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RESEARCH ARTICLE

Assessing a decade of phosphorus management in the Lake Mendota, Wisconsin watershed and scenarios for enhanced phosphorus management

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Abstract A phosphorus (P) budget was estimated for the watershed of Lake Mendota, Wisconsin, to assess the effects of nutrient management on P accumulation in the watershed soils. We estimated how nutrient management programs and legislation have affected the budget by comparing the budget for 2007 to a budget calculated for 1995, prior to implementation of the programs. Since 1995, inputs decreased from 1,310,000 to 853,000 kg P/yr (35% reduction) and accumulation decreased from 575,000 to 279,000 kg P/yr (51% reduction). Changes in P input and accumulation were attributed primarily to enhanced agricultural nutrient management, reduction in dairy cattle feed supplements and an urban P fertilizer ban. Four scenarios were investigated to determine potential impacts of additional nutrient management tactics on the watershed P budget and P loading to Lake Mendota. Elimination of chemical P fertilizer input has the greatest potential to reduce watershed P accumulation and establishment of riparian buffers has the greatest potential to prevent P loading to Lake Mendota.

Keywords Eutrophication Lake Mendota · Mass balance · Nutrient management · Phosphorus

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Introduction

Excess nutrient loading impairs water quality in surface waters worldwide. Although excess phosphorus (P) runoff to freshwater exceeds planetary boundaries for global water quality targets (Carpenter and Bennett 2011), P fertilizer availability limits agricultural production in some parts of the world, and some have argued that non-renewable global P reserves are declining (Cordell et al. 2009). Management of phosphorus loading to surface waters from agricultural runoff, urban fertilizers, storm water drainage, and wastewater effluent is crucial to prevention and control of cultural eutrophication (Schindler et al. 2008; Carpenter 2008), and for conservation of a limited resource upon which global food production depends (Carpenter and Bennett 2011; Cordell et al. 2009).

For decades, eutrophication of Lake Mendota, Wisconsin (WI) has generated attention in the public realm and scientific community (Lathrop 2007; Carpenter and Lathrop 2008; Brock 1985). For lakes in general, and for Lake Mendota specifically, the relationship between external P loading and water quality is well established (Schindler 1977; Schindler et al. 2008; Lathrop et al. 1999; Vollenweider 1976; Smith et al. 2006). Efforts to manage phosphorus loading in the Lake Mendota watershed began in the 1950s, nearly 70 years after nuisance algal blooms were first observed (Brock 1985), and have continued into the twenty first century. Eutrophication persists in Lake Mendota due to nonpoint agricultural sources of phosphorus in the watershed (Betz et al. 2002), as well as recycling from hypolimnetic and sediment P (Soranno et al. 1997; Kamarainen et al. 2009). Eutrophication in Lake Mendota appears to be reversible (Carpenter and Lathrop 2008; Lathrop et al. 1998).

Nonpoint pollution of Lake Mendota prompted researchers to compute a P budget (inputs, outputs, and accumulation) for the Lake Mendota watershed in order to understand the sources of high P inputs (Bennett et al. 1999). In the years since the publication of the 1995 budget, significant changes in agricultural practices, manure management, and fertilizer use may have occurred due to new regulations and changes in agricultural practices. To investigate this possibility, we updated the P budget for the Lake Mendota watershed for 2007. To examine comparative effects of additional P management tactics, we analyzed scenarios of altered watershed P budgets and nutrient loading to Lake Mendota. The results suggest a comparison of the efficiency (cost per unit of reduced loading) of different nutrient management tactics within the context of a managed watershed that may be relevant to water quality managers and policy-makers worldwide.

Materials and methods

Lake Mendota is located in south central Wisconsin, USA (43°06′24″N; 89°25′29″W). The lake and watershed have been described in detail elsewhere (Kitchell 1992; Brock 1985; Bennett et al. 1999). Approximately 88% of the watershed is contained within Dane County, WI; the remaining 12% is within Columbia County, WI.

Using a mass-balance approach, we calculated the inputs, outputs, and accumulation of P in the Lake Mendota watershed for 2007 using the methods of Bennett et al. (1999). We assumed a ‘best case’ scenario for 2007: full compliance by residents and farmers with local ordinances, nutrient management plans, and best management practices. To test the effect of additional P management techniques not currently employed in the watershed, we simulated four scenarios in order to represent the largest possible reduction in P loading to the watershed and to Lake Mendota at several control points (Fig. 1). The

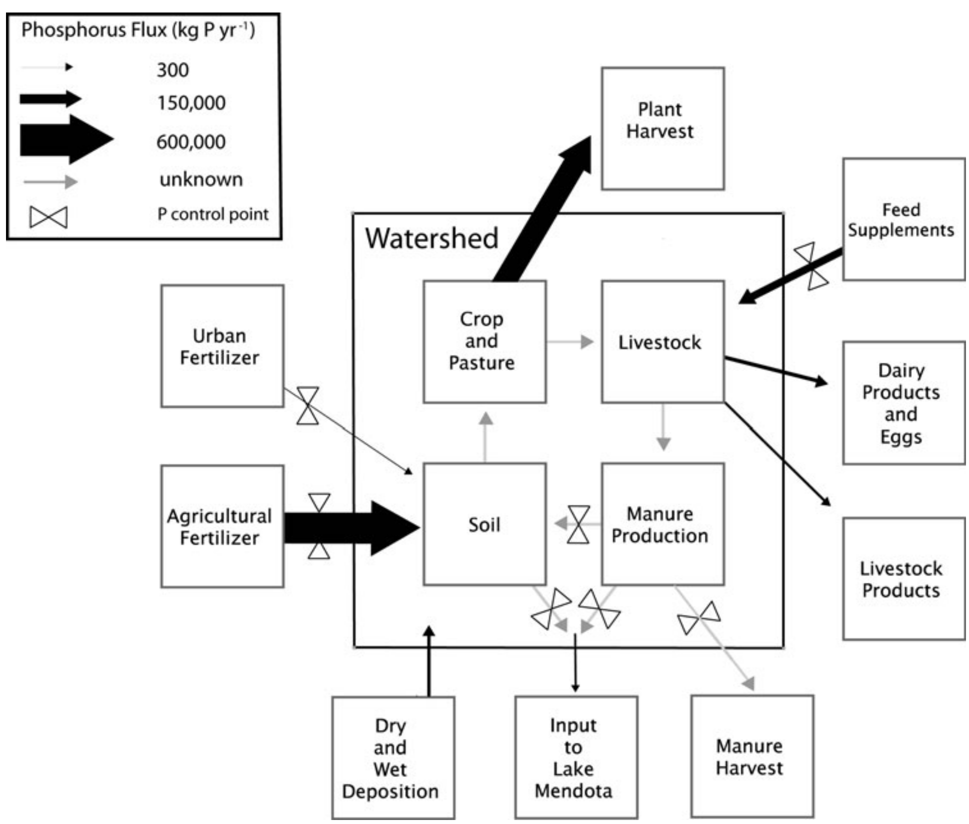

Fig. 1 Conceptual diagram for the 2007 Mendota watershed P budget. Inputs and outputs are represented by *arrows* whose width corresponds to the magnitude of the flux; *boxes* represent sources, sinks, or pools of P. *Bowties* represent control points identified in management scenarios. Agricultural fertilizer and plant harvest represent the largest input and output, respectively

Table 1 Sources of data used to calculate the 2007 phosphorus budget for the Lake Mendota watershed

Component	Subcomponent	Source
Inputs		
Fertilizer for agricultural crops	Amount of land planted in each crop	USDA-NASS (2009a)
	Recommendations for fertilizer application rates by crop and soil P concentration.	Laboski et al. (2006)
	Dane County soil P concentrations	Bennett et al. (1999)
Feed supplements for dairy cattle	Average feed consumed per cow per day in South Central WI	Powell et al. (2002)
	Percent of P in feed that is homegrown versus imported	Powell et al. (2002)
	Number of cattle in Dane County	USDA-NASS (2009a)
	Herd structure of cattle South Central WI	Powell et al. (2002)
Fertilizer for urban lawn	Urban land area in the watershed	Bennett et al. (1999)
	Percent of urban area that is lawn	Bannerman et al. (1993)
	Recommended fertilization rates	Soldat and Petrovic (2008)
Atmospheric deposition	Dry deposition	Lathrop (1979)
	Wet deposition	Lathrop (1979)
Outputs		
Crops harvested	Amount of each crop harvested in Dane County	USDA-NASS (2009a)
	% P in each crop	Laboski et al. (2006)
Animal products	Number of hogs, cattle and calves sold in Dane County	USDA-NASS (2009a)
	% P in cattle and hogs	Lorimor et al. (2000)
	Milk produced in Dane County, 2007	USDA-NASS (2009b)
	Number of Layers in Dane County, 2007	USDA-NASS (2009a)
	Eggs per layer per year, Wisconsin, 2007	USDA-NASS (2009b)
	Mass of eggs	USDA-AMS (2000)
	% P in milk and eggs	Lorimor et al. (2000)
Hydrologic export to Lake Mendota	Hydrologic export to Lake Mendota	Lathrop et al. (1998)

scenarios included (1) elimination of imported chemical fertilizer P, (2) elimination of imported animal feed supplements, (3) implementation of anaerobic manure digesters, and (4) implementation of riparian buffers to reduce P loss to Lake Mendota. The scenarios are intended to represent alternative control points in the watershed as a guide for future management within the watershed, as compared to the 'best case' scenarios for our calculated 2007 budget and the 1995 budget as estimated by Bennett et al. (1999).

Methods for calculating the 2007 phosphorus budget were based on the work of Bennett et al. (1999) and supplemented with information from publications, municipal reports, and local agricultural experts regarding relevant changes in local nutrient management practices since 1995. Detailed methods and examples are given in the Appendix. Inputs and outputs of P were calculated using 2007 data from various sources (Table 1). Where necessary, data were scaled to the watershed from studies aggregated at coarser scales, as described below and in the Appendix

We obtained values for cropland area, crop export, animal inventory and export, and animal products export from the United States Department of Agriculture National Agricultural Statistics Services (USDA-NASS) 2007 Census of Agriculture aggregated to Dane County (USDA-NASS 2009a, b). The county values were scaled to the watershed based on the proportion of the county's agricultural land within the watershed boundary. This proportion was estimated using 2005 land use coverage layers for Dane County (http://www.countyofdane.com/lio) and Columbia County (ftp://www.co.columbia.wi.us/lid), and watershed boundaries delineated by the Wisconsin Department of Natural Resources (ftp://dnrftp01.wi.gov/geodata). We assumed that the proportion of cropland area, export, animal inventory and export, and animal product export for the small fraction of watershed area within Colombia County (12%) was the same as for Dane County, WI.

Phosphorus inputs to the watershed included fertilizer for crops and urban lawns, feed supplements for cattle, commercial biosolid applications, and atmospheric deposition. Fertilizer for urban lawns was calculated based on the percent of turf-covered urban area in the watershed (Bennett et al. 1999; Bannerman et al. 1993) and the recommended fertilization rates (Soldat and Petrovic 2008). Mass of phosphorus imported in animal feed supplements was estimated using data particular to south-central Wisconsin dairy herds (Powell et al. 2002). Values for atmospheric P deposition were assumed to be the same as those calculated in a previous study (Lathrop 1979) and used in the 1995 P budget (Bennett et al. 1999).

Assumptions about fertilizer and dairy cattle feed supplements were different for the 2007 and 1995 budgets. For both budgets, estimates of agricultural fertilizer use were based upon recommendations for each crop by made by the University of Wisconsin Cooperative Extension (UWEX). In contrast to the 1995 budget (Bennett et al. 1999), the 2007 budget assumed that many goals for agricultural P management had been met. We assumed (1) farmers measured soil P concentration and chemical P was applied at a rate recommended by the UWEX for soil based on the outcome of that measurement, which would typically prescribe no P application for most crops grown in Mendota watershed soils (L. Lambert, Dane County Land Conservation Division, pers. comm.; Bennett et al. 1999); (2) P addition to crops as land-applied manure was credited by farmers as P fertilizer (Laboski et al. 2006), (J.M. Powell, US Dairy Forage Research Center, University of Wisconsin, pers. comm.); (3) a P ban on chemical fertilizer for urban lawns and turf was in effect (Dane County Code of Ordinances Chapter 80); and (4) dairy cattle P feed supplements did not exceed the animals' physiological requirements (Satter et al. 2005).

Phosphorus output included crops for human consumption (excluding forage crops), animal products (dairy and eggs), animals (cattle, hogs and pigs) and export to Lake Mendota. Export data for 2007 crops, dairy products, and animals were obtained from the USDA Census of Agriculture and scaled to the watershed as described above. Exports in eggs were determined using the number of laying hens in the watershed, the average annual egg production per layer, and P concentration of eggs (USDA-NASS 2009a; USDA-AMS 2000; Lorimor et al. 2000). Forage crops grown in the watershed were assumed to remain in the watershed for animal feed and were not counted as exports (J.M. Powell, US Dairy Forage Research Center, University of Wisconsin pers. comm.). Phosphorus exported via crops, animals, and animal products was calculated using conversion rates particular to the product (Lorimor et al. 2000; Laboski et al. 2006). Export to Lake Mendota was estimated using the mean annual P load to the lake for the years 1976–2005 as reported by Carpenter and Lathrop (2008).

Budget values that included uncertainties other than simple scaling from the county to the watershed scale were bracketed with minimum and maximum estimates based on extremes of plausible assumptions. All calculations of minimum and maximum values can be found in the Appendix. More uncertainty exists in estimates for inputs than outputs because agricultural exports are more consistently and clearly reported than are imported feed supplement and fertilizer use.

Within the budget, control points for P management were identified (Fig. 1). These control points were selected for their expected contribution to watershed P accumulation and loading to Lake Mendota. The effects of the elimination of chemical P fertilizer (Scenario 1) and feed supplement (Scenario 2) imports to the watershed were evaluated by simulating removal of all chemical P inputs for fertilizer and feed from the mass balance. In the manure digester scenario (Scenario 3), we assumed that 85% of the phosphorus in manure processed by digesters would be exported from the watershed as a solid by-product. The remaining 15% of the phosphorus remains in liquid form and would be used as fertilizer within the watershed (Strand Associates 2009). Not all manure is collectable; for this scenario, we assumed that 64% of total manure produced was collected and processed by digesters (Powell et al. 2005). In this case, manure exported that would otherwise have been credited as crop fertilizer was balanced with corresponding increases in the import of agricultural P fertilizer. The fourth scenario simulated reduced P output from the watershed to Lake Mendota by implementing riparian buffers along all waterways within the watershed, as outlined by Diebel and others (Diebel et al. 2009). The following assumptions for the scenario were made (M. Diebel, Center for Limnology, University of Wisconsin–Madison, pers. comm.): buffers in this scenario only affected agricultural runoff (70% of P load); 45% of the agricultural P load was delivered in winter (Dec through April) and 55% in the remaining months; of the winter P load, 75% was dissolved and of this, 90% passed through buffers; approximately half of the particulate P was retained by buffers during winter; of the summer P load, 25% is dissolved and half of the dissolved fraction passed through buffers; and the remaining 75% of summer P load was particulate and of this, 90% was retained by buffers.

Results

Assuming compliance with local ordinances, nutrient management plans, and best management practices, we estimated the 2007 inputs of P to the Lake Mendota watershed within a range of 275,000 to 1,130,000 kg P/yr, with a most likely estimate of 854,000 kg P/yr (Table 2). Fertilizer for corn accounted for the largest input of P (41%), with feed supplements for cattle (16%) and fertilizer for soybeans (12%) as the second and third largest inputs. Dry and wet deposition contributed to approximately 7% of the P inputs, while human-imported P (chemical fertilizer and animal feed supplements) made up 93% of total P inputs to the watershed.

The most likely estimate of P output for 2007 was 574,000 kg P/yr, with minimum and maximum estimates of 555,000 and 613,000, respectively (Table 3). Exports of P in corn accounted for 56% of all exports from the watershed, followed by soybeans (15%) and dairy products (12%). Loss of P to Lake Mendota represented 6% of the total output (34,000 kg P/yr). The most likely estimate of imports and exports yielded a calculated accumulation of 279,000 kg P/yr in the Lake Mendota watershed in 2007. The maximum and minimum estimates of net P accumulation are 522,000 and −280,000 kg P/yr, respectively (Tables 2, 3), where negative values indicates net loss of P from the watershed. The most notable differences between the 1995 and 2007 budgets are the reduction in accumulation of P stored in the soil and overall P inputs to the watershed. Phosphorus accumulation in soils was reduced by 52% from 1995 to 2007, while inputs to soil were reduced by 35%. Over 12 years, outputs from the watershed decreased by 27%, primarily due to reduced corn export.

Table 2 Estimates of phosphorus inputs to the Lake Mendota watershed

Inputs (kg P/yr)	Minimum	Most likely	Maximum
Dry deposition	43,000	43,000	43,000
Wet deposition	18,000	18,000	18,000
Biosolids	53,400	53,400	53,400
Feed supplements	79,000	141,000	203,000
Fertilizer for urban lawn	0	15,500	33,000
Fertilizer for corn	81,600	346,000	409,000
Fertilizer for soybeans	0	121,000	147,000
Fertilizer for oats	0	1,420	2,300
Fertilizer for wheat	0	12,700	17,100
Fertilizer for barley	0	151	224
Fertilizer for forage crops	0	101,000	206,000
Fertilizer for peas and beans	0	291	516
Fertilizer for tobacco	0	290	535
Sum	275,000	854,000	1,130,00

Minimum and maximum values represent the range of plausible values

Table 3 Estimates of phosphorus outputs from the Lake Mendota watershed

Outputs (kg P/yr)	Minimum	Most likely	Maximum
Dairy products	70,900	70,900	70,900
Eggs	397	397	397
Cattle	45,400	45,400	45,400
Hogs and pigs	0	0	5,640
Corn	320,000	320,000	320,000
Soybeans	86,700	86,700	86,700
Oats	1,750	1,750	1,750
Wheat	14,000	14,000	14,000
Barley	81	81	81
Forage	0	0	0
Peas and beans	530	530	530
Tobacco	600	600	600
Export to ME	15,000	34,000	67,000
Sum	562,000	576,000	598,000

Net results of implementing P control at various points in the watershed are summarized in Fig. 2. Under Scenario 1, assuming application of agricultural and urban chemical P fertilizer was eliminated, total P inputs would be reduced to 255,000 kg P/yr, a 75% decrease from estimated 2007 inputs. Assuming export was maintained at current levels, this scenario decreased stored P by 214%, from 279,000 kg P/yr accumulation in the watershed to 319,000 kg P/yr depletion. Eliminating inputs to the watershed as agricultural P feed supplements in Scenario 2 reduced inputs by 21%, from 854,000 to 671,000 kg P/yr. Assuming outputs remain unchanged, this scenario reduced accumulation from 279,000 to 96,500 kg P/yr. Implementation of manure digesters, Scenario 3, increased both input and output of P from the watershed. Digesters increased input to 919,000 kg P/yr and output to 763,000 kg P/yr. The net result was reduced P accumulation in the watershed to 155,000 kg P/yr, a 44% decrease in accumulation from the 2007 budget. Scenario 4, implementation of riparian buffers, reduced the P load to Lake Mendota by 76%, to 8,070 kg P/yr. This scenario did not affect any other inputs or outputs and had the net effect of reducing the P exported from the watershed by about 5% to 548,000 kg P/yr. Annual accumulation of P within watershed soil was increased in this scenario by 29%, to 360,000 kg P/yr.

Discussion

Nutrient management in the Lake Mendota watershed

Implementation of the Lake Mendota Priority watershed Project (PWP), an effort to control and reduce non-point sources of pollution to the lake by 50% (Betz et al. 2002), played a large role in the reduced estimates of urban and agricultural fertilizer use for 2007. Comparison of the 1995 and 2007 'best case' budgets revealed a 37% reduction in

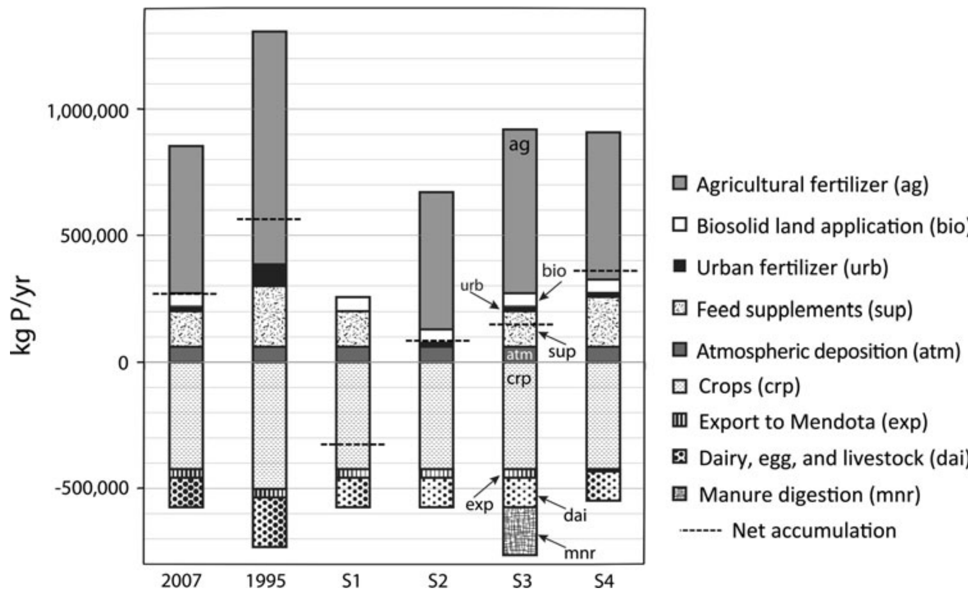

Fig. 2 Summary of budgets. 2007 and 1995 represent the budget presented here and by Bennett et al. (1999), respectively. Scenarios are represented by S1–S4. *Dashed line* indicates net watershed phosphorus accumulation. S1 results in largest net negative accumulation of P from watershed soil

agricultural fertilizer application attributed to more stringent nutrient management by farmers, according to reports by area experts. The PWP's 10 year implementation period began in 1998 and included changes to agricultural as well as urban nutrient management practices that affect water quality. Cropland was the target of changes in nutrient and water management and erosion control. The mid-term results of the project indicate that between 1998 and 2000 the majority of rural landowners had committed to implementing best management practices (Betz et al. 2002). Implementation of the PWP and the use of nutrient management plans on farms have reduced P fertilizer application and established rules regarding manure crediting. These changes are thought to have caused a decrease in P fertilizer use on agricultural land. This inference is supported by statistics on P fertilizer purchases adjusted for price and farm area, which indicated an 11% reduction in purchase of agricultural fertilizer in the watershed area between 1992 and 2007 (DATCP 2009). Nonetheless, the lack of direct data on P fertilizer application in the watershed or county scale leaves this component of the budget uncertain. If the actual reductions in P applications were smaller than believed by our sources of information, then the 2007 budget would be more similar to the 1995 budget.

A further debit in P inputs derives from the 41% reduction in imported feed supplements since 1995, even though animal numbers in the watershed have remained the same (USDA-NASS 2009a). Since 1995, farmers have been advised that supplements purchased for their protein or energy value contain varying amounts of phosphorus, sometimes in excess of an animal's physiological needs (Satter et al. 2005). This information may have caused farmers to purchase supplements that balance animal protein and energy needs with phosphorus levels in the diet (J.M. Powell, US Dairy Forage Research Center, University of Wisconsin, personal communication).

Finally, the Urban Phosphorus Ban enacted in Dane County in 2005 (Dane County Code of Ordinances Chapter 80) prompted our estimate of an 82% reduction of urban P fertilizer use from 1995 rates. The ordinance prohibits the use of P fertilizer on established lawns, golf courses, and other turf in the county; exceptions are granted when soil tests indicate limiting levels of soil P, though application for such exceptions in the county are rare (D. Soldat, Soil Science Extension, University of Wisconsin, personal communication).

Nutrient management scenarios

The nutrient management scenarios we presented act by two mechanisms: prevention of P from entering the watershed using legislation and collection/retention of P within the watershed (Fig. 2). Nutrient management scenarios 1 and 2 require management of P imports for agriculture. More stringent regulation of agricultural chemical P application would reduce the overall 2007 P inputs by as much as 61%, as estimated in Scenario 1. Soil P data (Peters 2010; Lathrop 2009) and UW Extension fertilizer recommendations (Laboski et al. 2006) indicate presence of ample P concentration in the majority of urban and agricultural soils in the watershed for growing turf and regional crops. A reduction in P application would likely not harm farmers' economic success, but rather enhance the profitability (Valentin et al. 2004) and promote conservation of this non-renewable resource (Cordell et al. 2009). Similarly, in Scenario 2, elimination of P mineral feed supplements would likely have little effect on the productivity of dairy cattle in southeast Wisconsin (Satter and Wu 1999), but the downstream effects on water quality in Lake Mendota could be potentially improved by measures banning chemical P supplements to mature dairy cows. Reduction in mineral P supplements would decrease manure P, thereby reducing the quantity of potentially unnecessary land-applied P-rich manures under this scenario.

Scenarios 3 and 4 use infrastructure to collect and/or retain P within the watershed. Diversion of manure to anaerobic digesters as described in Scenario 3 could eventually contribute to improved water quality by decreasing P soil accumulation and export to surface water during precipitation events, thereby mitigating eutrophication due to external P loading (Fig. 2). Currently, uncollected manure accounts for significant P inputs to surface water during rain events (J.M. Powell, US Dairy Forage Research Center, University of Wisconsin, pers. comm.), though the magnitude of the loading is not well quantified and we do not account for the direct effect of reduced export to surface water in this scenario. Scenario 3 would provide incentives to farmers to collect manure, rather than applying it to land, reducing additional accumulation of soil P (Fig. 2). This scenario could also provide methane gas production for electrical generation or other use and would generate products including liquid fertilizer and bedding derived from manure solids. Implementation of riparian buffers, as described in Scenario 4, would directly reduce the P load to Lake Mendota and could thereby reduce the occurrence of nuisance algal blooms. This reduction would have immediate implications for the recreational services provided by the lake as well as enhancing flood control and soil retention. The scenario has little effect on the P budget of the watershed, however, since its sole purpose is to increase P retention within the terrestrial landscape. Whereas buffers may have the greatest immediate benefit to the lake, management actions such as those explored in the other scenarios will be of long-term benefit as P is reduced in soils that may eventually be eroded due to conversion of agricultural land to other uses.

Uncertainty

The 2007 budget was informed by changes in regional nutrient management policies, information from local agricultural experts, current animal census, and crop export data. Particularly for P inputs from fertilizer and feed supplements, a large plausible range exists, representing uncertainty in the importation and use of P in agriculture. Bennett et al. (1999) also found a similarly large range of potential rates, but their estimates were, on average, much higher than those made here. The 'best case' scenario for the 2007 budget indicates that P is still accumulating, but more slowly than in 1995.

County-level soil P data were used by Bennett et al. (1999) to corroborate their results; we also used soil P data to estimate net change of P in soil for comparison against findings from the budget presented here (Fig. 3, data derived from the University of Wisconsin–Madison Soil and Plant Analysis Lab 2011). Assuming total soil mass in the watershed of 4.67×10^{11} kg (after Bennett et al. 1999), annual rates of change in P storage can be estimated from soil P concentration. Net changes in soil P estimated in this manner suggest net loss of ~467,000 kgP/yr from the watershed between 2004 and 2009, whereas the 'best case' mass balance presented here indicates a 280,000 kgP/yr accumulation. This discrepancy is within the range of uncertainties in both the budget and county soil P datasets. Our estimated range of plausible inputs was large compared to magnitude of output and net change, approximately 1,000,000 kgP/yr (Table 2). Likewise, soil P data should be interpreted with caution, as soil P is heterogeneous. A spatially explicit assessment of soil P variability in Dane County revealed a 99% confidence interval for soil P concentration ranging more than a thousand-fold (~1 to 1,000 mgP/kg soil, Bennett et al. 2005). Thus, the difference in estimates from the mass-

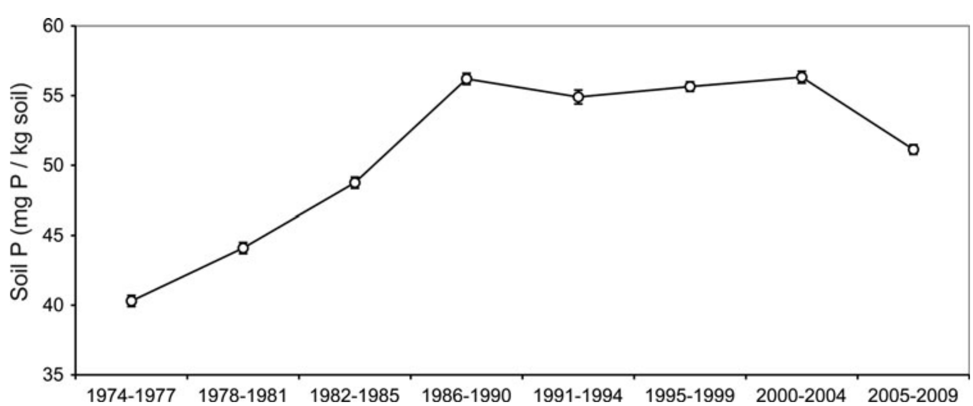

Fig. 3 Dane County soil P test (mg P/kg soil) levels for 35 years from the State of Wisconsin Annual Soil Test Summary Report (University of Wisconsin-Madison Soil and Plant Analysis Database 2011). *Error bars* represent 95% confidence intervals

balance budget and county soil P data is not unexpected, given the variance in soil P and the potential range of P inputs to the soil.

The modest changes and high variability in soil P are consistent with the high inter-annual variation and lack of trend in annual P inputs to Lake Mendota (Carpenter and Lathrop 2008). The lack of trend in input to the lake may be related to the long residence time of P in watershed soil. Because of this long residence time, P inputs to soil must be decreased for a long time in order to shift inputs to the lake (Carpenter 2005). Therefore, interventions that decrease erosion and retard P flow to the lake, such as vegetated buffers, have an important role in water quality management, especially while soil P levels remain elevated (Carpenter et al. 1998).

Conclusions

Lake Mendota exemplifies the many agricultural watersheds that have unbalanced nutrient budgets (MacDonald et al. 2011; Vitousek et al. 2009). In developed countries, the imbalance is generally in the direction of over-application of fertilizers, as has occurred in the Lake Mendota watershed. Meanwhile, in under-developed countries, P fertilizer is more expensive and less available to farmers, leading to P-deficient agricultural soils in regions with fewer resources and high population growth (Cordell et al. 2009). Watershed nutrient budgets are needed to mitigate excessive P inputs to P-rich watersheds, and allocate fertilizers to regions where agricultural production is most impaired by low nutrient availability (MacDonald et al. 2011). Yet very few countries collect nutrient balance data, and globally, water quality management is hampered by lack of information on terrestrial nutrient balances (Vitousek et al. 2009). Our study has shown how this data gap can be filled. Clearly, a great deal more work is needed to establish regional, continental and global views of agricultural nutrient imbalance and its consequences for water quality.

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Appendix

This appendix was created as a record of how the phosphorus budget for the Lake Mendota, WI watershed was derived. It is also a record of the numerous assumptions made in converting data available from various sources to watershed scale P imports and exports.

Converting county values to watershed values

In order to convert values for agricultural components of the budget which were only available to us at the county scale to the watershed scale, we divided the values by the area of agricultural land in the county to normalize to agricultural area. We then multiplied this by the agricultural area within the watershed which includes a small proportion of land in neighboring Columbia County. We assumed that agricultural practices in the Columbia County portion of the watershed were adequately represented by Dane County data.

e.g.

$$\frac{DaneCty\ Cattle}{DaneCty\ AgArea} * Watershed\ AgArea = WatershedCattle$$

where "DaneCty AgArea" was 395,369 acres and "Watershed AgArea" was 80,475 acres based on the 2007 USDA NASS Cropland Data Layer (as cited within the main body of the paper). This resulted in a factor of 0.204 to multiply by Dane County values to obtain watershed scale estimates.

These assumptions differed slightly from the Bennett et al. (1999) approach, which assumed that the distribution of livestock and crops in the watershed was proportional to the distribution in the county. Our approach allowed for the distribution of agricultural land to be different within the watershed than for the county as a whole. The net effect of this difference is small. If we followed the Bennett et al. convention our factor above would be 0.220 (686/3113 km^2, or watershed area divided by county area).

Calculating exports

Dairy products

Milk production for Dane County was obtained from the USDA-NASS Quick Stats website for 2007. This value was scaled to the watershed as described above and converted to P using the weight-weight conversion of 0.0009 units P per unit milk.

Eggs Our calculated mass of P exported in eggs differed by two orders of magnitude from the Bennett et al. value for 1995 (1999). The number of layers (hens of laying age) in the watershed was available from the USDA Census of Agriculture for 1992, 1997, 2002, and 2007. Of these four years, the 2007 value was the highest. By this metric alone, we would have expected to have higher P exported in eggs in 2007 than 1995, though Dane County data specifically for 1995 are not available through the USDA NASS online database. The number of layers in Dane County was 63,914 in 1992 and 75,052 in 2007.

We calculated egg P export as follows. The number of layers in Dane County was scaled to the watershed as described above. The number of eggs per layer per year was estimated for statewide data because county-specific data is not reported for years after 1992. For years 1981 through 1992 where data are available for both the state and county, there was no statistically significant difference between the mean for state and county numbers, though the year-to-year variance was greater for the county than the state. We used the mean value for the state as the most-likely estimate for eggs per layer per year (278). We bounded this mean value with a minimum, which was the historical low value for Dane County (215) and a maximum, which was the most likely value, plus approximately half of the historic range of the Dane County values in order to account for the increasing trend in egg yield (308). Data shown in Fig. 4.

To estimate mass of each egg, we bounded the calculation assuming that all eggs were "medium" in the minimum case, large/extra large in the most likely case, and "jumbo" in the maximum case according to the USDA grading standards for table eggs (USDA-AMS 2000). These corresponded to masses of 50, 60, and 71 grams per egg, respectively.

All eggs were assumed to have 0.0021 grams P per gram of egg (Lorimor et al. 2000).

Thus the minimum P exported in eggs was:

Number of layers * minimum yield * minimum egg size * proportion P, or (75,052 * 0.204) layers * 215 eggs per layer per year * 0.05 kg per egg * 0.0021 kg P per kg egg = 346 kg P per year. Likewise, the maximum value was (75,052 * 0.204) layers * 308 eggs per layer per year * 0.071 kg per egg * 0.0021 kg P per kg egg = 703 kg P per year.

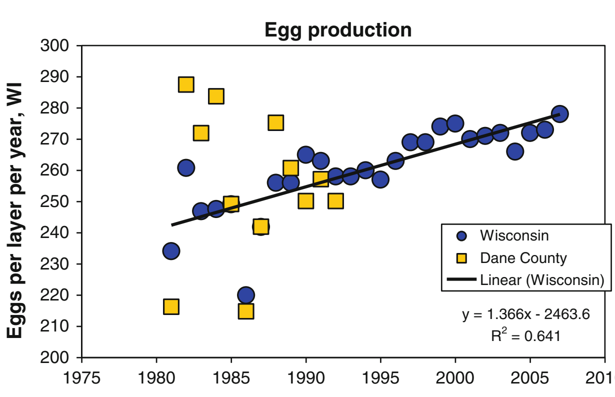

Fig. 4 Egg yield for hens in Dane County and Wisconsin

Animal export

Cattle

The number of cattle sold in Dane County was reported in the Census of Agriculture for 2007. This is broken down into categories of calves (<500 lbs) and cattle (>500 lbs).

Calves sold for veal can be sold immediately after birth to be raised in a dedicated veal farm or can be raised on location to full slaughter weight. We bracketed the mass of calves sold using these two extremes, with the mean as the most likely case. In the minimum, we assumed all calves were sold (and exported from the watershed) soon after birth at a weight of 100 lbs. In the maximum, we assumed all calves were raised within the watershed to a veal slaughter weight of 300 lbs.

Cattle (>500 lbs) sold are likely a combination of mature Holstein cows, which are being culled from the herd along with beef cows, and dairy steers. Cattle raised for beef have an average slaughter weight of 1140 lbs (Greiner 2002), while mature Holstein cows in Wisconsin have an average weight of 1500 lbs (Hoffman et al. 1992). We used these two values as minimum and maximum values for cattle export with the mean as the most likely.

For the proportion of P in cattle, we used 0.007 (Lorimor et al. 2000).

Hogs and pigs

According to communication with area experts, there are no longer any commercial swine operations within the Lake Mendota watershed (P. Nowak, University of Wisconsin-Madison, personal communication). Therefore, our minimum and most likely estimates for Hogs and Pigs export is set at zero. Our maximum estimate is calculated as if the watershed has a proportional share of Dane County's swine population.

The 2007 Census of Agriculture reported the total number of hogs and pigs sold from the county. In 1997 and years prior, this was split between feeder pigs (40–80 lbs) and non-feeder pigs. According to the data available, approximately 30% of the pigs sold in years with these data were feeder pigs. Therefore we estimated that 30% of the pigs sold were on average 60 lbs, while the remaining 70% were an average of 250 lbs.

Crop export

Corn, wheat, barley, oats, and rye for grain; soybeans (for beans); and tobacco

Total harvest for the crops above was obtained for Dane County from the 2007 Census of Agriculture. These were converted to watershed values as described above. Harvest was converted from yield units to P mass using conversion factors from Laboski et al. (2006, Table 4.3) for each crop.

Green peas and snap beans

Peas and beans were a minor component of the budget but were included to be consistent with the 1995 budget of Bennett et al. (1999).

County level harvest data for peas has not been reported since 2003. However acres planted in peas has continued to be reported. We used annual yields and acres planted from 1968 to 2003 to develop a linear model for yield (tons/acre) over that time period. Yield increased linearly from 1968 to 2003 ($R^2 = 0.56$). Predicted yield for 2003 was 2.45 tons per acre and as this was the last year data were available for Dane County yields. We did not extrapolate beyond 2003 and instead used the 2003 prediction as a conservative yield prediction for 2007. We did not use the actual 2003 yield as it appeared to be an outlier (Fig. 5). Interestingly, there has been a very steady decline in acres planted in peas in Dane County over the 35 year record, from 11,000 acres to approximately 500 acres.

Similar to green peas, harvest data for snap beans has not been reported for the county level since 2001. Acres planted in beans was reported in the 2007 data, however. We used the linear prediction for 2001 yield as a conservative estimate for 2007 yield as in the case for green peas. For both peas and beans we converted from mass harvested to mass P using conversions found in Laboski et al. (2006); Fig. 6.

Forage crops

Forage crops were assumed to stay within the watershed as these tend not to be cash crops but rather are grown to support livestock on the farm (J.M. Powell, US Dairy Forage Research Center, University of Wisconsin, pers. comm.). Therefore these were not counted as exports from the watershed.

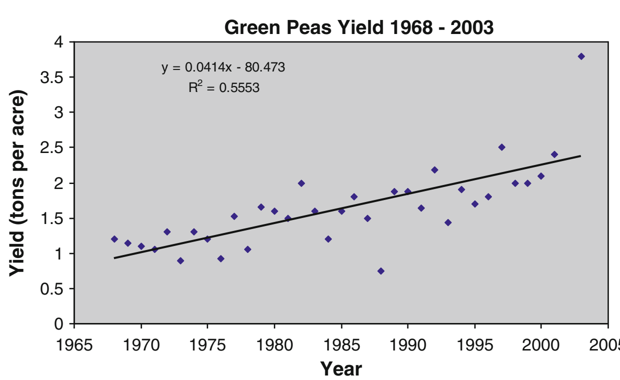

Fig. 5 Yield of Green Peas (tons per acre) for Dane County, WI. Data were not reported after 2003

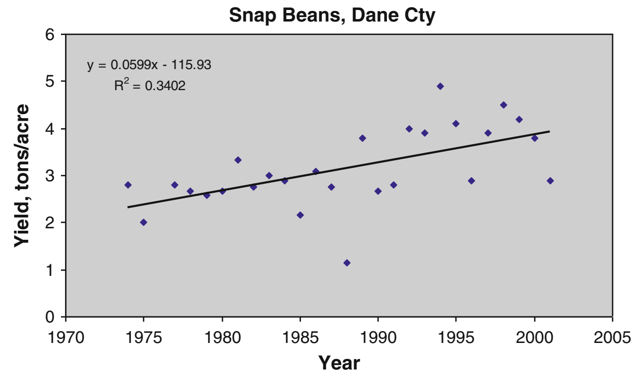

Fig. 6 Yield of snap beans (tons per acre) for Dane County, WI. Data were not reported after 2001

Export to Lake Mendota

Export to Lake Mendota was estimated to be the mean value of the Lake Mendota P load reported in Carpenter and Lathrop (2008). Minimum and maximum values were the 10th and 90th percentiles of the data, respectively.

Calculating imports

Feed supplements

Feed supplements were calculated based on a study of supplements to South Central Wisconsin dairy farms by J.M. Powell et al. (2002). Powell et al. reported the average mass of food consumed per cow per day, the percentage of that feed that is P, and the proportion of that feed that is from forage vs. mineral supplements. In personal communication with J.M. Powell, he suggested that amount of P supplements fed to cattle has decreased steadily over the last decade for reasons outlined in the main text of our paper (J.M. Powell, US Dairy Forage Research Center, University of Wisconsin, pers. comm.). We bounded our estimates of total feed supplements using a maximum value where all cows in the watershed receive supplements, a minimum where only lactating cows receive supplements, and a most likely value that is an average of the two.

Urban fertilizer

Our minimum estimate of urban fertilizer assumed that only lawns low in P were fertilized. To be in compliance with the Dane County P ordinance for lawns (Ord 80), a soil test demonstrating P-deficient soils needs to be conducted in order to legally apply chemical P to lawns. Since the ordinance went into effect, only 200 lawns have been tested in the watershed, and of those only 20% show low P. Thus of the approximately 200,000 lawns in the watershed, only 40 of them (0.02 percent) can legally apply P (D.

Soldat, University of Wisconsin Soil Science Extension, personal communication). We therefore used zero as our minimum estimate for urban P fertilizer use. Maximum estimates assumed that 20% of the 200,000 lawns in the watershed were fertilized twice a year which is a baseline recommended rate of application (Soldat and Petrovic 2008). The most likely estimate was an average of the maximum and minimum estimates.

Agricultural fertilizer

The import of chemical P fertilizer is one of the biggest uncertainties of this budget due to the lack of data available publicly at the county or watershed scale.We know that recommended rates of P application have declined and that Nutrient Management Plans in the watershed have made farmers more aware of their P needs and management.

Our estimates of fertilizer imports are based on recommendations for each crop at each of three different soil P test levels from the University of Wisconsin Extension – Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin (Laboski et al. 2006). On average, Dane county soils fall into the "Excessively High" phosphorus category for which the recommended P application to soils is zero. An exception is reluctantly made in the guidelines for applying starter fertilizer for corn crops even in excessively high phosphorus soils. Our minimum values for P imports thus include zero imports for all crops with the exception of a low rate of starter fertilizer application for corn in the watershed.

Despite the recommendation of zero P fertilizer, we suspected that farmers apply some P fertilizer in hopes that it will provide a "bumper" crop (P. Nowak, University of Wisconsin-Madison, personal communication). Therefore our "most-likely" values for fertilizer application used the recommendations for "high" soil P instead of "excessively high" soil P. In the maximum case, we used recommendations for the "optimal" soil test P category which allows for P to be applied at approximately the same rate as it is removed in crops.

In all cases, the amount of chemical P imported was reduced by the amount of manure P in the watershed available to be spread and credited. For the crediting, we assumed 64% of the manure was able to be collected and that, 60% of the manure P was plant-available and therefore credited.

Manure production in the watershed

The 2007 Census of Agriculture categorized cattle and cows into 3 categories: beef cows, milk cows, and other cattle. The "other cattle" category included heifers (cows which have not yet calved), and all male cattle (beef steers, dairy steers, bulls, and calves). In order to use these data with the Midwest Plan Service manure P production rates, we needed to further divide these categories to match the MPS categories as follows.

Previous years of the agricultural census further divided the "other cattle" category between heifers and male cattle and we used these data to determine the proportion of this category which were heifers (54%) versus male cattle (46%).

Cattle categorized as "milk cows" were further divided between lactating (84%) and dry (16%) cows based upon the ratio found for south central Wisconsin dairy farms by Powell and others (2002). All cows in these two categories were assumed to be full grown, mature Holstein cows (1500 lbs).

Cattle in the "beef cows" category were all assumed to be full grown and were assumed to be the average size for mature beef cows (1139 lbs, Greiner 2002).

Cattle in the heifers category were divided between "young" and "mature" groups using mean data from south central Wisconsin herds (Powell et al, 2002). "Young" heifers are between 0 and 7 months old and account for 42% of heifers. "Mature" heifers are older than 7 months but not yet 24 months and account for 58% of heifers. We used a linear age-weight relationship (Hoffman 2006) and assumed a uniform distribution of ages within each of these two categories to determine the mean size of heifers in each.

Male cattle (beef and dairy) are primarily used for veal and beef production with a very small number kept as bulls. We assumed all cattle in this category were steers and raised until age 13 months at which point they are exported from the watershed. Within this category, we assumed a uniform age distribution such that the mean age was 6.5 months. This was potentially a high estimate as it assumes all males are raised to full size. More likely, because this is a predominately dairy watershed, a significant portion of these would be veal calves and the mean age would be much lower.

Manure production rates (lbs maure/lbs animal), as well as P concentrations in manure, were obtained from Lorimor et al (2000) for heifers, lactacting cows, dry cows, beef cows, and beef steers. We multiplied these rates by the numbers and mean size of cattle in each of these categories to estimate the total amount of manure produced in the watershed.We bounded our estimates for cattle by +/− 30% (Lorimor et al. 2000).

Chicken manure was estimated for layers and broilers using manure P production data from Lorimor et al. (2000).

Hog manure was set to zero for our minimum and most likely values for the same reasons as hog and pig export above. The maximum value assumed hogs in the watershed are proportional to the county as a whole. However we did

Table 4 Estimates of manure production within the watershed

	Manure production		
	Min	Most likely	Max
Cattle manure P	308,120	440,170	572,220
Chicken manure P	3,180	3,180	3,180
Hog manure P	0	0	35,620
Total manure P	311,300	443,350	611,020

Scenario 3 manure digesters increase in output includes several loss terms related to collection and separation, which are described in the "Methods" of the main text

not have age/size structure data for hogs and pigs. Here we assume the average hog is 150 lbs, half-way to market weight, and used the Lorimor (2000) values for manure P production (Table 4).

A note on uncertainty in estimates

More uncertainty was associated with P inputs compared to outputs in the watershed. Uncertainties arose when estimating P fertilizer applied to agricultural soil because comprehensive and accurate fertilizer application and manure spreading rates in the watershed are not compiled or available publicly. Uncertainties in estimates of P fertilizer application to urban lawns also existed due to lack of reported fertilizer application rates on residential, commercial and industrial lawns. Estimates of animal feed supplements also introduced uncertainties in terms the quantity of supplements and to which types of cows the farmers are giving supplements to. Because of this lack of concrete data, we were forced to estimate based on recommended rates of fertilizer and feed supplement use combined with personal accounts and publications of scientists who investigate those areas.

Uncertainty in estimates also arises in converting county data to watershed data. This analysis assumes that agricultural practices are distributed uniformly across the agricultural land of the county. However, we have heard anecdotal evidence that the north-east part of the county may have more dairy operations, while the south west half of the county is more dominated by cash-grain operations (R. Lathrop, Wisconsin Department of Natural Resources, personal communication). If this is indeed the case, we may be overestimating agricultural fertilizer use while underestimating feed supplements, manure production, export of milk and cattle, etc.

Fewer uncertainties in outputs existed because production data and P content for crops are readily available in public databases. Uncertainties in outputs arose in estimates of P in livestock export because this is dependent on the size and type of animal exported. We attempted to capture the range of variability by examining exports at plausible extremes of animal sizes.

Nutrient management at the watershed scale would be greatly aided by aggregation of data at that scale rather than at political, county or state boundaries.

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