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Dynamic spatially explicit mass-balance modeling for targeted watershed phosphorus management
I. Model development

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ABSTRACT

Surface waters are frequently impaired by excessive phosphorus (P) from nonpoint sources, especially in regions of intensive livestock agriculture. Despite concerted efforts to apply new management measures, reductions in nonpoint source P loads have been difficult to accomplish. Watershed management to reduce P export could be more cost-effective if treatments were targeted to critical source areas at high risk for excessive P export. These critical source areas can be defined as the intersection of P source areas and active runoff contributing areas; such areas vary in space and time due to watershed characteristics and management practices. We developed an approach to identify, analyze, and map high-risk areas for P export by integrating spatial data with land use and agronomic data. We evaluated changes over time and space in soil P concentration and P export in response to changes in inputs and outputs with a dynamic mass-balance simulation model running in grid cells across a watershed. The temporal and spatial relationships that define the risk of P export are captured simultaneously using a raster-based distributed dynamic modeling approach and related to management interventions. Simulated responses to management interventions are analyzed and displayed spatially through a geographic information system (GIS). This approach allows the spatial distribution of P runoff risk to be tracked through time in response to long-term P input/output balance, evolving from either continuation of current practices or from management changes specifically targeted to areas of high P loss risk. Baseline simulations show that if present-day management continues, both soil test P and P export will increase dramatically in some parts of a test watershed; critical P source areas in a watershed will evolve over time and are likely to occur in limited areas that can be identified and tracked. Model results can contribute to improved targeting of scarce resources by focusing management interventions on those areas at highest risk of nutrient loss. This paper describes the underlying principles of the model, discusses the process of model development, and presents the final modeling system. Application of the model to alternative management scenarios is discussed in a subsequent paper.

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1. Introduction

Many U.S. surface waters are impaired by excessive phosphorus (P) from nonpoint sources (USEPA, 2000). Management to reduce watershed P export is a priority and a challenge, especially in regions of intensive livestock agriculture (Sharpley et al., 1997; Daniel et al., 1994). However, it has proven difficult to integrate specific management actions with the dynamics of human activity, watershed characteristics, and P storage, cycling, and transport processes to achieve P export reduction goals.

Many factors control watershed P export, including hydrology, geology, soils, land use, agricultural and industrial activities, population, and waste treatment (Dillon and Kirchner, 1975; Omernik, 1976, 1977; Clesceri et al., 1986). In agricultural areas, P may accumulate in soils from over-application of nutrients from fertilizer or manure relative to crop need. Excessive soil P levels have been linked to high P losses in runoff, especially in areas of

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animal-based agriculture (Breeuwsma et al., 1995; Pote et al., 1996; Lander et al., 1998; Sims et al., 2000). Contributions to watershed P load from urban land, including wastewater discharges and stormwater, are also significant and may exceed those from agricultural land on an areal basis (Frink, 1991).

Early approaches to nonpoint source P management focused on field-scale transport issues, with erosion control as the principal tool. Subsequently, source issues were also addressed, primarily at the farm scale through nutrient management. More recently, both source and transport issues have been considered at the watershed level (Gburek et al., 2000b). Today, nonpoint source P export from watersheds is understood to be controlled by interaction between P sources and transport mechanisms.

In agricultural watersheds, soils are the major stock of P available for loss, along with fertilizers and manure applied to soils. Soil P content is determined by both management activities (e.g., nutrient application, and cropping) and by soil characteristics (e.g., drainage class, P sorption characteristics). All of these conditions vary spatially. Areas of excessive soil P also vary in time in response to P accumulation or depletion due to changing balance between inputs and outputs.

Transport of P in a watershed occurs mainly through surface runoff and erosion. It is widely believed that only certain watershed areas generate surface runoff that may transport P to a stream. Overland flow results either from infiltration excess, where precipitation cannot infiltrate because rainfall rate exceeds infiltration capacity of the soil, or from saturation excess, where precipitation cannot infiltrate because the soil is already saturated. In the humid Northeast, most storm runoff is believed to derive from saturation excess (Dunne and Black, 1970; Ward, 1984). These saturated runoff contributing areas (RCAs) vary spatially and temporally by geology, topography, soils, rainfall characteristics, and storm magnitude (Dunne and Black, 1970). As RCAs change in size with season or storm magnitude, they are referred to as variable source areas (VSAs) (Dunne and Black, 1970; Frankenberger et al., 1999). In general, only a small proportion of a watershed is believed to be responsible for the majority of P exported in runoff (Sharpley et al., 1994; Daniel et al., 1994; Heathewaite et al., 2000; Walter et al., 2000).

The intersection of high P source areas and probable RCAs defines critical source areas at high risk for excessive P export. Watershed management to reduce P export could be more cost-effective if treatments were targeted to these high P source areas (Gburek et al., 2000a,b). Walter et al. (2001) suggested that a 25% reduction in watershed soluble P loading was possible by adjusting the timing and location of manure application on hydrologically sensitive areas. This kind of management requires the ability to identify source areas, visualize how they may change through time and space, and adjust management programs accordingly. But government programs such as the Environmental Quality Incentives Program (EQIP) (USDA-NRCS, 2005) often ignore the spatial variability of P export risk and strive to promote interventions through voluntary participation across an entire watershed. Without considering hydrologic pathways that govern P transport, blanket management programs are likely to be too restrictive, too expensive, or both.

We developed an approach to identify, analyze, and map high-risk areas for P export by integrating spatial data (e.g., soil characteristics, topography) with land use and agronomic data (e.g., P application rates, cropping patterns). We evaluated changes over time and space in soil P concentration and P export in response to changes in inputs and outputs with a dynamic mass-balance simulation model running in grid cells across a watershed. The temporal and spatial relationships that define the risk of P export are captured simultaneously using a raster-based distributed dynamic modeling approach and related to management interventions. We spatially analyzed and displayed simulated responses to management interventions using a geographic information system (GIS). This approach allows the spatial distribution of P runoff risk to be tracked through time in response to long-term P input/output balance, resulting from either continuation of current practices or from management changes specifically targeted to areas of high P loss risk.

This paper describes the underlying principles of the model, discusses the process of model development, and presents the modeling system. Application of the model to selected management scenarios in a test watershed is presented in Meals et al. (this issue).

2. Modeling approach

We combined principles of watershed mass-balance with the concepts of the P index and variable source area hydrology over a long temporal scale (decades). Our approach included four components – a dynamic watershed mass-balance P model, the Vermont P index, identification of runoff contributing areas, and GIS – combined in a spatial modeling environment.

2.1. Dynamic watershed mass-balance P modeling

Although we ultimately simulate the spatially and temporally dynamic behaviors of P at the watershed scale, the model is based on the building-block of a comprehensive accounting of rates at which P mass enters and leaves a homogeneous land unit (pixel) over time and the amount of P mass stored in that pixel at any time. Dynamic mass-balance models are based on the principle that if the sum of the inputs (fluxes) of P mass into a pixel exceeds the sum of the P mass outputs from the pixel, the mass (stock) of P stored in the pixel increases; if inputs are less than outputs the stock decreases. The amount of P in a pixel is an important determinant of the rate at which P is exported from the pixel. For dissolved P in runoff the rate of export is proportional to soil test P (Sharpley, 1995). This kind of model can be useful for assessing effects of alternative P management scenarios at the pixel-level.

At the watershed level, dynamic P mass-balance modeling can simulate P fluxes and stocks among agricultural, urban, and forest sectors of large watersheds by identifying and quantifying pathways of all significant import, export, cycling, and storage of P within the watershed. These principles are often used to develop scoping models useful in understanding how an ecological system works and to analyze the relative importance of processes and connections (Costanza and Voinov, 2001). This approach has been previously applied to the *Watershed Ecosystem Nutrient Dynamics* (WENDs) modeling process to explore long-term effects of watershed management strategies on environmental and economic goals (Cassell et al., 1998b, 2001, 2002; Aschmann et al., 1999). However, WEND models have not been spatially explicit and typically lump modeled activities into a single mass-balance model for agriculture, forest, and urban sectors, then link sector models together in a watershed model. Our challenge was to make mass-balance accounting for P spatially explicit over a complex watershed.

2.2. The phosphorus index

The P index (Lemunyon and Gilbert, 1993) was developed by scientists from the USDA-Natural Resources Conservation Service (NRCS), USDA-Agricultural Research Service (ARS), and several universities to identify landscape areas where the risk for P accumulation and loss is highest due to P inputs and land

characteristics. Versions of the P index are used in 47 states to evaluate the potential for P loss by accounting for source and transport factors (Sharpley et al., 2003). The P index has been able to accurately describe site vulnerability to P loss at the farm scale (Sharpley et al., 2001). Documented correlations between P index values and P concentrations in surface waters have shown that the P index can also be used at regional scales to prioritize P loss vulnerability (Birr and Mulla, 2001). Because the P index is a snapshot in time, it is limited in its ability to consider long-term changes in P accumulation in a watershed. We sought to embed the concept of the P index into the context of long-term mass-balance dynamics.

2.3. Runoff contributing areas

Our modeling framework incorporated the concept of variable RCAs as an indicator of P transport potential by surface runoff. We assumed that runoff is generated by saturation excess driven by topography and local hydrologic properties. Rapid interflow from upgradient, impaired drainage, and converging subsurface lateral flows commonly contribute to saturation excess runoff (Hewlett and Hibbert, 1967; Beven and Kirkby, 1979). We mapped potential RCAs based on storm magnitude and incorporated this transport potential into long-term simulations of watershed P loss.

2.4. Geographic information system

We used the capabilities of *ArcGIS* (ESRI, Inc.) to prepare, organize, tabulate, and analyze spatial data necessary for input into the modeling system and to display results of model simulations.

3. Methods

3.1. Mass-balance model

The starting point is a mass-balance model of a single pixel—the *PPBalModel*, formulated within the dynamic simulation modeling framework provided by the *STELLA* v. 8 software package (ISEE Systems Hanover, NH, http://www.iseesystems.com). The *PPBalModel* is defined by the pixel area (3600 m^2), the thickness of the active soil layer, and the height of vegetation. At any point in time, a mass of P is stored inside this pixel volume, some in the vegetation, but most in the soil layer. The volume of the soil layer is a function of pixel area and the thickness of the surficial layer in which applied P is stored, which varies with land use. We assumed a thickness of 14 cm for a pixel in corn, the typical plow depth in annual tillage, but a thickness of 5, 4, and 4 cm for the surficial soil layer of hay, pasture and urban pixels, respectively, because such soils are not subject to annual tillage (unless they are rotated with a tilled crop). For forested pixels, we assumed a soil layer thickness of 14 cm because of the relatively thick litter layer on the forest floor. *PPBalModel* calculations assume the characteristics of the surficial soil layer are homogeneous.

Phosphorus input and output mass fluxes accounted for in the *PPBalModel* include P input in atmospheric deposition, P added to the land in the form of mineral fertilizers and/or manure to support crop production or turf grass, P output in harvested crops, P lost by runoff, and P lost by leaching. The balance of all P inputs and outputs, reflected as the sum of P contained in the soil and vegetation in the pixel in an annual time step, determines how the amount of P stored in the pixel changes over time. This P balance is an index of both the long-term agronomic productivity of the pixel soils and the pixel's potential to affect water quality. Note that the mass-balance model does not include P input from adjacent pixels that might contribute runoff. Routing of water and P through the landscape was beyond the scope of preliminary model development.

Fundamental parameters of the *PPBalModel* vary across the landscape of pixels according to land use or other pixel characteristics. For example, initial soil test P is higher for a pixel in corn than for a hayland pixel; erodibility varies with soil type. Pixel-level accounting of the amount of P stored and the rates at which P enters and leaves a pixel over time, when modified by changing the characteristics of each pixel in time and space, provide a way to assess P dynamics at the watershed level.

The *PPBalModel* computes the P mass balance in a pixel in an annual time step over the duration of a simulation run. The model simultaneously tracks change in the annual P mass balance for pixels in five different land uses (corn, hay, pasture, forest and urban) for a number of management conditions that emulate real-world management of nutrient addition, erosion control, etc. The model is based on algorithms that incorporate fundamental notions describing P movement through managed landscapes. For example, for each pixel, the Revised Universal Soil Loss Equation (RUSLE) (USDA-ARS, 2006) is used to estimate annual soil loss, total annual runoff is determined by the USDA Curve Number Technique (USDA-SCS, 1985). The soluble P concentration in the runoff and infiltrating water is calculated from an empirical relationship describing runoff soluble P concentration as a function of soil test P (Modified Morgan) for soils in the Champlain Valley of Vermont (Jokela et al., 2004a).

Whenever the sum of all TP inputs exceeds the sum of all TP outputs, the pixel accumulates TP yielding an increase in the soil test P levels. If this condition persists, soil P levels may become high enough to cause off-site environmental degradation due to high P levels in runoff and infiltrating waters. The reverse occurs when TP outputs exceed TP inputs in a pixel and the surficial soil layer is depleted of its TP stock. This condition, if allowed to persist within the pixel, would eventually impair crop productivity.

Except for atmospheric deposition, TP inputs and outputs are defined by the pixel land use and land management. The fundamental parameters of the *PPBalModel* can vary across the landscape of pixels according to land use or some other condition of the pixel. An urban pixel may receive high fertilizer P inputs, but is unlikely to receive manure. Removal of P in harvested silage corn will differ from P removal in hay harvest. While the *PPBalModel* is a single unit model, it includes distinct internal pathways and parameters for different land uses.

The TP output from a pixel is the major factor causing degradation of off-site water bodies and management can affect this output. Because the TP in runoff is often predominantly associated with the soil particles lost from the pixel, a management practice that retains sediment particulates within the pixel (e.g., erosion control) can lower P loss. Likewise, a management practice that reduces the amount of surface runoff leaving the pixel can reduce losses of both particulate and soluble P. However, simultaneously, any practice that might increase soil P levels in the surficial soil layer increases runoff P losses because the concentration of P dissolved in runoff is proportional to soil test P level. Whenever practices are employed in which the sum of P inputs in manure and fertilizer exceeds P outputs in harvested crops, soil P levels increase in the surficial layer. This is prevalent in modern production agriculture and tends, over time, to increase P losses through both runoff and infiltration. Phosphorus output from a pixel is the result of a complex mix of all the above parameters.

Specific outputs from the *PPBalModel* allow tracking of many aspects of change in a pixel over time. These include parameters that track the level of P in pixel soils, and the rate of particulate and dissolved P exported from the pixel. All *PPBalModel* calculations are

Table 1
Input data for Vermont P index (Jokela, 2005)

Parameter	Explanation
Location (county)	Determines growing season and snowmelt volumes
Elevation zone	Higher elevations receive more precipitation and have more runoff
Soil test P	Available P, ppm by modified Morgan's extraction
Reactive soil aluminum	Value affects how much added P becomes tightly bound in soil, rather than appearing in runoff
Manure rate	One or two manure applications, lb/ac P_2O_5
Manure application times	Affects probability that runoff will occur (each application)
Manure application methods	Incorporation by tillage reduces exposure of manure P to runoff (each application)
Manure time to incorporation	Timing affects probability that runoff will occur (each application)
Fertilizer rate	Fertilizer application, lb/ac P_2O_5
Soil erosion rate	Estimated by RUSLE I, t/ac
Soil series	Defines the hydrologic soil group (determining runoff) and soil texture (determining influence of buffer on sediment retention)
Surface cover	% modifies base runoff amount estimated from elevation and location
Crop/vegetation type	Modifies base runoff amount estimated from elevation and location
Total distance to stream	Used to calculate a sediment delivery ratio
Vegetated buffer width	Used to modify sediment delivery ratio
Manure spreading setback	Width in feet of manure setback
Sediment trap/erosion control	Existence of sediment control reduces sediment delivery

carried on an annual time step so the input data and the model outputs are typically annual averages and annual totals. Simulation runs of any number of years can be defined.

In the *PPBalModel*, P is modeled as elemental P based on the "total P" typically analyzed in water (USEPA, 1983). Total P values are related to soil test P values by empirical (linear regression) relationships used by Jokela (2005) in his adaptation of the Vermont P index.

Finally, it should be emphasized that once the *PPBalModel* simulates P leaving a pixel, the model considers that it has moved directly into the drainage net and exported from the watershed. This has been a fundamental characteristic of previous watershed-scale versions of the dynamic mass-balance models (Cassell et al., 1998a). Thus, estimates of P export from our simulations cannot be directly compared to measured loads at the mouth of the watershed because model estimates ignore P transformations and attenuation that may occur with overland flow or in-stream cycling. Model calculations of P mass leaving a pixel can, however, be expressed as load per unit area and compared to published areal export coefficients as a means of assessing the reasonableness of simulation results.

3.2. Phosphorus index

The Vermont P index includes factors for P source potential (soil test P, fertilizer P, and manure P) and P transport potential (soil erosion, runoff, and buffer distance), as well as consideration of manure/fertilizer method, timing, rate of application, and reactive soil aluminum level (Jokela, 2000, 2005). Input data for the Vermont P index are given in Table 1.

We incorporated a modified version of the Vermont P index into the *PPBalModel*. Some parameters of the Vermont P index, including distance to stream, buffer width, manure setback, and sediment trap, were omitted because these data were not directly applicable to pixels, as compared to fields, for which the P index was originally intended. We rescaled values of the modified P index calculated in the model to be comparable to values of the original index with respect to relative risk levels. Values of the Vermont P index calculated for each pixel were used to target management measures in subsequent modeling of alternative management scenarios (Meals et al., this issue).

3.3. Runoff contributing areas

Because runoff contributing areas change with precipitation intensity, variability in contributing areas must be included in a long-term management framework. Approaches for watershed scale estimation of runoff contributing areas reported in the literature include complex engineering methods (Boughton, 1990), soil moisture balance models (Zollweg et al., 1996), the Natural Resources Conservation Service (NRCS) curve number method (Steenhuis et al., 1995), and empirical relationships between peak flow and contributing distance from the stream (Gburek et al., 2000b).

We delineated estimated runoff contributing areas (RCAs) for a test watershed in a series of steps using a set of design storms, land use, soil hydrologic group, and a digital elevation model (DEM). Design storms (24-h) for the region with return periods from 1 to 50 years were selected from published precipitation maps (USDA-NRCS, 1986) (Table 2). Runoff from each of the design storms was estimated using the NRCS curve number (CN) technique (USDA-SCS, 1985). We assigned curve numbers to each of the land uses and soil hydrologic groups occurring in the watershed coverage, assuming "good" hydrologic condition, antecedent moisture condition II, and prevailing agricultural practices in the region. We used a distributed CN approach to estimate runoff depth from each pixel using that pixel's appropriate CN, then calculated watershed runoff depth as the mean of all pixel runoff depths. This distributed approach is preferred because a composite approach based on areal weighting of component curve numbers tends to underestimate runoff due to the non-linear relationship between CN and runoff depth, especially for wide ranges of CN values (Grove et al., 1998). We used *Arc GIS* and a spreadsheet to calculate runoff depth based on CN and soil hydrologic group. Results are shown in Table 2.

For each design storm, we estimated the percent of watershed area contributing runoff as the ratio of estimated watershed runoff depth to precipitation depth, following the approach of Gburek et al. (2002). In this simplified application of the VSA concept, the extent of the watershed contributing to surface runoff, assuming

Table 2
Estimated runoff and percent of watershed contributing runoff from design storms in the test watershed

24-h storm return period	Precipitation depth (mm)	Runoff depth (mm)	Watershed area contributing runoff (%)
1 year	53.3	14.7	27
2 years	63.5	20.6	32
5 years	86.4	36.1	41
10 years	96.5	43.4	45
25 years	114.3	57.2	50
50 years	124.5	65.3	52

100% conversion of precipitation to runoff on saturated contributing areas, is

$$A_c = \left(\frac{R_d}{P_d}\right) \times A_w \quad (1)$$

where A_c is the watershed area contributing surface runoff, R_d is the estimated storm runoff depth, P_d is the precipitation depth, A_w is the total watershed area.

The ratio of R_d to P_d indicates the percent of the watershed that functions as an RCA for that storm. The percentage of test watershed area contributing runoff (i.e., the size of the RCA) for each design storm is shown in Table 2.

To designate which pixels comprised the RCA for each design storm, we used a topographic "wetness index" included in the Terrain Analysis Using Digital Elevation Models (TauDEM) analytical package, available as an extension for *Arc GIS* 9.0 (Tarboton, 2002):

$$\ln\left(\frac{\tan\beta}{a}\right) \quad (2)$$

where a is the cumulative upslope area draining through a point (per unit contour length), and $\tan\beta$ is the slope angle at the point.

The TauDEM wetness index is the inverse of the topographic index, which is a component of TOPMODEL, a topographically based variable source area watershed hydrologic model (Beven and Kirkby, 1979; Quinn et al., 1991), and reflects the tendency of water to accumulate at any point in the watershed (in terms of a) and the tendency for gravitational forces to move that water downslope (expressed as $\tan\beta$ as an approximation of hydraulic gradient) (Quinn et al., 1991). Watershed regions that drain large upstream areas or are very flat tend to yield high values of the index, are most likely to become saturated during precipitation, and are therefore most likely to be areas that contribute surface runoff (Page et al., 2005).

For this application, the lowest values of the wetness index represent the areas most likely to become saturated during precipitation and most likely to function as RCAs. We sorted pixels in rank-order of wetness index from lowest to highest. To assign pixels to a RCA for a particular storm, we identified the point in the cumulative frequency distribution of index values corresponding to the percent of watershed area estimated to contribute runoff for that storm (Table 2). Then, all pixels with index values less than or equal to that value were assigned to that RCA. For example, 27% of the watershed was estimated to fall in a RCA for a 1-year storm. The wetness index value at the 27th percentile in the distribution is 0.0000; all pixels with wetness values equal to 0.0000 were assigned to RCA 1. Similarly, the wetness value at the 32nd percentile (2-year storm) is 0.0001; all pixels with wetness values less than or equal to 0.0001 but greater than 0.0000 were assigned to RCA 2. Runoff contributing areas estimated by this method are mapped in Fig. 1.

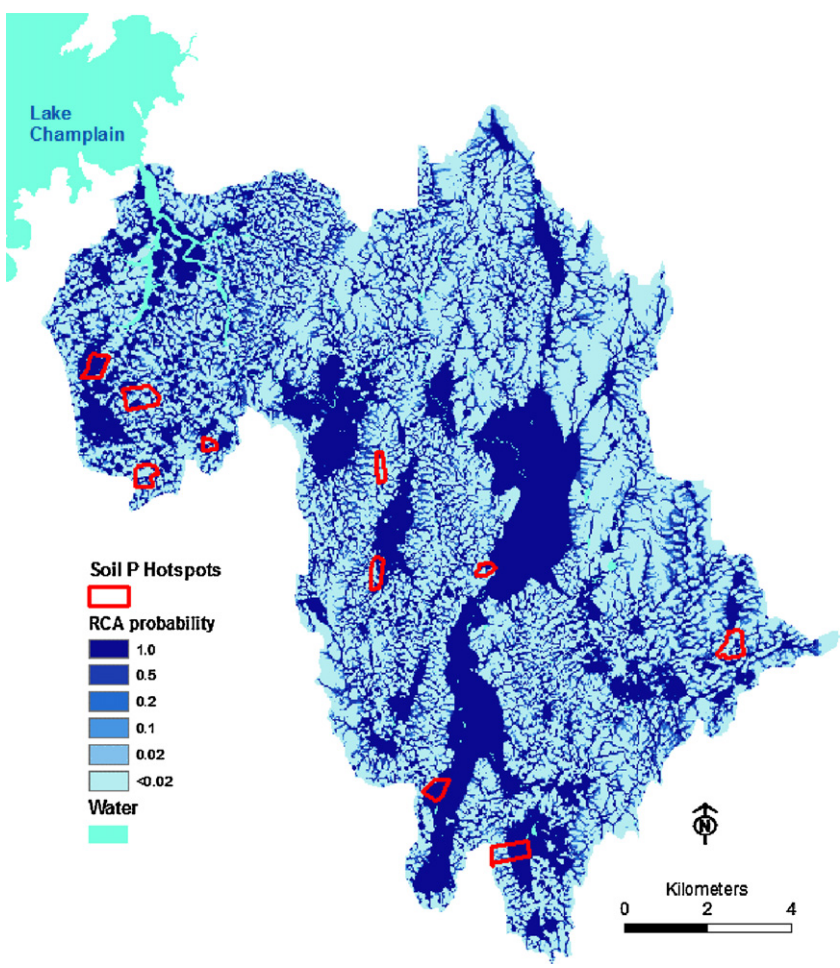

Fig. 1. Map showing runoff contributing area (RCA_p) probability for pixels in the test watershed. A pixel with $RCA_p = 1.0$ is expected to generate surface runoff in a 1-year storm, i.e., each year; a pixel with $RCA_p = 0.1$ is expected to generate runoff only from a 10-year or larger storm, i.e., 1 year in 10. Pixels assigned a $RCA_p < 0.02$ are expected to generate runoff only from storms exceeding those with a 50-year return period. Polygons outlined in red indicate zones of elevated initial soil test P.

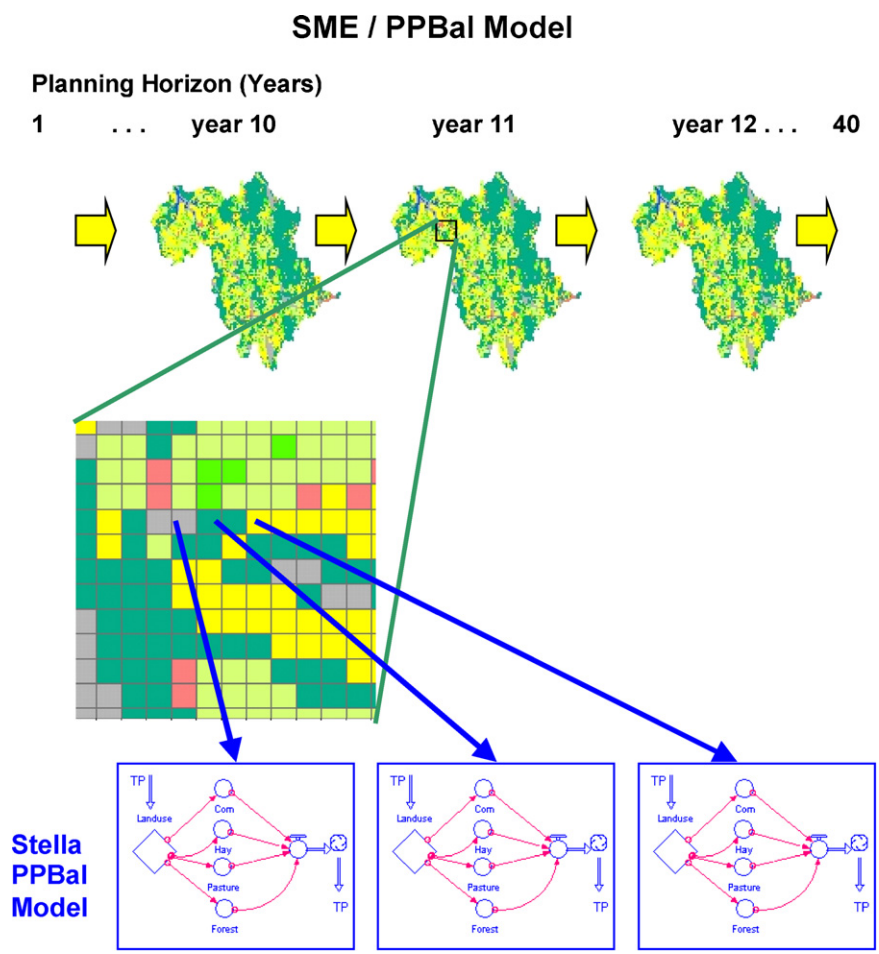

Fig. 2. Schematic diagram of the DISPLA approach based on the *Spatial Modeling Environment* (SME) and the *PPBalModel*.

3.4. Spatial modeling environment

We used the *Spatial Modeling Environment* (SME) (Maxwell and Costanza, 1997; Costanza and Voinov, 2001; Maxwell, 2003) to link the pixel-based dynamic mass-balance model with a watershed-level GIS. SME allows a STELLA model to be simultaneously executed across a complex multi-pixel (raster) landscape at an annual time step. Non-spatial models are run in each cell of a gridded model landscape (Fig. 2). SME is the computational engine (GIEE, 2004; Maxwell et al., 2003) that links local unit models with input time series and GIS spatial data.

4. Results

Following the approach described above, we combined a pixel-level mass-balance model, the P index, RCA, and GIS in a spatially and temporally explicit framework at the watershed level. We call this framework the *Dynamic Interactive Simulation of Phosphorus Loss Areas* (DISPLA) model. To fully illustrate model dynamics, we first present results of *PPBalModel* simulations for individual pixels, then results of a watershed-level baseline simulation in a test watershed. Application of DISPLA to alternative management scenarios is presented in Meals et al. (this issue).

Table 3
Values for some *PPBalModel* parameters that define the initial or present-day conditions for pixels in corn, hay, pasture, forest and urban

Model parameter (units)	Pixel land use category				
	Corn	Hay	Pasture	Urban	Forest
Manure TP input (kg P ha^{-1} $year^{-1}$)	53	24	0	0	0
Fertilizer TP input (kg P ha^{-1} $year^{-1}$)	29	15	0	9	0
Vegetative TP uptake (kg P ha^{-1} $year^{-1}$)	43	29	0	0	0
Soil P assay (mg MMP kg $soil^{-1}$)[a]	9.0	6.0	5.5	15.0	3.0
Depth surficial soil (cm)	14	5	4	4	14
Curve number[b]	86	81	74	84	70

These values remain unchanged during *PPBalModel* baseline simulations.
[a] MMP = modified Morgan soil P.
[b] CN for hydrologic group C.

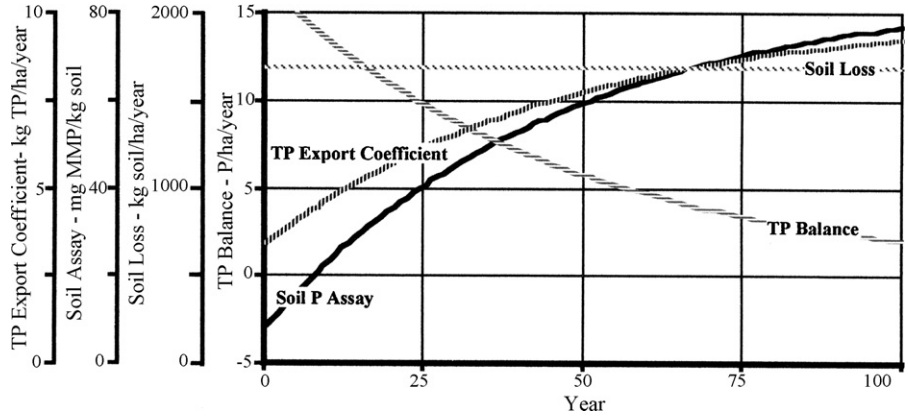

Fig. 3. Graph of long-term P dynamics for a pixel in corn as computed by the *PPBalModel*. The simulation shown represents baseline conditions in which present-day conditions in the pixel are those shown in Table 3 for the entire 100-year period; no management measures were implemented.

4.1. PixelPBalance model

Interpretation of the patterns of spatial and temporal variability in P export and soil P levels as well as long-term watershed-scale trends in P export are facilitated by first understanding the fundamental dynamics modeled by the *PPBalModel*.

For pixels in all land use categories, the *PPBalModel* permits the user to:

- define the soil and hydrologic conditions for the pixel; such inputs specify characteristics of the pixel that do not change over time;
- designate the level of soil test P for the surficial layer of the soils in the pixel; this input designates an initial condition for the pixel, a condition that changes over time and is tracked by the *PPBalModel*;
- assign the level of P additions to the pixel in manure and/or fertilizer; these levels are inputs to the model and may change in accordance with nutrient management;
- assign the level of P exported from the pixel in harvested vegetation (crops or trees);
- specify the density of grazing animals and grazing conditions of pixels in pasture; and
- emulate a number of different P management practices for agricultural pixels in corn or hay and for urban pixels, e.g., by changing levels of P additions and soil loss or changing pixel land use during the simulation.

Table 3 lists some of the most important parameters for each land use category that must be defined at the beginning of a simulation. The values represent a present-day condition for each land use selected in consultation with state and local agronomists, agricultural specialists, and agency professionals; however the degree to which the values selected accurately represent all watershed land is uncertain.

Fig. 3 shows long-term trends in several important model outputs from a 100-year baseline (present-day condition) simulation for a pixel in corn. Whenever *TP Balance* (the sum of all P inputs to the pixel minus the sum of all P outputs) is positive, the soil test P (*Soil P Assay*) in the pixel increases and P export in runoff (P export *Coefficient*) also increases, because export of both particulate and dissolved P is proportional to soil test P. The increase in the P *Export Coefficient* is due *solely* to the increased soil test P because soil erosion rates (*Soil Loss*) remained constant over the 100-year simulation. For this simulation, *TP Balance* remained positive over the entire 100-year period; thus both *Soil P Assay* and *P Export Coefficient* increase over the entire simulation period.

The distinct set of specific conditions that characterize each land use can yield different long-term trends in *Soil P Assay* and *TP Export Coefficient*. Fig. 4 shows results from 100-year *PPBalModel* baseline simulations that compare the long-term trends for pixels in corn, hay, pasture, urban, and forest. Soil loss differed among

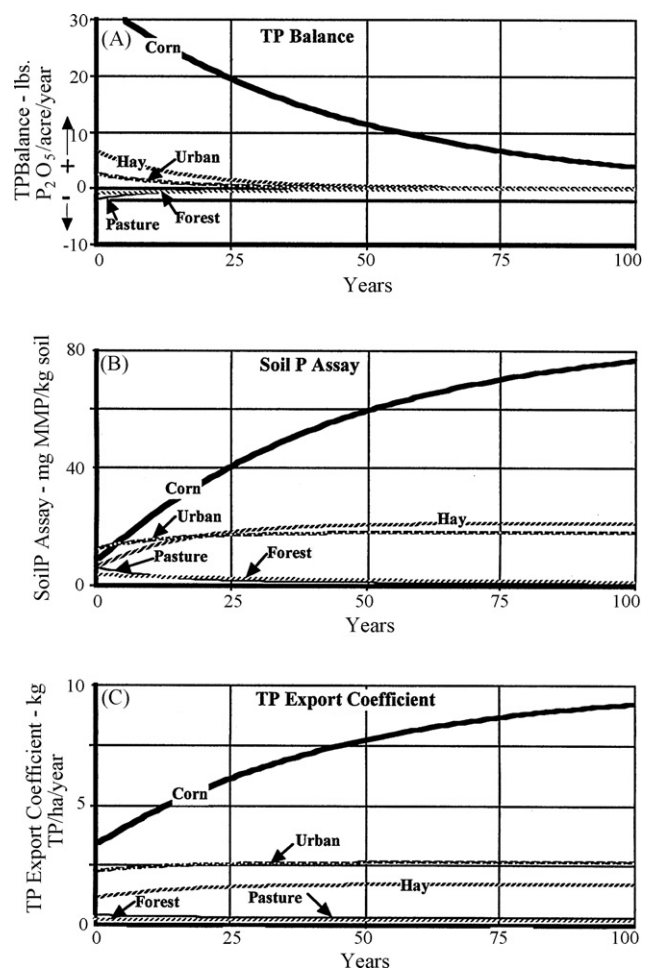

Fig. 4. Graph of long-term P dynamics for pixels in corn, hay, pasture, urban, and forest land use as computed by the *PPBalModel*. Trends are shown for: TP Balance (A), soil P assay (B), and TP Export Coefficient (C). The simulations shown represent baseline conditions in which present-day conditions in the pixel are those shown in Table 3 for the entire 100-year period; no management measures were implemented.

land uses but remained constant for each land use over the entire simulation.

At time zero the *TP Balance* for corn, hay, and urban pixels was positive, because more P enters the pixels than leaves. The *TP Balance* for pasture and forest pixels was negative, as pixel P export exceeds import (Fig. 4A). We assumed that forest land does not receive P fertilizer or manure and that pastures receive no fertilizer, while animal waste P inputs balance the P removed in vegetation consumed. Consequently, *Soil P Assay* and *TP Export Coefficient* initially increased for the corn, hay and urban pixels but decreased for the urban and forest pixels (Fig. 4B and C). While the *TP Balance* for the corn pixel remained positive over the entire 100-year simulation, the balance for hay and urban pixels approached zero by year 50, as does the *TP Balance* for the forest and pasture pixels. After year 50, the *TP Balance* was essentially zero (P inputs = P outputs) and the pixels approached an equilibrium condition with respect to P. On the other hand, the *Soil P Assay* and *TP Export Coefficient* for the corn pixel continued to increase for the entire 100 years because P inputs to the pixels continued to exceed P outputs.

Fig. 4C clearly indicates that if present-day conditions persist, the P exported from pixels in corn will continue to increase to levels much higher than present-day and higher than other land uses. On the other hand, if current conditions persist for pixels in pasture and forest, P will be "mined" from the soil so that soil P may become deficient in an agronomic sense. Even though *TP Export Coefficients* eventually stabilize for urban and hay pixels these coefficients are likely to be higher than levels needed to control nonpoint source pollution from P.

4.2. Management simulation

In this study, we used the *PPBalModel* to simulate three agricultural practices alone or in combination that are commonly used to manage P loss from corn fields. In model simulations, these measures are triggered for any given pixel by specific conditions or criteria for that pixel. The practices simulated and the parameters that trigger them (in parentheses) were Nutrient Management (soil test P), Land Use Change (P index), and Erosion Control (RCA values). More detail and results of simulations using these management practices are presented in a subsequent paper (Meals et al., this issue).

4.3. Runoff contributing areas

Runoff contributing areas were incorporated into the *PPBalModel* as probability values assigned to each pixel, representing the likelihood that runoff would be generated from that pixel in any given annual time step. Pixels in RCA 1 were assigned an RCA probability (RCA_p) of 1.0, indicating that they generate surface runoff every year. Pixels in RCA 2 were assigned an RCA_p of 0.5, indicating that the chance of surface runoff from that pixel was 50% in any given annual time step. Pixels falling outside of the RCA 50 category ($RCA_p = 0.02$) were assigned a RCA_p of 0.002 to avoid zero values. The RCA_p assigned to each pixel was subsequently used to attenuate runoff and P export from that pixel simulated by the *PPBalModel*. Pixels of $RCA_p = 1.0$ exported P at 100% of the base simulated amount; pixels in $RCA_p = 0.1$ (runoff only in 10 year storm or greater) exported P at only 10% of simulated amount in a single time step.

4.4. SME configuration and operation

SME was run on a Pentium 3 1000 MHz computer using Red Hat Enterprise Linux version 3. SME can also run on Unix and Macintosh operating systems.

Preparation of a model for running in SME requires a series of steps that build the model from imported *Stella* equations, generate the *Simulation Markup Language* code, and create the default configuration file that can subsequently be edited manually. The SME configuration file defines the input data sets, including input raster maps and variable lookup tables, output datasets and those data routed to SME's interactive graphic output utility (*Viewserver*). For this application of the model, a simulation of 80 years took under 30 min of processing time.

SME output can be collected corresponding to a time series for a single pixel, the sum of a group of pixels, or as a series of raster maps for specified variables. Pixel output data were used to test and check the model to ensure that output was consistent with the original *Stella* pixel-based model. Class output data (e.g., P export from all corn pixels) were generated and summed across the entire watershed for each time step, then exported to a GIS or spreadsheet for further analysis.

4.5. Baseline simulation

Following development and testing of the DISPLA model, we simulated the long-term effects of baseline (present-day) conditions in a test watershed in the Champlain Valley of Vermont, USA. Model input parameters, including geospatial data layers, were developed as inputs to DISPLA from existing and estimated data. A complete description of the test watershed and input data development can be found in Meals et al. (this issue). We ran simulations for a period of 80 years from present day with land use held constant, so that neither crop rotations nor changes in watershed land use distribution were considered. Results were assessed by two principal parameters: soil test P and pixel P export. These parameters were viewed in three ways: pixel average for each land use, watershed aggregate (mean or total), and a spatial (mapped) distribution.

A true validation of DISPLA results is not possible because of the long-term simulations conducted in an annual time step and the lack of appropriate field data. However, comparisons of DISPLA output with published data provide a reality check on the model. Baseline year 1 simulations of pixel-level P export show average values of 1.4 kg ha^{-1} for corn pixels and 0.5 kg ha^{-1} from hay pixels. These modeled values are well within the range of published export coefficients for corn (~0.8–2.4 kg ha^{-1}) and hay (~0.4–1.3 kg ha^{-1}) (e.g., Budd and Meals, 1994; Frink, 1991; Haith and Shoemaker, 1987). Secondly, although DISPLA simulates P export from land to the drainage net rather than P load at the watershed outlet, the simulated baseline year 1 aggregate P load of 8.8 t $year^{-1}$ compares quite well with the magnitude of the P load from the test watershed measured from 1995 through 2000 (5–15 t $year^{-1}$, mean of 10 t $year^{-1}$) (Medalie and Smeltzer, 2004).

Mean annual soil test P (mg kg^{-1}) for pixels of each modeled land use is plotted over the 80-year DISPLA simulation in Fig. 5. The values plotted are mean annual values for all pixels within a land use class across all soil types, initial soil test P, RCA_p, and other pixel characteristics. Soil test P increased over time in most land uses, as P inputs continued to exceed P outputs. For pixels in hay and urban use, soil test P leveled off 40–50 years into the simulation, reflecting the approach of P inputs and outputs to equilibrium, as shown in the *PPBalModel* runs discussed earlier. Soil test P in corn pixels, however, increased throughout the 80-year simulation. Driven by the high levels in corn pixels, average soil test P across the test watershed also increased throughout the simulation. Soil test P in pasture and forest pixels that receive no anthropogenic P inputs, gradually declined through the simulation. Note that while urban pixels began with the highest soil test P, soil P in corn pixels rapidly exceeded that level and corn pixels represented the highest

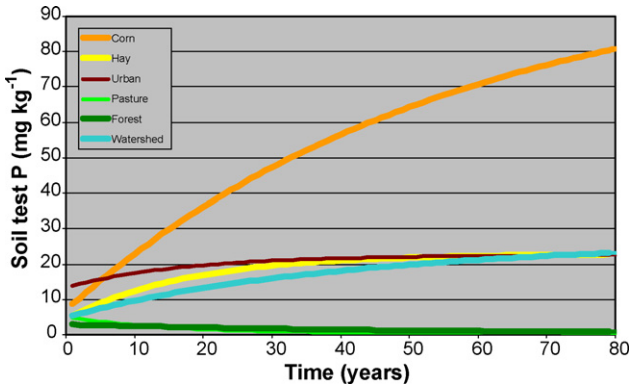

Fig. 5. Graph of pixel-average soil test P (mg kg^{-1}) in pixels of different land uses in the test watershed generated by DISPLA in the baseline scenario. The line labeled "Watershed" represents the average soil test P concentration across all modeled pixels in the test watershed.

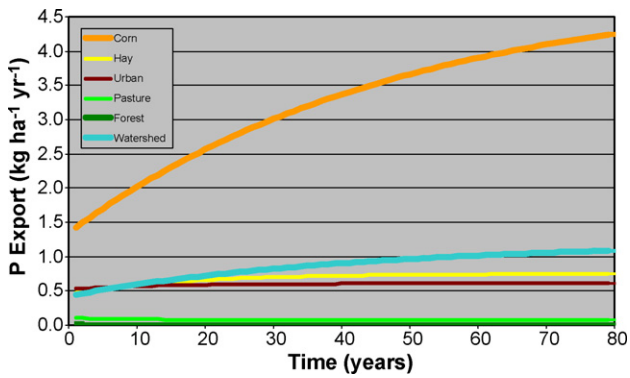

Fig. 6. Graph of pixel-average P export (kg ha^{-1} year^{-1}) in pixels of different land uses in the test watershed generated by DISPLA in the baseline scenario. The line labeled "Watershed" represents the average P export across all modeled pixels in the test watershed.

soil P among the modeled land uses through the end of the simulation.

Annual P export (kg P ha^{-1} year^{-1}) from an average pixel of each modeled land use is plotted over the 80-year DISPLA baseline simulation in Fig. 6. As shown, P export tended to increase inexorably through time because soil test P increased as P inputs exceed P outputs. This was particularly noticeable for corn pixels, which continued to increase in P export through the simulation, whereas export from hay and urban pixels appeared to level off as P export increased to equilibrium with P inputs. This is the same pattern observed in the *PPBalModel* for an individual pixel. P export from pasture and forest pixels, where soil test P declined through the simulation, gradually declines as well.

To show long-term temporal patterns in DISPLA simulations, we examined the means and totals for each decade through the 80-year simulation. Averaging or totalling within a decade smoothes out cyclic behavior of some variables and simplifies visualization of long-term patterns.

Analysis of decade mean soil test P over time (not plotted) indicated that soil test P increased on land in corn, hay, and urban use over time in response to continuation of present-day P management. Soil test P in corn land was particularly high, increasing more than fourfold from an average 15.9 mg kg^{-1} in years 1–10 to a mean 78.9 mg kg^{-1} in years 71–80. Considering that soil test P of 4–7 mg kg^{-1} is considered optimum and greater than 20 mg kg^{-1} is considered excessive (Jokela et al., 2004b), the

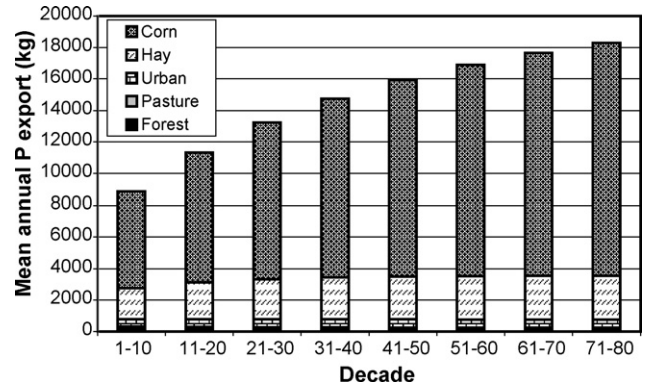

Fig. 7. Graph of total annual P export from modeled pixels in the test watershed, averaged within decades of the simulation, as projected by the DISPLA baseline simulation.

predicted soil P concentrations represent no agronomic benefit but a clear environmental threat.

Mean annual P export from the entire test watershed over time in the baseline simulation is shown in Fig. 7, with annual export averaged over decades. Unlike the "average pixel" data plotted in Fig. 6, the data plotted in Fig. 7 capture the variability of soil test P, RCA_p, and P export across the test watershed. Trends in P export are directly driven by the trends in soil test P. Clearly, P export from cornland pixels was the dominant contributor to aggregate P export, with export from hayland representing an important secondary component. In this particular test watershed, urban land comprised only about 5% of the watershed; consequently, P export from urban pixels is a very small proportion of the aggregate P load. P export in runoff from pasture and forest pixels is essentially negligible. Most importantly, the simulation shows that if present conditions persist, P export will increase significantly into the future. From an average of approximately 8.8 t year^{-1} over years 1–10, P export is projected to increase more than 25% to an average 11.3 t year^{-1} over years 11–20. Over the course of the entire 80-year simulation, estimated P export from pixels in the test watershed more than doubles from 8.8 to 18.3 t year^{-1}. This increase is the direct consequence of increases in soil test P brought about because of the excess of P inputs over P outputs across much of the test watershed.

The key to the DISPLA approach is in portraying the spatial patterns of P behavior. Fig. 8 presents maps of soil test P for the watershed predicted by DISPLA under baseline conditions for simulation years 1 and 50 only.

The maps show that soil test P does not increase uniformly with time across the LOC watershed. In the DISPLA simulation, the change in soil test P is a synthesis of initial conditions, and P management all of which vary across the landscape. As shown in Fig. 8, soil test P increases in specific areas that can be considered "hot-spots" of elevated soil test P. The spatial variability shown by these maps is probably considerably muted because most input parameters such as initial soil test P and P application rates were broadly estimated; actual data would have been considerably more heterogeneous.

Fig. 9 presents maps of simulated annual P export from pixels of the test watershed predicted by DISPLA for the baseline simulation for years 1 and 50. As with soil test P, areas of high P export are not uniformly distributed across the watershed; rather, they are quite scattered across the landscape and appear to represent a minority of watershed land. Because P export is driven by runoff, areas of highest simulated export occur in areas of high probability of runoff. Note that many of the soil test P hot-spots (Fig. 8) do not

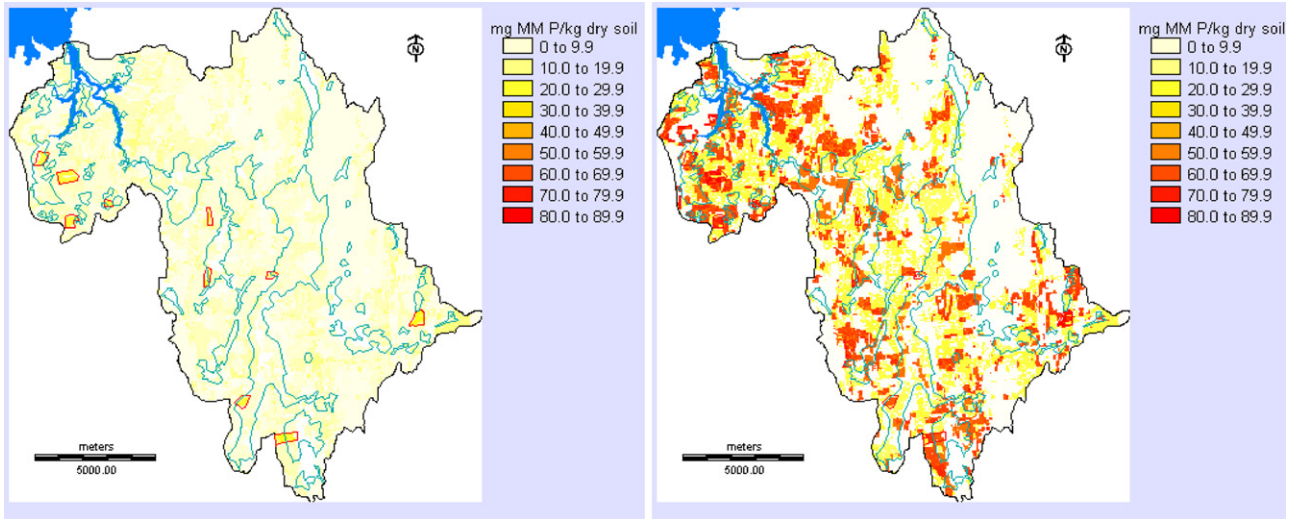

Fig. 8. Maps of soil test P in the test watershed simulated by DISPLA for the baseline scenario in year 1 (left panel) and in year 50 (right panel). Polygons outlined in red indicate zones of elevated initial soil test P. Areas of $RCA_p = 1.0$ are outlined in blue.

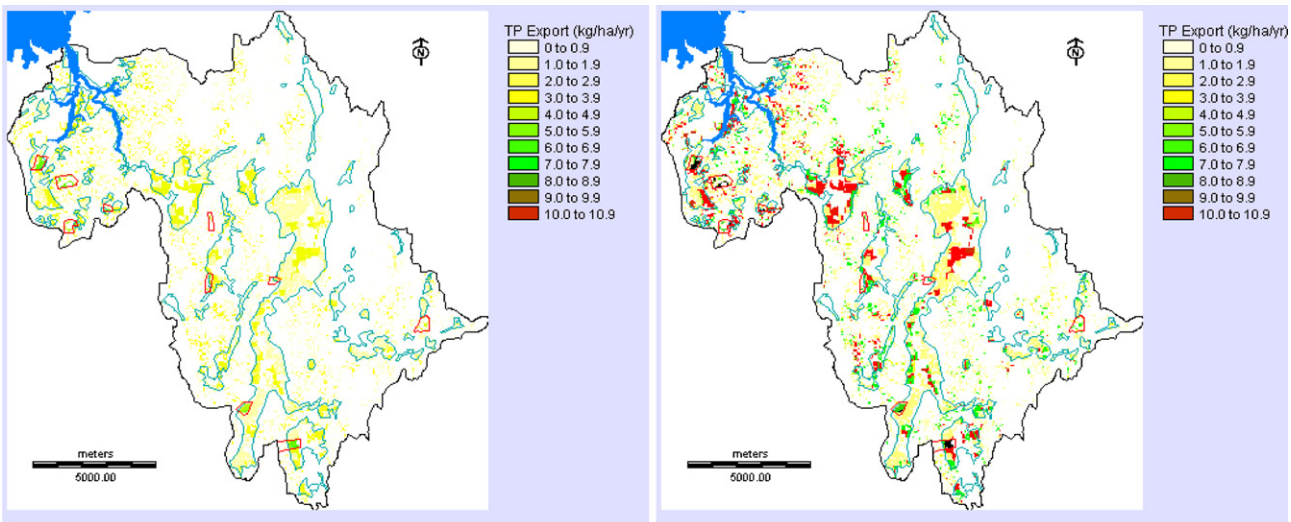

Fig. 9. Maps of P export from pixels in the test watershed simulated by DISPLA for the baseline scenario in year 1 (left panel) and in year 50 (right panel). Polygons outlined in red indicate zones of elevated initial soil test P. Areas of $RCA_p = 1.0$ are outlined in blue.

result in hot-spots of P export (Fig. 9) because they are not in a high runoff area. The light blue polygons in Fig. 9 outline the area with $RCA_p = 1.0$, and it is apparent that most of the high P export pixels are contained within these regions.

5. Conclusions

DISPLA successfully combines the temporal features of dynamic mass-balance P modeling with spatial variability across a complex watershed landscape. Long-term simulations using DISPLA can capture the spatial variability of factors influencing P storage and flux, while accounting for the driving force of P mass balance as it evolves over time. Our simulations – even in a test watershed where the full extent of natural variability was not captured – demonstrate clearly that areas of P accumulation and therefore of high risk of P export are not uniformly distributed across a watershed or even within a particular land use. "Hot-spots" exist that reflect unique combinations of geophysical and management characteristics and those hot-spots change through time and in response to management.

DISPLA simulation of present-day conditions shows that:

- If present-day management continues, both soil test P and P export will increase dramatically over much of the test watershed.
- Under present management, land in corn represents the greatest concern for increasing soil test P concentrations and for P export.
- Increases in soil test P over time in the test watershed are not uniform, but vary spatially in response to variability in initial conditions and in ongoing natural and management processes; DISPLA analysis can identify hot-spots of projected high soil test P.
- Areas of high P export risk are also identified in DISPLA simulations; these areas tend to be the coincidence of high soil test P and high probability of runoff.

Results from DISPLA under the baseline scenario suggest that nonpoint sources of P in a watershed will evolve over time and are likely to occur in limited areas that can be identified. In response, improved management could be applied preferentially to hot-

spots to reduce nonpoint source P losses. The structure of DISPLA allows us to do just that and to predict the results.

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