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Monitoring runoff from cattle-grazed pastures for a phosphorus loss quantification tool

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ABSTRACT

Nitrogen (N) and phosphorus (P) loss from agriculture persists as a water quality impairment issue. For dairy farms, nutrients can be lost from cropland, pastures, barnyards, and outdoor cattle lots. We monitored N and P loss in runoff from dairy and beef grazed pastures for two years in southwest Wisconsin, USA and tested the accuracy of the Annual P Loss Estimator (APLE) model to predict runoff P from pastures using study and literature data. About 3–10% of annual precipitation became runoff from the pastures, and sediment loss was very low due to well-established vegetation. Measured annual nutrient loss in runoff was also low, averaging 1.0 kg ha^{-1} for total P and 2.9 kg ha^{-1} for total N. Runoff sediment and particulate N and P concentrations were well related to each other and tended to be greater in rainfall-induced runoff than snowmelt runoff. Conversely, dissolved N and P runoff concentrations were greater in snowmelt runoff. APLE was able to reliably predict annual P loss in runoff, estimating that the average relative contribution to total pasture P loss was about 10% from fertilizer, 15% from soil dissolved P, 30% from dung, and 45% from soil erosion. Our study has increased the ability to develop reliable models for estimating the impact of cattle grazing pastures on nutrient runoff, which will be valuable in estimating whole-farm P loss from dairy production systems and identifying areas on dairy farms where P loss remediation should be targeted.

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1. Introduction

Non-point source pollution of surface waters by nitrogen (N) and phosphorus (P) can accelerate eutrophication and limit water use for drinking, recreation, and industry (Parris, 2011). Because N and P loss from agricultural systems 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 nutrient loss from farms, identify the major sources of farm loss, and develop management practices to reduce that loss. For cattle farms, possible sources of runoff N and P loss include cropland, grazed pastures, and outside cattle holding areas, such as feedlots, barnyards, exercise lots, or over-wintering lots. On such farms, it is necessary to estimate nutrient loss in runoff from all of these sources to effectively target remediation practices (McDowell and Nash, 2012).

There has been significant research conducted to monitor N and P loss in runoff from grazed pastures (Edwards et al., 2000; Halliwell et al., 2000; Nash et al., 2000; O'reagain et al., 2005; Haan et al., 2006; Owens and Shipitalo, 2006; Capece et al., 2007; McDowell et al., 2007; Dougherty et al., 2008). However, considerably less pasture runoff research has been conducted compared to nutrient loss from cultivated cropland, and most of it has been conducted in Australia, New Zealand, and the United Kingdom. In the U.S., only limited field-scale, natural precipitation, pasture runoff research have been conducted where the major source of nutrient addition is through grazing animals (Olness et al., 1975; Menzel et al., 1978; Chichester et al., 1979; Schepers and Francis, 1982; Owens and Shipitalo, 2006; Capece et al., 2007). The reason for this is unclear. It may be that relative to row crops, pastures constitute much fewer acres on cattle farms in areas where water quality impairment is a problem and are not seen as a major contributor to waterbody eutrophication, especially since pastures typically have less nutrient inputs and soil erosion than row crops. However, as the demand for improved water quality increases, the use of pastures and the associated decrease in nutrient loss through soil erosion may become a more attractive land use on cattle farms (Rotz et al., 2009). There is thus a need to document the potential water quality impact of cattle pastures and have tools to estimate this impact relative to other land uses on cattle farms.

As quantifying runoff nutrient loss from all sources on a cattle farm through physical monitoring is expensive and lengthy,

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simulation models can be a more rapid, cost effective ways to estimate N and P loss (Radcliffe et al., 2009). For P, quantitative agricultural loss models can generally be grouped into two categories. The first group is 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) or the Agricultural Policy/Environmental eXtender (APEX) (Gassman et al., 2010). The second group is more user-friendly, seasonal to annual time-step models, such as the Annual P Loss Estimator (APLE) (Vadas et al., 2009, 2012) and the Wisconsin P Index (WI PI) (Good et al., 2012), that are a combination of process-based and empirical P loss equations. However, all of these tools have shortcomings when simulating P loss via surface runoff from cattle-grazed pastures. The WI PI and APLE have been developed to estimate P loss from agricultural cropland, but have not been tested for grazed pastures; IFSM apparently does not simulate P loss from dung deposited during grazing; and 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 dung in pastures. Therefore, these tools should be updated to better simulate P loss from dairy farms in general and cattle-grazed pastures in particular. Vadas et al. (2011) recently developed a daily time step model for P loss from grazing cattle pastures that could be integrated into models like IFSM, SWAT, and APEX. Similar updates are needed for annual models like APLE and the WI PI.

The objectives of our project were to: (i) monitor N and P loss in runoff from beef and dairy-grazed pastures in southwest Wisconsin, USA, and (ii) use the runoff data, as well as data from published scientific literature, to test the ability of APLE to predict P loss in runoff from cattle-grazed pastures. The long-term goal of this research is to develop modeling tools that can estimate whole-farm P loss from dairy farms and appropriately target farm areas for P loss remediation. Assessing the pasture component of dairy farms is one step in that process.

2. Methods and materials

2.1. Pasture runoff monitoring

We established eight, hydrologically isolated basins ranging in size from 0.3 to 0.4 ha in an existing cattle pasture at the University of Wisconsin-Platteville Pioneer Farm (42.71°N, 90.39°W) (Fig. 1). The Pioneer Farm is a 174 ha production farm located in the unglaciated area of southwest Wisconsin in the Northern Mississippi Valley Loess Hills. The dominant soil is a moderately eroded Tama soil series (fine-silty, mixed, superactive, mesic Typic Argiudoll), with B and C slope classes. The runoff basins were oriented so that four were on a south-facing slope (5–8%) and four were on a north-facing slope (5–8%), with a ridge separating the two groups. The eight basins were within existing pastures grazed by beef and non-lactating dairy cattle, and were separated from each other either by the ridge at the upslope edge or by earthen berms. The southern four basins were within a 7.3 ha pasture grazed by beef cattle, and the northern four basins were within a 6.1 ha pasture grazed by non-lactating dairy cattle. Thus, the eight basins all received generally the same management. Cattle were given free access to the pastures starting in mid-May until mid-November, with daily numbers of dairy cattle ranging from 14 to 34 and beef cattle from 18 to 28. Annual stocking rates were approximately 2.7 animal units ha^{-1}, with one animal unit defined as a mature cow at about 450 kg. Excess pasture growth was cut for hay and baled, typically in mid-July. This management for non-lactating cattle is typical for this region, with cattle generally given access to pastures for grazing from early to mid spring until late fall, with supplemental feeding as needed. Outside of this period, cattle are housed off of pastures, typically in small, dedicated lots known as over-wintering areas.

Fig. 1. Aerial view of the field showing the location of the eight runoff basins within an existing cattle pasture.

We installed runoff collection systems at the outlet of each basin. Each system consisted of wooden wing walls that channeled surface runoff into an H-flume. Ultrasonic sensors (Automated Products Group IRU-5000) measured and logged (Campbell Scientific CR206) water stage in the flumes in one-minute intervals to estimate runoff volumes. Flow-paced composite runoff samples were collected from flumes using an automated sampler (ISCO 3700), with sampling frequency adjusted remotely for each event to ensure collection of representative samples for an entire event, such that samples were collected more frequently as flow increased. Samples were pumped into 1-L containers and collected within 24 h of the end of the runoff event. A discharge-weighted sample was then produced for each runoff event by calculating the percentage of the total runoff-event volume that each discrete sample represented, collecting appropriate aliquots from each discrete sample by using a churn splitter, and combining aliquots into one composite sample. Flow-compositing monitoring is a common procedure that reliably estimates pollutant loads for runoff events (Harmel and King, 2005).

The sampling system was inside a covered shelter and was equipped with radiant heaters to allow runoff collection year round. We measured daily rainfall with existing equipment at the Pioneer Farm, and obtained snowfall data from a weather station located ~35 km to the southwest of the field site. In this region, there is predominately frozen precipitation from December through March. Runoff from snowmelt and rain-on-snow events is typical throughout February and March and can account for a majority of total annual runoff. Outside of this snowmelt period, runoff does occur, but is typically less and occurs inconsistently, often as a result of large storms.

The runoff sampling protocol described above generated a single, composite runoff sample for each event for each runoff basin. We analyzed all composite runoff samples for sediment, N, and P at the USDA–ARS Dairy Forage Research Center in Madison, WI. We measured total sediment gravimetrically by drying a known quantity (~50 mL) of a well-shaken runoff sample at 60 °C until all water had evaporated. We then determined the weight of the remaining sediment and determined sediment content (g L^{-1}) as the mass of that sediment in the original volume of sample. We filtered runoff samples through 0.45 μm filters, and analyzed filtered samples for dissolved P (Murphy and Riley, 1962), and

NH_4–N and NO_3–N using QuickChem methods 12-107-06-2-A (ammonium) and 12-107-04-1-B (nitrate) on a Lachat automated N analyzer (Lachat, 1996). To measure total N and P, we digested unfiltered samples in an autoclave with potassium persulfate, with digested samples analyzed for N and P by the same methods as the filtered samples (Langner and Hendrix, 1982). We refer to the difference between total and dissolved nutrient forms as particulate N or P.

We collected soil samples from each pasture basin from 0–2.5 and 0–15.0 cm to assess the historical P accumulation in soils and the degree of P stratification (i.e., greater P in the 0–2.5 cm layer than the 0–15.0 cm layer due to historical surface manure applications and minimal soil mixing due to lack of tillage). Soil samples were analyzed at the University of Wisconsin Soil and Plant Analysis Lab for Bray-1 P extractable soil P (Bray and Kurtz, 1945) and organic matter (OM) by loss-on-ignition. These data were used as inputs for the APLE model as described below.

2.2. Determination of event and annual N and P loads

To determine event sediment, N, and P loads from each pasture basin, we multiplied the concentration of sediment and measured N and P forms (mg L^{-1}) in runoff samples by the runoff amount from each basin (L ha^{-1}) to determine a load (kg ha^{-1}). Analysis of runoff and nutrient loss data did not reveal any consistent trends in differences between the eight basins. Given this and that all pasture basins had similar management, we treated the basins as replicates and averaged loads across all eight for a single load per event. For annual sediment or nutrient loads, we summed all event loads for two 365-d periods, which were from August 1 to July 31 for both 2010–2011 and 2011–2012.

2.3. Testing APLE for runoff P loss from pastures

2.3.1. APLE description

APLE is a fairly simple, user-friendly, Microsoft Excel spreadsheet model that runs on an annual time-step and estimates field-scale, sediment bound and dissolved P loss (kg ha^{-1}) in surface runoff for agricultural field. APLE is intended to have the simplicity of P-indexes, but to quantify P loss through more process-based equations rather than estimate a risk of P loss. It has been tested for its ability to reliably predict P loss in runoff for systems with machine-applied manure and for soil P cycling using data from a wide variety of agricultural fields and regions (Vadas et al., 2007, 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 describe the model in detail. Here, we present a summary of APLE and how we adapted and tested it for P loss in runoff from grazed pastures.

Pertinent APLE user-input data for this project include topsoil properties (Mehlich-3 soil test P, clay, organic matter); surface area of the field; annual precipitation, runoff, and erosion; annual crop P export; number of annual cattle days in the field; and information for manure and fertilizer P application. APLE operates on an annual time-step, and therefore does not consider variations in climate, hydrology, or other variables that occur throughout a year. It also does not consider landscape or management impacts on runoff and erosion, but instead allows user-input precipitation, runoff, and erosion to account for these variations. Thus, APLE does not predict annual runoff or erosion, but instead estimates P loss and soil P cycling for a given set of runoff, erosion, and P application (fertilizer, manure, grazing) conditions. Annual erosion and runoff can be estimated with models such as RUSLE2 (http://fargo.nserl.purdue.edu/rusle2_-dataweb/RUSLE2_Index.htm).

APLE estimates annual sediment P loss (kg ha^{-1}) in runoff as:

$$\text{Sediment P loss} = (\text{eroded sediment})(\text{soil total P})(\text{P enrichment ratio})(10^{-6}) \tag{1}$$

where eroded sediment (kg ha^{-1}) is annual soil erosion; soil total P (mg kg^{-1}) is estimated using soil Mehlich-3 P, clay, and OM; and P enrichment ratio is a unitless ratio of total P in eroded sediment to that in the source soil, and is estimated from annual soil erosion. In this study, we used measured soil Bray-1 P and OM data and assumed that Mehlich-3 was equivalent to Bray-1 (Vadas et al., 2012). APLE estimates dissolved inorganic P loss in runoff (kg ha^{-1}) from soil as:

$$\text{Dissolved soil runoff P} = (\text{soil labile P})\ (0.005)\ (\text{annual runoff})\ (10^{-6}) \tag{2}$$

where soil labile P (mg kg^{-1}) is estimated as one half of soil Mehlich-3 P and annual runoff is in cm.

In APLE, manure is applied in either 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 P applied that are incorporated. APLE estimates annual dissolved P loss directly from any manure or fertilizer remaining on the soil surface. For applied manure, APLE assumes a portion of the manure total P is in a water-extractable P (WEP) form. APLE estimates dissolved manure P loss in runoff from this manure WEP on the soil surface. The portion of manure P that is not in a WEP form (non-WEP) at application can mineralize during the year and add to manure WEP on the soil surface. APLE estimates annual manure or fertilizer dissolved P loss in runoff (kg ha^{-1}) as:

$$\text{Manure runoff P} = (\text{manure WEP})(\text{annual runoff/precipitation})\ (\text{P distr. factor}) \tag{3}$$

$$\text{Fertilizer runoff P} = (\text{fertilizer P})\ (\text{annual runoff/precipitation})\ (\text{P distr. factor}) \tag{4}$$

where manure WEP and fertilizer P are in kg ha^{-1} and precipitation and runoff are in cm. The P distribution factor is an empirical factor between 0.0 and 1.0 that distributes released P between runoff and infiltration, and is calculated as:

$$\text{Manure: P distribution factor} = (\text{annual runoff/precipitation})^{0.225} \tag{5}$$

$$\text{Fertilizer: P distribution factor} = 0.034\ \exp\ ((3.4)\ (\text{annual runoff/precipitation})) \tag{6}$$

The precipitation (cm) represents total rain, snow, and irrigation for an entire 12-month period.

2.3.2. APLE testing for pastures

The processes described above for P loss in runoff from soil, manure, and fertilizer have been well tested (Vadas et al., 2009; Good et al., 2012). For this project, we adapted and tested APLE so it would simulate P loss in runoff from dung applied by grazing cattle. In APLE, a user specifies how many dairy or beef cattle graze the field during the year. This adds dung and P to the field and increases the amount of dissolved P loss in runoff. APLE assumes daily dung production and dung total P content for dairy and beef cattle as listed in Table 1 (Nennich et al., 2005). Dung WEP at deposition is set at 55% of total P, and 75% of dung WEP is available the same year for P loss in runoff and 25% is available the following year. APLE also assumes that 20% of dung non-WEP on the soil surface mineralizes into WEP the same year.

Table 1
Assumptions used in the APLE model for daily dry mass dung production and dung total P content for grazing dairy and beef cattle.

Animal type	Daily dung production kg	Dung total P content kg kg^{-1}
Lactating dairy cow	8.9	0.0088
Dairy heifer	3.7	0.0054
Dairy dry cow	4.9	0.0061
Dairy calf	1.4	0.0054
Beef cow	6.6	0.0067
Beef calf	2.7	0.0092

APLE uses Eqs. (3) and (5) to calculate annual dissolved P loss in runoff from grazing dung. In addition, APLE also reduces the amount of dung dissolved P loss in runoff by a factor that accounts for the fact that dung does not evenly cover the entire soil surface, as would be the case for machine applied manure, and not all of the annual precipitation interacts with it to contribute to runoff P. In calculating the annual reduction factor for grazing dung, APLE first assumes that each 250 g of dung (dry weight) covers an area of 659 cm^2 (James et al., 2007) and calculates what percentage of the field area is covered by the annual mass of dung deposited. APLE then calculates the dung reduction factor as:

$$\text{Reduction factor} = 1.2x\ (250x\ \%\ \text{annual cover})/((250x\ \%\ \text{annual cover}) + 73.1) \tag{7}$$

where % annual cover is expressed as a decimal. Eq. (7) is a non-linear equation that returns a reduction factor greater than the portion of the pasture area covered by dung. We found that during APLE adaptation for pasture P runoff, a non-linear equation gave better predictions of dissolved P loss in runoff than a linear equation that reduced runoff P in direct proportion to the pasture area covered by dung. Eq. (7) is taken from the daily time-step, manure P runoff model of Vadas et al. (2007), where it is used to determine what portion of manure WEP is leached by rain from manure on the soil surface during a storm. Thus, the important new parts of APLE to test were the assumptions for cattle dung production rate and P content (Table 1) and Eq. (7) to reduce dung P loss in runoff according to the amount of pasture area covered.

To test APLE for grazing cattle, we used data from 20 published studies in the literature that monitored field-scale P loss in runoff from grazed pastures (Table 2), as well as data from our pasture runoff monitoring. All literature studies were conducted for at least 6 months, and most for multiple years. The studies all reported the input information needed for APLE, including size of field; annual stocking rate; soil P concentration; fertilizer applications; soil OM and clay content; and annual rain, runoff, and sediment loss. We entered all required input information into APLE, predicted annual P loss in runoff, and then compared measured and predicted P loss (both total P and dissolved P) by linear regression to assess how reliably APLE simulated annual P loss from grazed pastures.

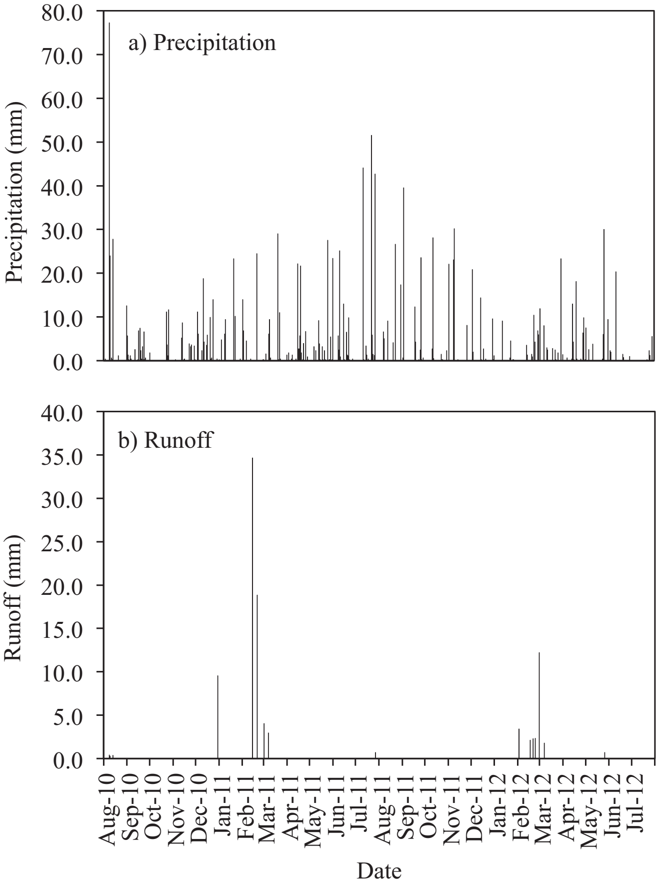

Fig. 2. Precipitation and runoff depths from the eight pasture basins from August 2010 to July 2012.

Table 2
Details of 20 studies used to validate APLE for P loss in runoff from cattle-grazed pastures.

Reference	Location	Duration months	Field area ha	Cattle type	P forms measured
(Capece et al., 2007)	Florida, USA	72	20.2–32.4	Beef	DRP
(Cournane et al., 2011)	New Zealand	25	1.3	Beef	TP, DRP
(Edwards et al., 1996)	Arkansas, USA	24	1.2	Beef	DRP
(Fleming and Cox, 1998)	Australia	12	2.4	Dairy	DRP
(Harmel et al., 2009)	Texas, USA	84	1.2	Beef	TP, DRP
(Holz, 2010)	Tasmania	36	12.1	Dairy	TP, DRP
(Kurz et al., 2006)	Ireland	16	0.5–1.5	Beef	DRP
(Lambert et al., 1985)	New Zealand	36	0.1–1.5	Sheep	TP
(Mapfumo et al., 2002)	Canada	36	2.2	Beef	DRP
(McDowell et al., 2003)	New Zealand	6	3.0	Dairy	TP, DRP
(Melland et al., 2008)	Australia	30	0.5	Sheep	TP
(Menzel et al., 1978)	Oklahoma, USA	120	11.0	Beef	TP, DRP
(Olness et al., 1975)	Oklahoma, USA	12	9.6–11.0	Beef	TP, DRP
(O'reagain et al., 2005)	Australia	12	1.0	Beef	TP
(Owens and Shipitalo, 2006)	Ohio, USA	120	17.2	Beef	DRP
(Owens et al., 1983a)	Ohio, USA	72	28.2	Beef	TP
(Schepers and Francis, 1982)	Nebraska, USA	36	32.5	Beef	TP, DRP
(Smith, 1987)	New Zealand	20	16	Sheep	TP, DRP
(Smith and Monaghan, 2003)	New Zealand	36	0.09	Beef, dairy	DRP
(Vankeuren et al., 1979)	Ohio, USA	24	17.2	Beef	TP

3. Results and discussion

3.1. Runoff monitoring at Pioneer Farm

Fig. 2 shows precipitation and runoff depths for our pasture-monitoring period between August 2010 and July 2012. There were 16 runoff events during this period that generated 102 runoff samples (Table 3), meaning that not all eight basins had runoff for all events. Only five events and 30 samples were caused by rain outside of winter periods (December 1–March 31), with all other events and samples due to snowmelt or rain-on-snow. Although runoff is clearly weather dependent, these data suggest that most runoff from pastures in Wisconsin on similar soil types may occur in winter and early spring from snowmelt, with less runoff from rain outside of this period.

Tables 3 and 4 show results for sediment and nutrient loss in runoff for the grazed pastures. In the 102 runoff samples, sediment concentrations were consistently very low, averaging only 0.20 g L^{-1}, with a maximum of only 1.3 g L^{-1}. Sediment runoff concentrations did not vary appreciably through time. However, average sediment runoff concentrations were greater during the non-winter period than the winter period, showing that rainfall-induced runoff was more erosive than snowmelt runoff. Overall though, data clearly show that well-established pasture vegetation can effectively eliminate soil erosion (Owens et al., 1983b; Butler et al., 2006; Bartley et al., 2010).

Runoff dissolved NO_3–N and NH_4–N concentrations were generally low throughout the study and did not vary substantially through time (Tables 3 and 4). Particulate runoff N concentrations (total N less NO_3–N and NH_4–N) were fairly well, non-linearly related to runoff sediment concentrations (particulate N = 1.03x ln runoff sediment −1.85; $r^2 = 0.46$). Runoff particulate P concentrations were similarly related to runoff sediment (particulate P = 0.24x ln runoff sediment −0.69; $r^2 = 0.43$). Strong relationships between sediment loss and particulate nutrient loss are common (Vadas et al., 2004; Kleinman et al., 2011). Generally, runoff P concentrations did not vary drastically through time. About 80% of runoff samples had dissolved P between 0.5 and 2.5 mg L^{-1}, and total P between 1.0 and 3.0 mg L^{-1}. Dissolved P averaged 80% of total P in the winter-period, snowmelt samples and 60% in the non-winter, rain-runoff samples. The magnitude of these P concentrations is consistent with runoff observations from the similar study of Owens and Shipitalo (2006), where well established pastures were grazed by beef cattle over several years under similar climate conditions in Ohio, USA.

The chemical forms of runoff nutrient concentrations did vary as a function of season. Average particulate N and P concentrations were greater during the non-winter period (3.83 vs 3.25 mg L^{-1} for N, and 0.63 vs 0.43 mg L^{-1} for P), which follows the runoff sediment data. These results were statistically significant ($p = 0.05$) for P, but not for N. Conversely, dissolved N and P concentrations were both significantly ($p = 0.05$) greater during the winter period. This is despite the relatively long time between fresh dung deposition during grazing and winter runoff events, which is somewhat contrary to research that shows nutrient concentrations in runoff are often greatest shortly after grazing events (Dougherty et al., 2008). Greater winter dissolved nutrient concentrations, especially for P, may have been caused by freezing of vegetation and associated greater release of nutrients upon thawing, which may not occur for dung (Miller et al., 1994; Bechmann et al., 2005). Overall, the increase in particulate concentrations during non-winter periods was less than the increase in dissolved concentrations during the winter period, so that overall total nutrient runoff concentrations were greater

Table 3
Date, runoff depths, and flow-weighted sediment and nutrient concentrations in runoff for the 16 individual runoff events monitored from August 2010 to July 2012. Data for a given event are averages of the eight cattle pasture basins.

Date	Runoff	Sediment	Dissolved P	Total P	NH_4–N	NO_3–N	Total N
	cm	mg L^{-1}					
8/8/10	0.04	108.81	0.51	0.84	0.54	0.40	4.37
8/9/10	0.03	225.77	0.71	1.26	0.59	0.61	4.82
8/13/10	0.04	156.35	1.02	1.53	0.80	0.39	4.88
12/30/10	0.96	74.65	1.46	1.60	0.75	0.73	2.93
2/14/11	3.47	80.38	1.99	2.27	5.07	0.75	9.10
2/20/11	1.88	69.68	1.26	1.48	2.47	0.72	5.33
3/1/11	0.41	123.92	1.62	2.14	3.11	0.83	3.76
3/7/11	0.30	295.42	3.25	4.09	3.05	1.81	9.19
7/27/11	0.07	567.66	1.33	2.26	0.33	1.31	5.58
2/2/12	0.34	167.35	2.11	2.82	1.97	1.09	6.14
2/17/12	0.21	72.53	1.81	2.17	1.37	0.47	4.19
2/21/12	0.23	112.23	1.74	2.13	1.68	0.82	5.11
2/24/12	0.23	377.48	1.71	2.24	1.44	0.81	6.60
2/29/12	1.22	239.57	1.26	1.74	1.24	0.40	5.29
3/7/12	0.18	269.18	2.38	2.94	1.26	0.78	6.25
5/26/12	0.07	388.07	2.55	3.50	3.48	0.80	12.03

Table 4
Summary statistics for runoff depths, and flow-weighted sediment and nutrient concentrations in runoff for the eight cattle pasture basins and 16 runoff events monitored from August 2010 to July 2012. Data are across all samples for all events.

Statistic	Sediment mg L^{-1}	Dissolved P	Total P	NH_4–N	NO_3–N	Total N
Average	200.1	1.5	2.0	1.8	0.8	5.9
Maximum	1331.8	4.3	5.2	12.3	4.4	21.0
Minimum	13.3	0.1	0.5	0.1	0.0	2.4
Std. dev.	206.3	0.8	0.9	2.0	0.5	3.2
Winter average	152.7	1.7	2.2	2.3	0.8	6.1
Non-winter average	279.9	1.0	1.5	0.7	0.7	5.2

Table 5
Measured 12-month period precipitation, runoff, and sediment and P loss in runoff from cattle pastures from August 2010 to July 2012.

Time period	Precipitation cm	Runoff cm	Sediment kg ha^{-1}	Dissolved P kg ha^{-1}	Total P kg ha^{-1}
2010–2011	86.0	6.7	66.6	1.2	1.4
2011–2012	58.3	2.0	62.6	0.4	0.6

during the winter period. These results were statistically significant ($p = 0.05$) for P, but not for N.

We compiled measured runoff volume and sediment and P concentration data from all events to calculate annual runoff, erosion, and P loss from the cattle pastures (Table 5). Both annual precipitation and runoff were greater in the 2010–2011 period than the 2011–2012 period. Average annual precipitation for this location (1971–2001) is 91.7 cm. Thus for years with about average precipitation (2010–2011), about 5–10% of annual precipitation may be expected to become runoff from similar grazed cattle pastures. In years with less than average precipitation (2011–2012), less than 5% of precipitation may become runoff. These results are consistent with data from Owens and Shipitalo (2006) where average annual runoff from grazed pastures ranged from about 2 to 13% of average annual precipitation. Such information is useful for models like APLE that require annual precipitation and runoff as input. Model users will readily know typical annual precipitation, and annual runoff can be estimated as a percentage of that precipitation for a given soil type and land use. Thus, a model user could be confident in assuming annual runoff from similar pastures may be 5–10% of annual precipitation.

Annual erosion from the pastures was very low, at less than 70 kg ha^{-1}, and annual nutrient loss was only 1.5–4.3 kg total N ha^{-1} P and 0.6–1.6 kg total P ha^{-1}. These P results are consistent with data in the literature on the magnitude of P loss from grazed pastures. For example, of the 20 pasture runoff studies in Table 2, about 85% of the site years had less than 2.0 kg ha^{-1} of annual total P loss and less than 1.5 kg ha^{-1} of dissolved P loss. Based on our cattle stocking rates, and assuming that cattle excrete 0.23 kg N day^{-1} and 0.04 kg P day^{-1} on a dry weight basis (Nennich et al., 2005), annual nutrient application rates to pastures were about 225 kg N ha^{-1} and 39 kg P ha^{-1}. Thus the rate of nutrient loss in runoff per unit of applied nutrient was about 1.3% for N and 2.5% for P. In general, these results show that annual runoff, erosion, and nutrient loss from similar cattle-grazed pastures in Wisconsin are likely low relative to other agricultural land uses (Beaulac and Reckhow, 1982), and may not pose as much of a risk to local water quality. However, management practices that increase runoff, erosion, and nutrient loss, such as significantly greater cattle stocking rates and related erosion, or excessive fertilization, could increase the risk of negative environmental impact. As demonstrated below, the APLE model could be easily used to quantify how much more P would be lost due to greater erosion, stocking rate, or fertilization.

3.2. Testing of APLE for P loss from cattle pastures

To assess APLE for grazing cattle, we used data from 20 published studies in the literature that monitored annual P loss in runoff from grazed pastures (Table 2). The data represented a variety of stock types, field areas, and locations and associated climate. This variety provided a robust test to see if APLE could reliably estimate annual P loss in runoff from pastures. Since we used measured runoff and erosion as model inputs, this assessment assessed the ability of APLE to reliably estimate the impact of P sources (i.e., soil P and dung P) on P loss given a set of transport (i.e., runoff and erosion) conditions.

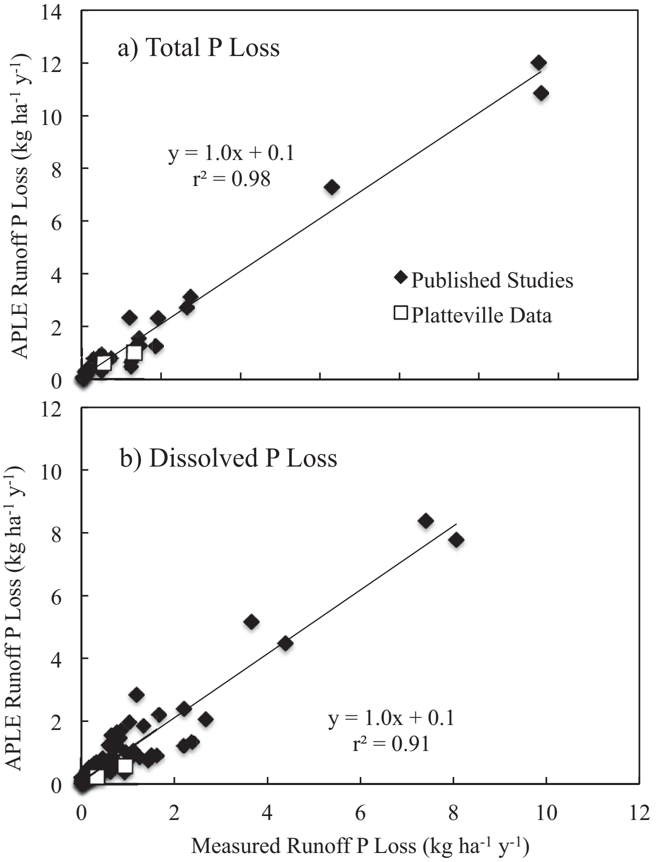

Fig. 3. Measured and APLE-simulated runoff P loss from cattle-grazed pastures. Data are from 19 published studies and from monitoring at the UW Platteville Pioneer Farm, for (a) total P in loss ($n = 33$) and (b) dissolved P loss ($n = 82$).

Fig. 3 shows the relationship between measured and predicted, annual total and dissolved P loss in runoff from cattle pastures. Results show APLE was able to reliably estimate annual P loss in runoff. The slope and intercept of both regression lines relating measured and predicted values were not significantly ($p < 0.05$) different from one or zero, respectively. The model predicted the measured total P data with an efficiency of 0.98 and the dissolved P data with an efficiency of 0.89 (Nash and Sutcliffe, 1970). Nash–Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 corresponds to a perfect match of modeled and observed data. An efficiency of zero indicates that model predictions are as accurate as the mean of observed data, and efficiency less than zero occurs when the observed mean is a better predictor than the model.

The important new parts of APLE to validate for pasture P runoff were the assumptions for dung production and P content (Table 1) and Eq. (7) to reduce dung P loss in runoff according to the amount of field area covered by dung. Runoff P prediction results in Fig. 3 suggest that these two parts of the model provided reliable estimates of pasture P runoff. In fact, without the dung area reduction factor (Eq. (7)), which would ultimately treat grazing dung the same as machine-applied manure, P loss predictions were about 50% greater than measured data. This demonstrates the importance of simulating dung deposited during grazing differently from machine-applied manure.

We also conducted a model sensitivity analysis to determine how much assumptions about dung and P production as well as dung cover influence model predictions compared to runoff volume, which is the model transport variable for manure P loss. To do this, we determined how much both increasing and

Table 6
Results of the APLE model sensitivity analysis. Data show the impact of increasing and decreasing the value of each model variable by 10% or 20% on the model prediction for annual dissolved P loss in runoff from cattle dung.

	% Change in predicted dissolved P loss in runoff from dung per change in model variable			
Model variable	+10%	−10%	+20%	−20%
Runoff	12.4	−12.1	25.0	−23.9
Dung total P excreted	10.0	−10.0	20.0	−20.0
Dung WEP content	6.0	−6.0	12.0	−12.0
Dung cover	6.0	−6.5	11.7	−13.6
Dung reduction factor	10.0	−10.0	20.0	−20.0

decreasing each variable by 10% and 20% changed model predictions for manure P loss in runoff. Specific model variables changed were runoff amount, the amount of dung total P excreted by grazing cattle, the WEP content of the grazing dung, the amount of area covered by the dung, and the reduction factor in Eq. (7). Sensitivity results are shown in Table 6. The model was most sensitive to changes in annual runoff, showing this transport factor significantly influences model prediction of dung P loss. The model was linearly sensitive to assumptions for dung total P excretion and the dung P loss reduction factor, so that each unit change in input had the same unit change in output. These changes were also nearly as much as changes for runoff volume, showing that the new assumptions developed in this project for dung P excretion and dung reduction factor are important model parameters. Model predictions were least sensitive to changes in dung WEP content and dung area covered, with the influence of these parameters about half of the influence of the previous parameters.

One benefit of the APLE model is that it gives information on the relative contribution of different sources to total P loss in runoff from pastures, including fertilizer, dung, soil, and eroded sediment. The relative importance of each source will of course depend on pasture management. For example, for the studies in Table 2 that monitored total P loss in runoff, APLE estimated that P loss from applied fertilizer ranged from 0 to 37% of total P loss, with ranges for dung from 3 to 67%, soil from 3 to 56%, and eroded sediment from 13 to 89%. However, on average for the same studies, the relative contribution to total P loss was about 10% from fertilizer, 15% from soil dissolved P, 30% from dung, and 45% from soil erosion. In New Zealand, McDowell et al. (2007) used data from a series of controlled experiments and empirical equations to make similar estimates of annual P loss from grazed pastures. They found that of the estimated P losses, fertilizer comprised 12–13%, soil P (combination of dissolved and eroded P) comprised 29–45%, dung P losses comprised 28–38%, and P from pasture-plants was 15–21%. These New Zealand P source divisions for fertilizer, soil, and dung agree well with estimates from our pasture P runoff research, except that APLE does not consider loss from pasture plants. Such P loss source data are a potentially powerful benefit of APLE and similar models for considering how to better manage P loss. Since P loss sources can vary considerably from site to site, these models become invaluable tools for site-specific P management, especially because it is infeasible to rely on physical monitoring of all sites of interest.

4. Conclusions

Our project monitored sediment and nutrient loss in runoff from dairy and beef grazed pastures for typical Wisconsin conditions. Results over two annual monitoring periods show that pasture sediment and nutrient loss were generally low, likely having less negative impact on local water quality than other agricultural land uses. We used these data along with data from 20 studies in the literature, to update the APLE model to estimate annual P loss in runoff from grazed pastures. Our results demonstrate that APLE is able to reliably estimate P loss from beef and dairy grazed pastures given reliable estimates of annual runoff and erosion. Models like APLE can be used to rapidly and cost-effectively identify which sources (i.e., dung, soil dissolved P, or particulate P) dominate P loss, making them valuable tools for site-specific P loss assessments and mitigation strategies. APLE will also play a critical role in our future research to simulate whole-farm P loss on dairy farms and identify which land uses represent the greatest risk for P loss and help target remediation.

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