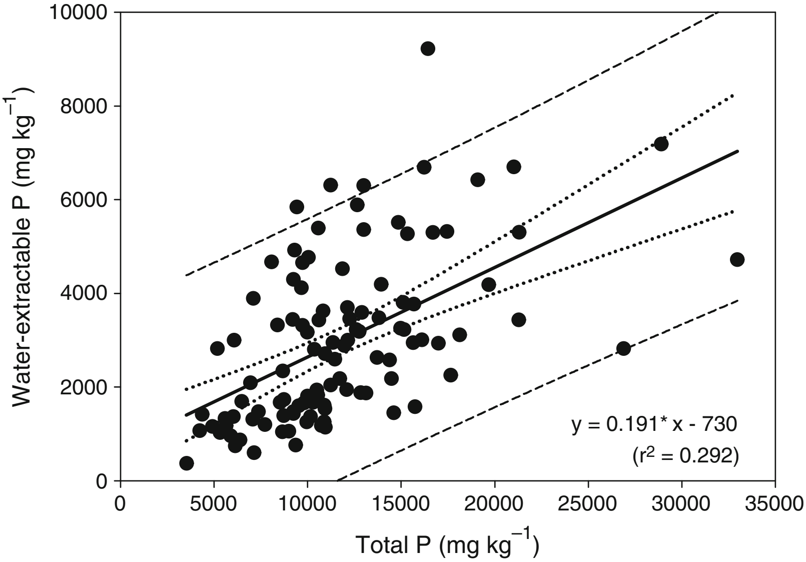

Fig. 16.3 Relationship between WEP and total P concentrations in manure suspensions collected from 107 dairy farms across five states of the northeastern USA. *Dotted lines* represent 95% confidence intervals for predicted values of WEP and *dashed lines* represent the prediction 95% confidence intervals. *Solid line* is best fit (Dao et al. 2006)

Table 16.1). Adding a small amount of the ligand EDTA to the water extractant enhanced the mobilization of this pool of complexed Pi in the manures. Total extractable Ca^{2+} in the EDTA-extracting solution was correlated to EEPi concentration. A slightly stronger relationship existed between these EEPi forms and the sum of Ca^{2+} and Mg^{2+}. The linear relationship suggested that primary forms of the EEPi were derived from Ca and Mg phosphates that are bound to the suspended manure solids.

The variability in feed P composition is exacerbated by the variability in P intake, retention, and assimilation by the animal. The net results are highly variable manure organic P contents. The net ligand-exchangeable phosphohydrolase-labile P (EDTA-PHP) content of all samples of the manure set averaged 32 (+/−16%) of manure total P of this heterogeneous collection of dairy manures. These results confirmed the presence of organic P substrates that include *m*IHP. Complexation with polyvalent cations was previously shown capable of inhibiting *m*IHP dephosphorylation and would explain the excretion and presence of intact *m*IHP in manure of ruminant livestock (Dao 2004a; Toor et al. 2005; Jayasundera et al. 2005). Table 16.1 summarizes the extractability and proportion of dairy manure P forms as a function of total P content of this collection of manure samples. In spite of the heterogeneity of the manure set, these results suggested a marked consistent extraction efficiency of bioactive P forms in all five manure groups, except for WEP as previously discussed. Manure organic P forms are hydrolyzed to yield Pi by endogenous phosphohydrolases in the stored manure slurries, just as in the long-term incubation-fractionation study of fresh dairy cattle excreta conducted by Dao and Schwartz (2010). To give further support to the occurrence of a substantial organic P pool in ruminant manures, Fuentes et al. (2009) observed the activity of phosphohydrolases on fecal *m*IHP during the aerobic degradation of dairy cattle feces over the initial 40-day period following excretion. Dominant groups of bacteria that produced the phytate-degrading enzymes were identified as *Enterobacter* and *Rahnella* species.

During storage, the concurrent transformations of manure C and N in such a microbially active medium also influence the accumulation and turnover of WEP in manures (Dao and Schwartz 2010). In a study of P transformations in dairy manures containing C and P in proportions ranging between 83:1 and 130:1, these researchers have shown that the C load of dairy manure suspensions controls the rate of mineralization of manure C and organic P under non-limiting N conditions. The mineralization of organic P forms occurs in all manure C:P treatments, in spite of initial Pi levels that range from 1,200 to 2,250 mg kg^{-1}. The rate of WEP accumulation follows a first-order kinetic model, and is largest at wide C:P conditions (130:1) and can be up to 156% faster than in narrow C:P manure suspensions. Water-extractable C is positively correlated to manure N:P, particularly at narrow C:P (i.e., non-limiting P conditions). These findings have important implications for dairy slurry management in confined animal production operations. Manure is collected and stored in a central location, undergoing biological transformations before disposal. The manures contain bacterial and fungal populations in sufficient numbers to secrete and release extracellular phosphohydrolases and oxidative enzymes to degrade organic C and N substrates. Wide C:P enhances organic P dephosphorylation and N immobilization, given the biological need to assimilate C substrates and obtain metabolic energy for cell growth and development of manure-borne microorganisms. Manure handling and storage conditions can be managed to minimize gaseous C losses (which reduce enrichment of nutrients in manures) and to moderate the transformation of insoluble complexed Pi and organic P forms to soluble bioactive ones (Dao 2007, 2010; Dao and Schwartz 2010).

It would appear that the mineralization of organic P during storage and the production of Pi enhances the availability of manure P and its value as a biofertilizer in plant production systems; however, a well-cured manure may not be a desirable P source from an environmental perspective. High-available-P manure would be more prone to loss via convective transport, should a plant not be present to absorb and assimilate the soluble P. Maintaining a stable pool of organic P forms in stored manure would provide a slow-release effect of delaying the availability of the organic P fraction to meet the continual need of the plant during the growing season. The potential drawback of this approach, as in managing manure organic N, resides in our inability to accurately predict the rate of dephosphorylation under various soils and climatic conditions. In any case, the phosphorylation–dephosphorylation (i.e., immobilization–mineralization) is a dynamic equilibrium phenomenon, following a biochemical first-order kinetic law. Therefore, P forms in manure will continually be a mixture of Pi and organic P, as observed in a year-long incubation-fractionation study of dairy manure (Dao and Schwartz 2010). In addition, the conservation of the manure C and nutrients under aerobic fermentation conditions commonly found in on-farm liquid manure storage structures would minimize atmospheric emissions of harmful greenhouse gases, and mitigate the confined animal feeding operations' neighbor health concerns associated with current methods of manure management (Schiffman et al. 1995; Pew Commission IFAPS 2008; USEPA 2008b).

16.3.1.1 Loss Pathways of P in Liquid Manure Management Systems

Losses of P occur primarily via its transport in rainwater or snowmelt running off from animal housing, open surfaces of animal pens, manure storage areas, and/or leaching from slurry-amended fields and grasslands (Turner and Haygarth 2000; Toor et al. 2003; Koopmans et al. 2003; Green et al. 2007; Dao et al. 2008). The animal wastewaters and runoff are channeled to detention ponds or large lagoons for settling and periodic cleanup of the sediments upon evaporation. Seepage losses and overflows from manure storage structures and lagoons can contribute to P lost to the environment. Manure slurries stored in underground pits undergo constant mineralization, while Pi forms are being re-immobilized in microbial tissues. These processes continue when the effluent is flushed to an outside detention pond or lagoon. Although notorious for emitting ammonia and other greenhouse gases and malodorous compounds, earthen lagoons are also sources of losses to the subsurface via seepage and failure of the clay liner (Ham and DeSutter 1999; DeSutter et al. 2005). Coarse manure solids, particularly spilled feeds, and bedding materials are mechanically separated before the wastewater enters the lagoon. However, typical mechanical separation efficiencies have ranged from 5 to 30% of particulate removal, which resulted in rapid loss of capacity in these manure storage structures. Chemical coagulants used in the drinking water treatment industry have been shown to improve the separation and removal of particulate P and organic matter from the wastewaters, thus resulting in the transport and reuse of a relatively smaller and lighter volume of nutrient-enriched solids as a soil amendment or as feedstock for the production of bioenergy and chars (Zhang and Lei 1998; Dao and Daniel 2002; Sørensen and Thomsen 2005). The heating of plant materials such as manure solids or crop residues to moderate temperatures to produce a charcoal-like material (called char) that can be incorporated into soil to more permanently sequester the C is well beyond the scope of this review. The reader is referred to selected recent works on the role of chars in soil C sequestration and bioenergy production (Laird 2008; Ro et al. 2009). Much remains to be learned about the potential availability of P forms contained within these materials, depending upon how they were generated (Dao, personal communication).

Anaerobic digestion, a fermentation process in which microorganisms break down organic matter in the absence of oxygen, is an alternative method for treating dairy or swine manure slurries. Biological nutrient reduction technology is used to concentrate nutrients from dilute wastewaters, and generates biogas as a source of renewable energy (Hill 1984; Møller et al. 2004). Bacterial decomposers and methanogens convert the organic matter into methane, carbon dioxide, and low molecular weight organic acids under anaerobic conditions. The residual solids typically contain mineral and complex organic compounds and are rich in P and N, particularly ammonia. Lignin and other residual macromolecules are available for degradation by aerobic microorganisms and for recycling in agricultural soils as previously mentioned. The digester's effluent contains a high concentration of Pi and an elevated level of chemical and biochemical oxygen demand, and must therefore be aerated to reduce the reactivity of the wastewater prior to land application.

16.3.2 Transformations of P in Dry Solid Manure Management

16.3.2.1 Beef Cattle and Dry Manure Management

On open feedlots, 10.5×10^6 Mg of manure solids were generated by the 11.6 million head of beef cattle on feed across the USA in 2007 (NASS 2009). In semi-arid climates, such as the Panhandle of Oklahoma,Texas, or southern Alberta, Canada, the manure in feeding pens is scraped every 4–6 months, and stored in huge uncovered piles. This has resulted in intensive land applications in the immediate vicinity of the feedlots because of the high cost of transporting such material for distances greater than 30 km. Otherwise, the manure is placed in stockpiles that dot the region to contain nutrient escapes to the surrounding area, because transport and recycling of manure in plant production becomes cost-prohibitive, in comparison to nutrient-dense fertilizers. Mineralization of labile C fractions and P-containing organic matter results in an enrichment of P in the stockpiled manure (Hao et al. 2001; Dao and Cavigelli 2003).

Composition and rate of P released from stockpiled and composted manure solids have been quantified in numerous studies (Barnett 1994; Dao 1999; Larney and Hao 2007). Dao and Cavigelli (2003) observed initial large flushes of CO_2–C, exceeding 100 mg kg^{-1} day^{-1}, in stockpiled and composted cattle manure and manure-amended soils. Net mineralizable C, N, and WEP flux densities were log-normally distributed during the incubation period. Significant nonlinear relationships exist between cumulative CO_2–C and inorganic N and between cumulative CO_2–C and WEP and suggest the presence of multiple organic substrate pools of variable stability, as shown in Fig. 16.4.

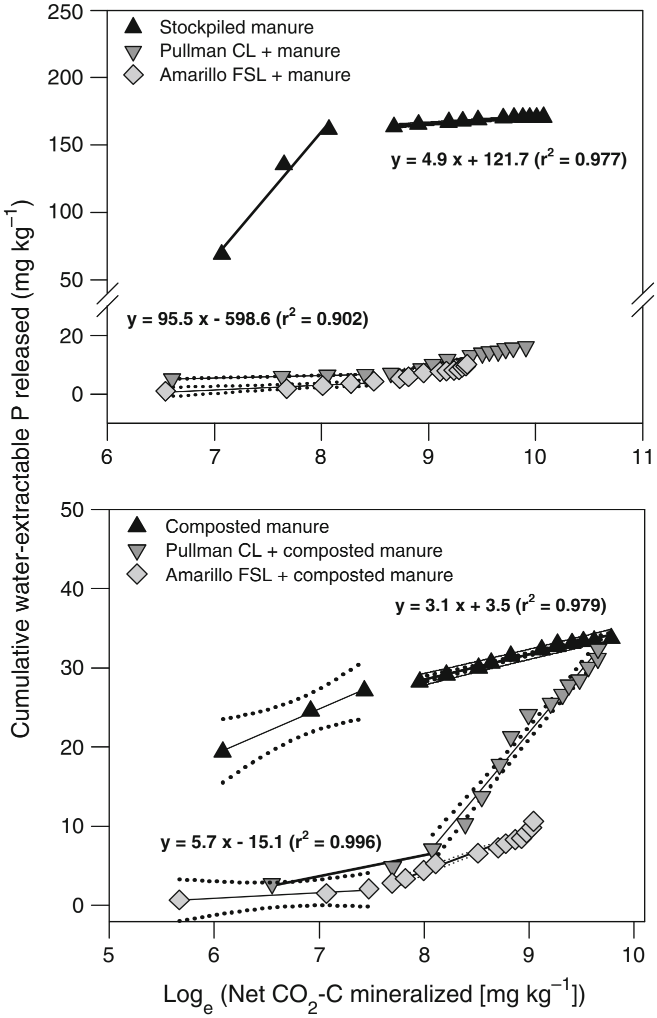

Fig. 16.4 Relationships between WEP released and cumulative CO_2–C evolved from stockpiled manure (*top*) and composted manure (*bottom*) and manure-amended Amarillo and Pullman soils during a 322-day incubation at 35°C. *Dashed lines* represent the 95% confidence limits and *solid lines* the best fit (adapted from Dao and Cavigelli 2003)

16.3.2.2 Poultry Manure and Litter Management

In a study of 87 samples of poultry litter collected across two major regions of industrial poultry production in the USA, an even larger fraction of poultry manure total P in comparison to that of cattle manure, was made up of organic P species, which were susceptible to enzymatic hydrolysis to release Pi, just as previously discussed in Sect. 16.3.1 (Dao and Zhang 2007; Dao and Hoang 2008). From a typical dietary concentration of 3–4 g P kg^{-1}, the variability in litter management practices across farms and producing regions resulted in highly enriched and variable WEP and bioactive P composition (Fig. 16.5). Overall, the WEP fraction and total bioactive P (i.e., WEP + EEP$_i$ + EDTA-PHP) fraction were proportional to the total P content of the litter samples, representing about 24% and over 60% of the litter total P, respectively. In addition, the total P concentration distribution suggested that approximately one-fifth of the litter samples had elevated total P levels that exceeded 21 g kg^{-1} and WEP concentrations $\geq$5 g kg^{-1}.

The all-inclusive total bioactive P fraction in broiler litter also showed a high correlation to Ca concentration or slightly higher correlation to the sum of Ca and Mg concentrations (Fig. 16.6) (Dao and Zhang 2007). Most of the inorganic and organic P forms were complexed with polyvalent counterions but were exchange-able with EDTA and similar ligands. Organic phosphomonoesters or organic enzyme-labile P occur in significant concentrations in poultry litter at current diet formulation and feeding regimes practiced on farms in the Maryland Eastern Shore

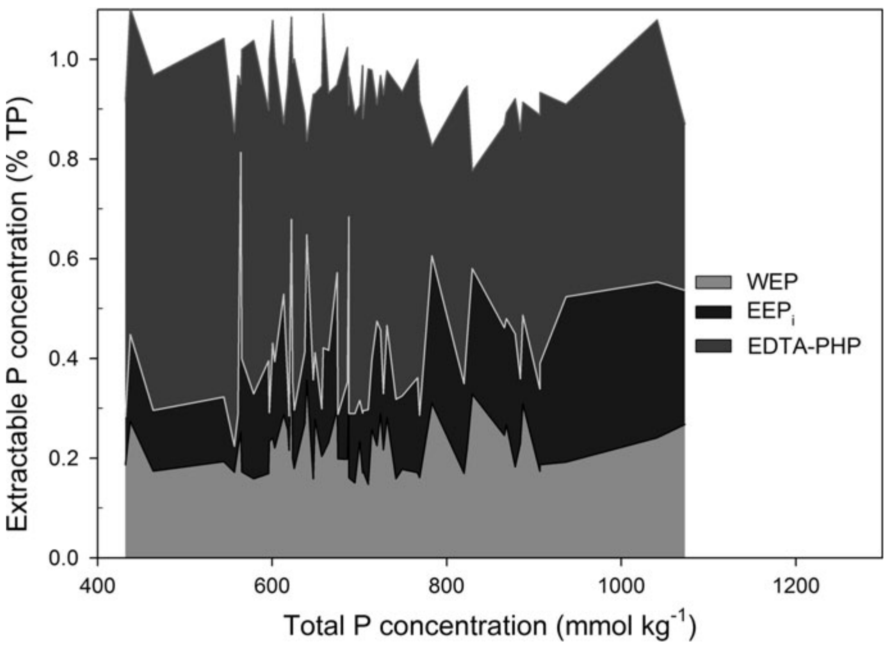

Fig. 16.5 Extractable bioactive P fractions in 87 poultry litter samples (Dao and Hoang 2008)

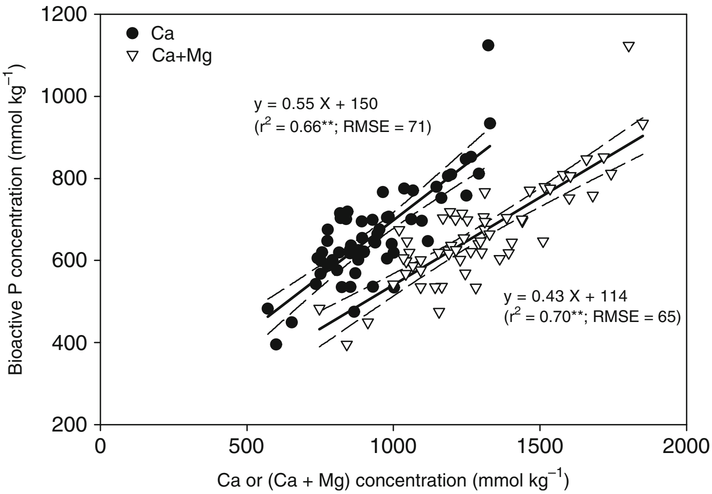

Fig. 16.6 Extractable calcium–magnesium–P relationships in 87 poultry litter samples. *Dashed lines* represent the 95% confidence limits and *solid lines* the best fit (Dao and Hoang 2008)

and the Arkansas–Oklahoma region of the USA Because of the inorganic–organic P composition of poultry litter, there are serious consequences of current feeding management practices and land-based litter options to the quality of the environment. The reduction in dietary P in feed to essential levels must continue to decrease P excretion. Recent research has demonstrated that organic species are highly dynamic (Dao et al. 2005; Dao and Schwartz 2010) and hence potentially biologically active in the environment, particularly in a carbon-rich environment. Previous research has shown internal rearrangement and interpool transfers over time that affected the mineralization of the enzyme-labile organic P pool in manure and manure-amended field soils (Dao 1999, 2004b; Dao et al. 2001, 2005). Such transformations have been observed during the composting of livestock manure and poultry litter. These management-induced alterations of P forms in manure include chemical shifts from the WEP and ligand-exchangeable EEPi fractions to the formation of more stable calcium- and iron-associated phosphates (Traoré et al. 1999; Dao et al. 2001). The changes in P exchangeability occur during the early stage of the composting process, i.e., during the initial intense period of organic matter mineralization (Traoré et al. 1999; Dao 1999; Dao and Schwartz 2010).

16.3.3 Loss Pathways of P in Solid Manure Management Systems

16.3.3.1 Open Feedlots and Dry Cattle and Poultry Manure Stockpiles

On large cattle feedlots, manure solids in animal pens are removed and stacked in the open to dry and, in essence, undergo a slow aerobic fermentation. There is a progressive reduction in volume over the years of stockpiling and containment of manure-borne pollutants in accordance with the conditions of the permit of operation (USEPA 2008b). In large broiler houses, the litter, which is a mixture of bird excreta and bedding materials (i.e., wood chips, rice hulls, etc.), is scrapped every two to three cycles of production a year. In egg-layer housing, manure is deposited on floors equipped with a conveyer-belt transport system to remove it from the poultry house. A typical commercial egg-laying operation can generate 70 Mg day^{-1} of manure, which must be removed daily to be stockpiled nearby. Current regulations require a water-impermeable cover of manure piles to keep rainfall away from the stockpile in sub-humid and humid climatic regions. Loss of concentrated "liquor" from the internal drainage of covered piles of high-moisture manure or poultry litter must also be contained to prevent any discharge from escaping off-site, contaminating wellhead areas, or reaching nearby streams (USEPA 2008b).

16.3.3.2 Losses of P from Grazed Lands

In a grazingland-based system, the P extracted from the forage is returned to the soil from which the forage was grown, except for the 2–5% that leaves the cycle in exported meat products and/or milk. Approximately 75–90% of the nutrients consumed by grazing animals are cycled back to the soil in urine and primarily in feces, which accounts for over 70% of the total excreted P (Betteridge et al. 1986). However, offsite loss of P is known to occur via erosional processes affecting the soil subject to grazing animal traction (Nash et al. 2000; Haynes and Williams 1993; Blackshaw and Blackshaw 1994). By selective grazing, livestock produce a highly heterogeneous distribution of plant species and, consequently, a spatially variable distribution of excreta. Manure nutrients are also concentrated in certain small areas of the pastures where the animals gather to drink, rest, and get shade or shelter from the wind during cold weather. Livestock also cause substantial increases in soil bulk density, which restricts water, air, and plant root penetration, and thereby restricts vegetation growth (Dao et al. 1994; Drewry 2006; Bilotta et al. 2007). Reduced water infiltration leads to increased overland flow, which varies with time of the year and with precipitation frequency and intensity (Nash et al. 2000; McDowell et al. 2006). In alpine meadows, losses of P and other nutrients occur primarily through catastrophic events because these areas are prone to disturbance through soil erosion, landslides, and avalanches (Jewell et al. 2007). Grazing livestock with access to streams and waterways can drop manure P and other contaminants directly into the water; they can damage stream banks and accelerate the loss of vegetation in buffer zones along the streams. However, grazingland-based systems contribute relatively little to the P-induced impairment of surface waters, provided that best grazing management practices, soil erosion control measures, and riparian buffer zones around waterways are used.

16.3.3.3 Loss of P from Land-Applied Manure in Mixed Crop–Livestock Systems

Where plant and animal production coexist on a farm, manure and bedding materials are recycled back to the land to improve the fertility and tilth of the soil for plant production. For all practical purposes, animal manure is managed and land-applied as if manure contains only Pi. It is used to reduce reliance on expensive inorganic fertilizers. However, manure inorganic and organic P forms build up in the soil when applications are made to meet the N requirements of crops and forages, and also when P rates exceed P removal by plants. In a study conducted on a permanent orchardgrass–red clover stand, long-term additions of dairy manure increased total soil organic C, storing the manure C in the near-surface zone (Dao 2004b). Increases in total P, comprising enzyme-labile P as well as Pi (i.e., WEP and Mehlich 3-extractable P, i.e., plant-available P) fractions paralleled the increase in organic C. Added organic P also became increasingly resistant to enzymatic hydrolysis, explaining its preferential accumulation in these soils (Dao 2004b). Sorption mechanisms of *m*IHP and Pi have been postulated to include a binuclear surface complex and monodentate complexes, as summarized in a recent review (Dao 2010). Although Fe and Al hydroxides have a high affinity for Pi and phosphomonoesters, an increase in the desorption of these P forms is observed when polydentate ligands or organic complexing agents are present in the soil solution (Pavinato et al. 2010). Soluble Pi and easily exchangeable P forms that are embodied in WEP assays play an important role in plant nutrition, transfer and loss to runoff, and potential dispersal in the environment (Turner and Haygarth 2000; Toor et al. 2003; Dao 2004b; Dao et al. 2008; Green et al. 2007; Rao and Dao 2008). Green et al. (2007) showed that the concentration and mass distributions of P forms in runoff over time were log-normally distributed. The more inclusive total bioactive P fraction was found in greater concentration and mass than WEP. Peak concentrations and mass loads were greater from soil amended with 30 kg ha^{-1} of manure P than from untreated soil and from soil under orchardgrass–clover than from soil under soybean–wheat rotation, where the application rate was well within the annual P removal rate by these crops. Moreover, the correlations observed between soil bioactive P and P distribution in runoff suggested that runoff P forms were directly associated with soil available P fractions that were partly derived from enzyme-mediated processes in the soil.

Once the quantities and forms of P subject to transport off a particular field location are established, fate and transport models can be used to route P losses to water bodies to permit the assessment of the larger impacts on the watershed and surface water quality. Models can be either a simple approach, such as using the NRCS curve numbers to estimate runoff, or more complex ones such as surface water and sediment routing algorithms contained in fate and transport models (e.g., GLEAMS, AGNAP, or SWAT). Thus, tracking the runoff and soil leachate will reveal the mechanisms of the dispersal and convective transport of the various forms of P described in the previous paragraph.

16.4 Conclusions

Livestock and poultry production play a vital role in agricultural and rural communities of many developing and developed economies and goes well beyond the direct production of eggs, meat, and meat by-products. Whereas mixed plant–animal production systems strive to maintain a closed loop for nutrients used and nutrient outputs, the on-going intensification of industrial animal production has led to a regional imbalance in nutrient distribution. Their local buildup in livestock manures is the result of the geographical separation of the feed production and feed utilization sectors. An understanding of the fate and biological transformations of feed P inputs in an animal and the fraction excreted in manure largely depends upon the settings in which livestock are raised and fed. Recent studies have shown that, whether it is a monogastric or a ruminant species, livestock utilize feed P very inefficiently because they retain 30% or less of the ingested total P. A strong relationship exists between feed P intake and fecal forms and concentrations. As nutritionists and producers attempt to optimize diet formulations, unavoidable loss of dietary P remains large. Though Pi additions are reduced, feed organic P is not fully utilized, short of novel transgenic sources of low-*m*IHP grains. Use of dietary phosphohydrolases can improve feed digestibility and recovery of these organic forms, but the practice also increases the proportion of water-soluble P excreted in feces. Management-induced transformations of the excreted P further increase the risks of soluble P losses from either grassland-based systems or, especially, in the large confined animal feeding operations. Although manure P is influenced by the composition and amount of feed P intake, the chemistry of the solution phase and the solid matrix, as well as the microbiology of the external environment where manure P is deposited, become equally important in P turnover and environmental dispersal. In a nutrient-rich and microbially active environment, manure C and N also influence the fate of P in manure and manure-amended soils, and therefore influence the eventual protracted release of agricultural P in impaired watersheds.

Once manure is disposed on land, the bioactivity of manure P forms is highly dynamic and depends on interactions with the reactive surfaces of soil particles and on biologically mediated transformations. Thus, the contribution of biological processes to the release, transformations, and transport of organic P species must be well understood to develop sustainable management practices for recycling bionutrients in plant production systems. Biological tools that combine ligand exchange and enzyme-mediated mineralization of organic P can mimic plants and microorganisms in their ways of acquiring P from their environment; they can be valuable tools in the exploration and study of the environmental behavior of these organic P sources. They can also provide insights into the loss of P from animal production systems that can occur via its transport in rainwater or snowmelt running off animal housings, manure storage areas, and/or leaching from manure-amended fields, pastures, and rangelands. Off-site P transport is dominated by the runoff–erosion processes, where it is conveyed in dissolved forms or in association with suspended colloidal and larger particulate matter. These transport processes interact in a complex way with the composition of manure, the timing of manure applications, the hydrological characteristics of the application site, and the conservation practices in place. Together, these factors will ultimately determine the extent of P export.

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