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# Whole-farm phosphorus loss from grazing-based dairy farms

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ABSTRACT

Phosphorus (P) loss from agricultural farms persists as a water quality impairment issue. For dairy farms, P can be lost from cropland, pastures, and open-air lots. A need remains for user-friendly, readily applied, decision-support tools that simulate all areas of dairy farms, and determine their relative contribution to whole-farm P loss. We used the Snap Plus and APLE models to estimate annual P loss from all areas on four grazing-based dairy farms in Wisconsin, USA. At the whole-farm level, average annual P loss (kg ha$^{-1}$) from grazing-based dairy farms was low (0.5 to 1.8 kg ha$^{-1}$), generally because a significant portion of land was in well-vegetated pastures or hay and had low erosion. However, there were areas on the farms that represented sources of significant P loss. For cropland, the greatest P loss was from areas with exposed soil, typically for corn production, and especially on steeper sloping land. The farm areas with the greatest P loss were concentrated animal housing, including barnyards, and over-wintering and young-stock lots. These areas can represent from about 5% to almost 30% of total farm P loss, depending on lot management and P loss from other land uses. Our project builds on research to show that producer surveys can provide reliable management information to assess whole-farm P loss. It also shows that we can use models like RUSLE2, Snap-Plus, and APLE to rapidly and reliably estimate P loss in runoff from all areas on a dairy farm and identify critical P source areas in greatest need of alternative management.

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## 1. Introduction

Non-point source pollution of surface waters by phosphorus (P) can accelerate eutrophication and limit water use for drinking, recreation, and industry (Parris, 2011). Because P loss from farms via surface runoff has consistently been identified as a non-point pollution source (Bennett et al., 2001), there is a need to quickly and accurately quantify runoff P loss, identify the major sources of P loss, and develop management practices to reduce that loss. For dairy farms, possible sources of runoff P include cropland, grazed pastures, and open-air cattle holding areas such as feedlots, barnyards, exercise lots, or over-wintering lots. On such farms, it is necessary to conduct a whole-farm assessment and estimate the relative P loss from all of these sources to most effectively target remediation practices (McDowell and Nash, 2012; Monaghan et al., 2008).

At the whole-farm scale, quantifying runoff P loss from all sources on a dairy farm is impractical, and arguably impossible, given the number of areas to monitor, the expense, and the time required to monitor an appropriate duration of weather. Studies that attempt to attribute P loss to specific areas on dairy farms may measure P loss at a watershed outlet and then use computer simulation models to assess which land uses represent the greatest source of P (Easton et al., 2009; Easton et al., 2008; Rao et al., 2009). Such agricultural P loss models can generally be grouped into two categories. The first group consists of highly parameterized, daily time-step, process-based models like the farm-scale Integrated Farm Systems Model (IFSM) (Sedorovich et al., 2007), or field to watershed-scale models like the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), Agricultural Policy/Environmental eXtender (APEX) (Gassman et al., 2010), or Variable Source Loading Function (VSLF)(Easton et al., 2009). The second group is more user-friendly, seasonal to annual time-step models, such as the Wisconsin P Index (WI PI) (Good et al., 2012), that are a combination of process-based and empirical P loss equations. However, tools like SWAT, APEX, or VSLF are too complex or require too much input and calibration data to be readily and widely used by the farm advisors or government agency personnel likely to be developing farm management plans. Furthermore, currently available versions of SWAT and APEX do not simulate manure or dung on the soil surface, which precludes adequate simulation of P loss from surface-applied manure on cropland, and have also not been well tested for P loss from barnyards and open-air lots. Tools like the WI PI have been developed to be much more user-friendly and readily applied, and may appropriately simulate P loss from surface manure, but have not been tested for grazed pastures or barnyards and open-air lots. Similar limitations are true for IFSM. The challenge is thus to apply a tool or combination of tools that

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appropriately simulate the physical conditions and management present on all areas of dairy farms, but yet remain user-friendly enough so they can be readily applied with easily obtainable information and without calibration.

The Annual P Loss Estimator (APLE) is a model that estimates annual soil P cycling and P loss in surface runoff and erosion at the field scale, and it has been extensively tested (Vadas et al., 2009)(Vadas et al., 2012). It has also been recently adapted and tested for P loss in runoff from cattle-grazed pastures and open-air cattle lots (Vadas et al., 2014; Vadas et al., 2015). APLE can therefore be used to estimate whole-farm P loss from cattle farms and identify areas on the farm that represent the greatest risk of P loss, but has not yet been applied to real-world farm situations. The objective of our project was to demonstrate how a user-friendly model like APLE can be readily used to estimate annual P loss from all areas on four grazing-based dairy farms in Wisconsin, USA and to determine the relative contribution of cropland, pastures, and lots to whole-farm P loss. Because APLE has been well tested in previous projects, this project represents a demonstration of model application rather than model verification.

## 2. Materials and methods

### 2.1. APLE description

We used two versions of the APLE model for this project. For cropped fields and pastures, we used APLE, which is a spreadsheet model that runs on an annual time-step and simulates field-scale, sediment bound and dissolved P loss in surface runoff. APLE has been well tested for its ability to reliably estimate P loss in runoff for fields with machine-applied manure, grazing cattle, and for soil P cycling, as well as estimates of uncertainty in results (Bolster and Vadas, 2013; Bolster et al., 2012; Vadas et al., 2014; Vadas et al., 2007; Vadas et al., 2012). APLE is available to download at (http://ars.usda.gov/Services/docs.htm?docid=21763), along with Theoretical Documentation and a user's manual that describes the model in detail. For barnyards, exercise, and over-winter lots, we used a modified version of the model called APLE-Lots. APLE-Lots is also a spreadsheet model that runs on an annual time-step and simulates sediment bound and dissolved P loss in surface runoff. APLE-Lots has been tested for paved and unvegetated, earthen cattle barnyards and feedlots (Vadas et al., 2015). Both APLE and APLE-Lots are designed to be user-friendly and use as little input data as possible, and thus estimate only an annual loss of P. They are not designed to be spatially integrated, or to investigate hydrological processes at finer time-steps (e.g., daily or storm-based) or the timing of management practices (e.g., incidental loss of manure P soon after spreading). Other models may be better suited for these purposes (Vadas et al., 2007; Vadas et al., 2011). The models are also designed to simulate edge-of-field or edge-of-lot P loss and do no simulate connection of delivery to local streams.

Pertinent APLE cropland and pasture input data for this project included topsoil properties (Mehlich-3 soil test P, clay, organic matter); surface area of the field; annual precipitation, runoff, and erosion; number of annual cattle days in the field; and information for manure and fertilizer P application. APLE estimates annual sediment P loss (kg $ha^{-1}$) in runoff based on user-defined annual erosion and model-estimated soil total P content. APLE estimates dissolved inorganic P loss in runoff (kg $ha^{-1}$) from soil based on user-defined annual runoff and soil P content. In APLE, manure can be applied in both a solid or liquid form, and fertilizer in a solid form. If tillage occurs, APLE incorporates any applied manure or fertilizer according to user-specified depths of incorporation and percentages of applied P that are incorporated. The model estimates annual dissolved P loss directly from any manure or fertilizer remaining on the soil surface based on user-defined annual runoff and empirical factors based on the ratio of annual runoff to annual precipitation. For grazing in APLE, a user specifies how many dairy or beef cattle graze a pasture during the year. This adds dung P to the pasture and increases the amount of dissolved P loss in runoff the same as for machine-applied manure, but accounts for the fact that dung does not cover the entire field area and not all of the annual precipitation interacts with it to contribute to runoff P.

Vadas et al. (2015) developed APLE-Lots to estimate P loss from cattle barnyards and other lots. Barnyards and lots loosely refer to outdoor areas that are used for holding, exercising, or over-wintering cattle and do not provide significant forage intake from growing vegetation. Barnyards refer to smaller lots adjacent to barns that are permanently unvegetated or concrete/paved, have high stocking densities, and may be regularly cleaned because of heavy manure accumulation. These may be areas where cows are held while being milked or while barns are cleaned. Open-air lots refer to areas that typically have lower stocking densities than barnyards, may be vegetated or partially vegetated, from which manure is typically not collected, and which may have less erosion and P loss in runoff than barnyards (Powell et al., 2005; Vadas and Powell, 2013). These lots may be used to house non-lactating cattle, to exercise cattle typically housed in barns, or in colder climates to hold cattle for several months over the winter. They may typically be larger than barnyards and not necessarily near barns.

APLE-Lots requires a user-specified depth of annual precipitation, which is used to develop a dataset of annual precipitation events, from which annual runoff is estimated with the NRCS Curve Number (CN) approach (USDA-SCS, 1972). The model estimates CN with empirical equations that are based on user-specified annual precipitation, as well as lot surface type and vegetative cover. APLE-Lots then estimates annual sediment loss (Mg $ha^{-1}$) from a lot using an empirical equation relating sediment loss and annual runoff. For earthen lots, coefficients in that equation vary as a function of vegetative cover so sediment loss decreases as cover increases.

The APLE-Lots model estimates annual sediment-bound P loss based on annual sediment loss and sediment P content. For paved or concrete barnyards, the sediment P content is the same as manure P content. On earthen barnyards or lots, the model can reduce the sediment P content based on how much of the lot is covered by manure to represent the idea that sediment is a mix of both manure and soil and will have a lesser P content. The model also reduces sediment P loss in runoff to account for the frequency of lot cleaning based on how much of the lot is covered by manure between user-specified cleanings.

The APLE-Lots model uses the approach described in Vadas et al. (2007)and Vadas et al. (2014) to estimate dissolved P loss in runoff from manure on the lot surface. For each event in the precipitation dataset, the model estimates dissolved P leached from manure on the lot surface based on precipitation and the amount of manure and its P content. If runoff occurs, some leached manure P is transferred to runoff using empirical factors based on the ratio of runoff to precipitation. Three important variables for these calculations are manure P content, manure mass, and manure cover area, which account for how much manure cattle deposit and how often a lot is cleaned.

### 2.2. Simulating whole-farm P loss from grazing-based dairy farms

We gathered management information from four Wisconsin grazing-based dairy farms as input data needed to use APLE and APLE-Lots to conduct whole-farm P loss assessments. Most dairy production in the region is confinement-based farms where cows are kept in barns; feed is mostly alfalfa and corn-based, is from home-grown or imported sources, and is stored on-farm; and manure from barns is collected, stored, and redistributed onto local cropland. Farm size can range from <100 lactating cows to thousands of cows. Because this research was part of a larger project that focused on grazing-based dairies, the farms in our study in general represent smaller operations that integrate grazing into their production, where lactating cows and other stock graze permanent pastures for six to eight months of the year, and are supplemented by home-grown or imported feeds. Manure