

A polygon-based spatial (PBS) model for simulating landscape change

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Abstract

A spatial model of long term habitat succession at a degrading Louisiana wetland was constructed based upon simulating exchanges across irregularly shaped polygons. Polygons represented the natural morphology which is indicative of the natural landscape. The PBS model was partially successful in simulating spatial habitat changes over a 28-year period when more than 1000 ha of wetland loss occurred ($r^2 = .56$). General landscape trends did, however, emerge from the model development. Areas of high annual water level fluctuations, and high primary productivity were less likely to change from wetlands to open water and were most likely to recover if altered. We discuss the potential for predictive improvement and for integration with polygon-based geographic information systems, and conclude that a **PBS** model demonstrates the need for spatially explicit landscape management.

Introduction

Explicit incorporation of spatial parameters into ecological simulation models is important because of the strong spatial aspect of many ecological processes. As a result: decisions made by environmental regulatory agencies often require information on spatial and temporal responses (Weinstein and Shugart 1983, Risser *et al.* 1984, Sklar *et al.* 1985, Forman and Godron 1986, Turner 1987). For example; how will the placement of dikes and weirs alter fish migration, or how does the alteration of water flow patterns impact marsh productivity, or what types of coastal developments lead to habitat modifications (Chabreck 1972, Mendelsohn *et al.* 1983, Steiner 1983, Costanza *et al.* 1986)? These decisions are difficult to make without at least a conceptual model of spatial interactions. Then an important question is, how does one incorporate

spatial interactions? To address this question we present a spatial model of a case study which uses wetland loss in Louisiana as the focus for analysis, irregular shaped grid cells (*i.e.*, polygons) as the spatial classification, and population interaction equations (May and MacArthur 1972; Maynard Smith 1974) as the basis for habitat succession.

Numerous researchers have documented that wetlands in Louisiana are diminishing at a rate estimated to be as high as 100 km² a year (Gagliano and van Beek 1970; Adams *et al.* 1976; Craig *et al.* 1979; Hopkinson and Day 1980; Gagliano *et al.* 1981; Boesch 1982; Scaife *et al.* 1983; Leibowitz *et al.* 1988; Turner and Cahoon 1987). Factors influencing land loss include: (1) rising sea levels, (2) subsidence of deltaic sediments, (3) nutrient and inorganic sediment depletion, (4) canal construction (5) salt water intrusion, and (6) decreasing bio-productivity. Attempts to model land loss as the

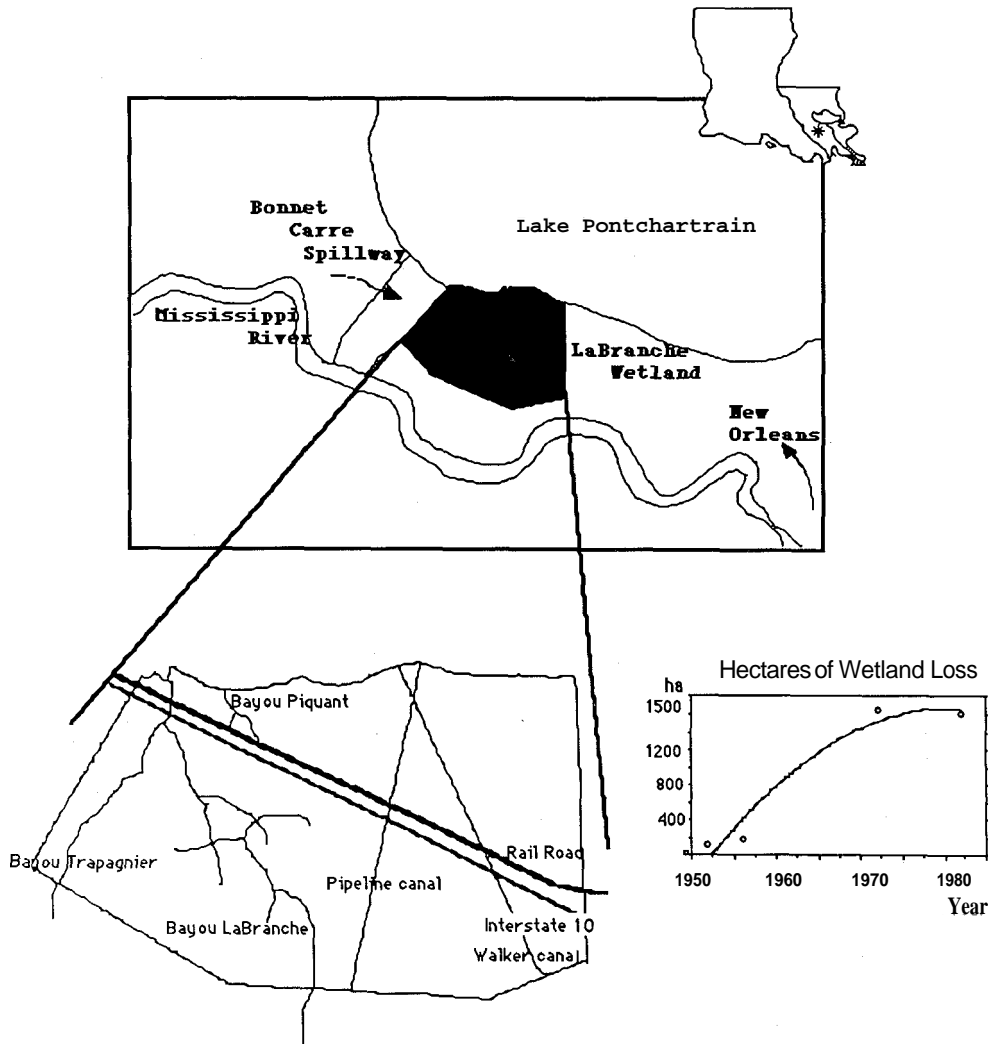


Fig. 1. Map of the LaBranche Wetland study area along the eastern coastline of Lake Pontchartrain, Louisiana. Wetland loss has been getting progressively worse in this area as subsidence produces increasing hectares of open water as illustrated in the small plot on the right from Pierce *et al.* (1985).

cumulative impact of all these parameters have focused on multivariate regression analyses (Scaife *et al.* 1983; Deegan *et al.* 1984) and process-based simulation models with fixed grid cells (Sklar *et al.* 1985; Costanza *et al.* 1988). We continue this analysis by designing a spatial model of land loss which uses irregularly shaped grid cells that conform to the natural hydrological “mini-basins” in a landscape.

The use of polygons in a spatial ecosystem model is new. Previous models with spatial detail were mostly of the fixed grid type (Costanza and Sklar 1985), the node-network type (Hopkinson and Day 1980), and the finite element models so often used

for hydrodynamic simulations, such as EPA’s Storm Water Management Model (1975). The polygon approach has the advantage of being less constrained by artificial boundary conditions and hence the “more natural” way to subdivide a landscape. The LaBranche wetland in Louisiana was chosen to test this approach because it had been dissected into five separate sub-basins by attempts at flood control and agriculture early this century.

We approached simulation of habitat succession within a polygon-based model differently than earlier fixed grid models. In a fixed grid design the simulation of habitat succession is a simple process

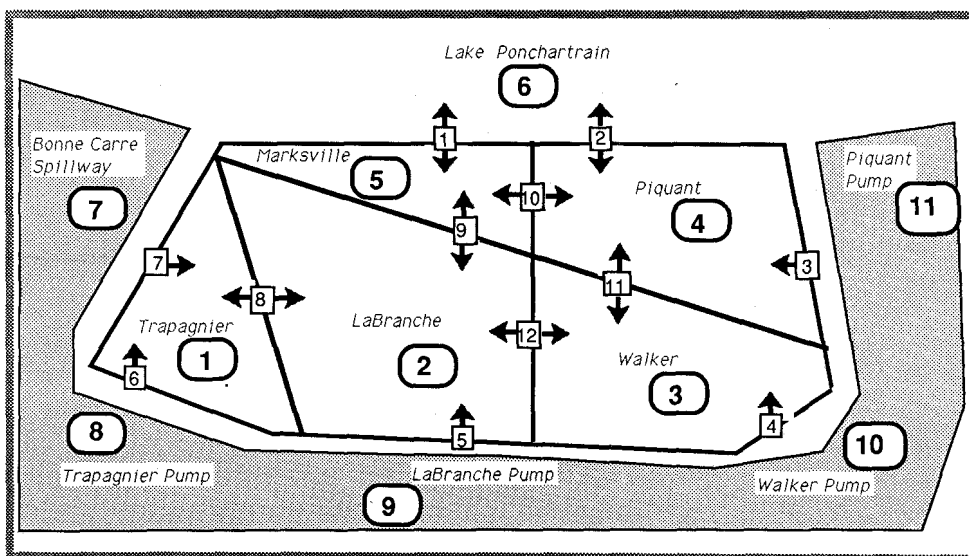


Fig. 2. Internal polygons (1 to 5) and external drainage basins (6 to 11) were chosen to represent the different hydrological drainage units found in the study area. The arrows represent the direction of water flow between the polygons. The numbers in the boxes (1 to 12) represent the coding used to designate the proportional flow coefficients (Res.).

because each cell is composed of only one habitat and the rules governing change are implemented on a cell basis (Sklar *et al.* 1985; Costanza *et al.* 1986; Sklar *et al.* 1989). In an irregular grid design, such as the one we present, the cells can be composed of many habitats and succession is implemented on a habitat by habitat basis within each cell. We simulated the “competition” for space within a polygon by modifying the population models of May and MacArthur (1972). These equations were used in the PBS model because the temporal interactions of the three major habitat types within a polygon (swamp, marsh, and open water) appear to mimic competitive exclusion processes; that is, open water habitats give way to marsh habitats and marsh habitats give way to swamp habitats as deltas and coastal marshes prograde, and vice versa as deltas and marshes degrade (Gagliano and van Beek 1970; Baumann *et al.* 1981). These equations are widely accepted by population ecologists and we do not question their validity in this paper.

The LaBranche wetland, located on the southern shore of Lake Pontchartrain between the Bonnet Carre Spillway and New Orleans (Fig. 1), is among the largest and most productive low salinity habitat within the lake Pontchartrain basin (Cramer *et al.* 1978). Since 1900, when 1000 ha of marsh were

reclaimed (*i.e.*, impounded and drained) for an unsuccessful agricultural project, the wetland has undergone a progressive deterioration resulting in considerable land loss. Total land loss has increased over the last 50 years in the LaBranche wetland (Fig. 1) from 106 ha in 1952 to 165 ha in 1956 to 1645 ha in 1972, decreasing slightly to 1607 ha in 1982 (Pierce *et al.* 1985).

Methods

The LaBranche PBS model (Fig. 2) divides the wetland study area into five different hydrological polygons based on the description of the area by Pierce *et al.* (1985) and the geometry of the sub-basins. Each polygon and each boundary condition was given a name and number to facilitate discussion and simulation. Borders along interconnected cells were registered in the model as numbers 1–12 and for each border a flow parameter, indicative of the degree (0–100%) of impoundment in each cell, was assigned. Polygons completely impounded, with no exchange with surrounding cells, were assigned flow values, RES, ($x = \text{border number}$), of zero for each border. RES_{*x*} values for borders 1 to 12 are shown in Table 1.

Table 1. Flow parameter values are indicative of the connectivity across the interface of adjacent polygons. Subscripted values correspond with flow parameter designations in Fig. 2.

RES ₁ = 0.30	RES ₇ = 0.00
RES ₂ = 0.10	RES ₈ = 0.40
RES ₃ = 0.00	RES ₉ = 0.40
RES ₄ = 0.20	RES ₁₀ = 0.00
RES ₅ = 0.00	RES ₁₁ = 0.30
RES ₆ = 0.20	RES ₁₂ = 0.20

The hydrologic forcing functions in the PBS model were based upon the head difference between Lake Pontchartrain water levels and the water levels inside the polygons. Water flowed into Lake Pontchartrain when the sum of runoff and waterlevel in a cell exceeded that of lake water, and flowed into the cells when the sum was less than that of the lake. The average water height of Lake Pontchartrain, based upon water gauge data in the middle of the lake (U.S. Army Corps of Engineers, Stone and Hinchee 1980), varied bimodally over a year (Fig. 3). This bimodal distribution was described as:

$$\text{LAKE} = 3.81 + \text{SIN}(\text{Day} \cdot (-0.035))$$

where, LAKE equals the water levels (cm) in Lake Pontchartrain and Day equals the time of year.

Water inside the polygons accumulates as a function of lake water inputs, rainfall and each polygon's ability to drain (*i.e.*, RES, values). Runoff values equal surpluses of water based upon actual rainfall events from 1910 to 1983, taken from the National Oceanic and Atmospheric Administration's monthly publication, *Climatological Data*, and from the U.S. Weather Bureau's *Decennial Census of U.S. Climate* and incorporated into a Thornthwaite and Mather (1955) water budget program (Yoshioka 1971). The annual average distribution of this runoff (Fig. 3) was used by the PBS model as fresh water inputs according to the sin function:

$$\text{RUNOFF} = 5 + 3.7 \cdot \text{SIN}(\text{Day} \cdot 0.0175)$$

where, RUNOFF equals the water level in the polygon due to surplus rain and Day equals the time of

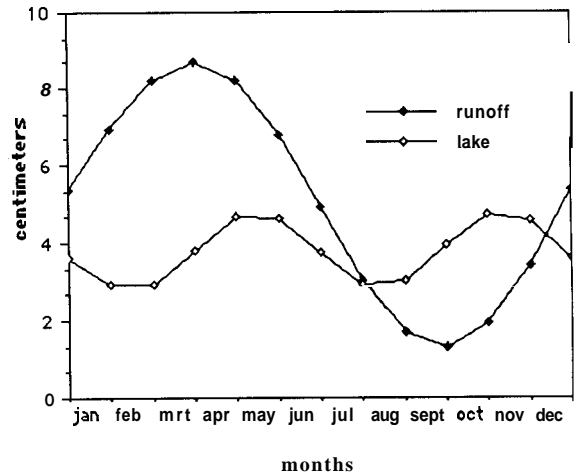


Fig. 3. The PBS model uses average rainwater surplus (runoff) and average water levels in Lake Pontchartrain (lake), recorded by the U.S. Army Corps of Engineers, as forcing functions. Runoff is the waterdepth due to excess rainfall as calculated by the Thornthwaite and Mather (1959) water budget. This cycle is repeated annually for each of the 28 years of simulation

year. Most of the year RUNOFF is greater than LAKE and water flows from the wetlands into the lake. When the water elevation in the wetlands is lower than that of the lake, typically during late summer, there is a net flow of lake water into the area.

Flows of water between polygons were calculated as difference equations:

$$\text{Flow}_{(a \text{ to } b)} = (\text{WL}_{(a)} - \text{WL}_{(b)}) \cdot \text{RES}_{(x)} \cdot A_{(a)}$$

where, $\text{WL}_{(a)}$ is the waterlevel in polygon (a) and $\text{WL}_{(b)}$ is the water level in polygon (b), RES, is a flow coefficient indicative of the degree of connectivity between polygons (a) and (b), and $A_{(a)}$ is the area of polygon (a). Flows of sediment-poor water from urban runoff were simulated as inputs into the Trapagnier, LaBranche, Walker, and Piquant polygons through flood-control pumping stations (RES₁, RES₄, RES₇, and RES₉) as a function of RUNOFF, the pumping capacity of the station (RES₁), and the urban drainage area (Area₁) according to the following:

$$\text{Flow}_1 = \text{RUNOFF} \cdot \text{RES}_1 \cdot \text{Area}_1$$

Habitat succession in the LaBranche PBS model

was simulated with a population sub-model such that each polygon “evolved” separately as a function of elevation. We choose this approach because polygons were large and composed of multiple habitats. The original May and MacArthur (1972) equations described how the niches of species can overlap in a fluctuating environment. We use the same principle in the form of landscape elements (*i.e.*, swamp, marsh and open water) to explain community overlap and landscape succession in each polygon. Each landscape element had a preferred position in a one-dimensional resource spectrum which we set as the area flood duration. The flood durations were actually land elevations relative to the average tidal fluctuations for the adjacent Lake Pontchartrain, which vary between 0 and 60 cm (Pierce *et al.* 1985).

To estimate the preferred position of each landscape element along the 0 to 60 resource spectrum (elevation), the percent habitat distributions within each polygon were calculated from remotely sensed images taken in 1952, 1956, 1965, 1972, and 1978 (Pierce *et al.* 1985) and compared with the theoretical relationships predicted by the following competitive exclusion equations of May and MacArthur (1972):

$$\frac{d(S)}{d(e)} = \int_0^{60} 1.7 S_{(e)} - S_{(e)}^2 - .4 S_{(e)} M_{(e)} - .9 S_{(e)} W_{(e)}$$

$$\frac{d(M)}{d(e)} = \int_0^{60} 1.8 M_{(e)} - M_{(e)}^2 - .8 S_{(e)} M_{(e)} W_{(e)}$$

$$\frac{d(W)}{d(e)} = \int_0^{60} 2 W_{(e)} - W_{(e)}^2 - .7 W_{(e)} S_{(e)} - .74 W_{(e)} M_{(e)}$$

where:

- e = land elevation as cm from 0 to 60.
- S = percent swamp area.
- W = percent open water area.
- M = percent marsh area.

In the May-MacArthur model, changes in the percent dominance of one habitat occurs at the expense

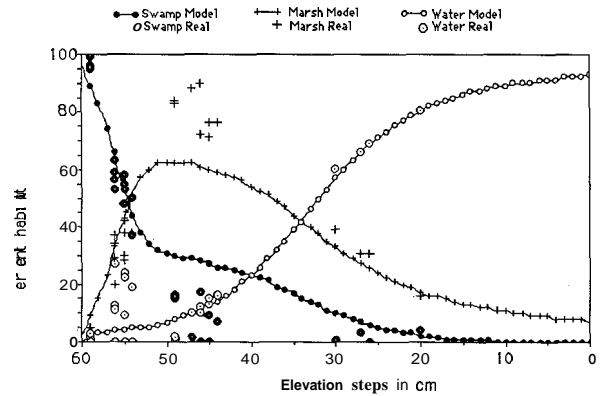


Fig. 4. The population model of May and MacArthur (1972) was modified to simulate the distribution of swamp, marsh, and open water habitats within a polygon, as a function of wetland elevation. The equations for the three habitat curves are given in the text. The “real” data points for swamp, marsh and water percentages are the values measured for each polygon in 1952, 1956, 1965, 1972, and 1978 by Pierce *et al.* (1985).

of the others. To estimate these relationships we plotted actual habitat areas, based on the equations above, as a function of relative elevation (Fig.4). The theoretical habitat proportions in each cell were calculated iteratively from elevations of 0 to 60 cm. At an elevation (EL) of 60 the stable solution of the May-MacArthur equations produced a polygon of water, marsh, and swamp which was dominated by swamp (1%, 5%, and 94%, respectively). At the minimum elevation of 0, the composition of water, marsh, and swamp was just the opposite (94%, 5%, and 1%, respectively). Proportions were converted to hectares in each cell based upon the size of each cell.

The maximum correspondence between the theoretical and actual habitat distributions were found by adjusting the coefficients of the May-MacArthur equations and by moving the actual habitat data sets (*i.e.*, three data points per polygon) across the x-axis of Fig. 4 until the greatest degree of correspondence between the two were obtained. The degree of correspondence was calculated as the minimum sum of squares (MSS), where a MSS of zero denotes perfect correspondence as discussed by Steel and Torrie (1960). The end result was the set of theoretical curves relating habitat distributions to elevation shown in Fig. 4 with a MSS of 0.03.

Elevation, in turn, was modeled as a function of

subsidence, sedimentation, and biological production according to the following equation:

$$\frac{dEL_{(c)}}{dt} = EBM_{(c)} + ESS_{(c)} - \text{Subsidence}$$

where:

$EL_{(c)}$ = Relative elevation (cm) in cell c.

$EBM_{(c)}$ = Contribution of organic matter to the maintenance of relative elevation (cm) in cell c.

$ESS_{(c)}$ = Contribution of suspended sediments to the maintenance of relative elevation in cell c (equals $K_{sed} \cdot SS_{(c)}$).

Subsidence = Decrease in elevation (0.00587 cm/day) relative to average sea level due to:

- 1) Dewatering and compaction of deltaic sediments (Berner 1980),
- 2) Subsidence tectonics through sediment loading (Kenneth 1982),
- 3) Eustatic sea level rise (Nummendal 1983).

The elevation equation responds to community composition as a synergistic loop where primary production increases with elevation and elevation increases with organic deposition. If this were the only synergism however, it wouldn't be long before all Louisiana wetlands rose out of the mud to become hardwood forests. Succession to forested uplands is not occurring in Louisiana wetlands because organic deposition alone can not compensate for subsidence, decomposition, and compaction (Leibowitz *et al.* 1988). Marshes and swamps must capture suspended sediments to enhance the fertility of the sediments and adjust for erosion and subsidence (Baumann *et al.* 1984).

The deposition of suspended sediments (ESS) and the burial of organic matter (EBM) were designed as synergistic processes such that land loss tends to increase as elevations begin to decrease (*i.e.*, dEL/dt negative). Organic matter contributions to the elevation of a polygon according to the equation:

$$\frac{dEBM_{(c)}}{dt} = S_{(c)} P_{(s)} + M_{(c)} P_{(m)} + W_{(c)} P_{(w)}$$

Where:

$EBM_{(c)}$ = Contribution of organic matter to the maintenance of relative elevation (cm) in cell c.

$S_{(c)}$; $M_{(c)}$; $W_{(c)}$ = Areal extent (m^2) of swamp, marsh, and water, respectively, in polygon c.

$P_{(s)}$; $P_{(m)}$; $P_{(w)}$ = Coefficients for the accumulation of soil due to primary production ($cm/m^2/d$) in swamps (.003), marshes (.0048), and open water habitats (.0001), respectively.

The P values were based on the swamp production data of Conner and Day (1986), the marsh production data of Cramer *et al.* 1978, and the relationship between bioproductivity and elevation according to Gosselink & Hatton (1984).

Relatively little suspended sediments enter the marsh or swamps via runoff because the entire LaBranche study area is semi-impounded with a closed levee on the upland side. Although urban runoff can contain significant quantities of suspended sediments, we assume that most, if not all, of the inorganic sediments available for sedimentation in the LaBranche Wetlands comes from Lake Pontchartrain and that the exchange of suspended sediments as $mg.l^{-1}$ is proportional to the hydrologic flows according to the following.

$$\frac{d(ss)_c}{d(t)} = \sum_{c=1}^m \frac{F_i}{V_i} \cdot SS_i - \sum_{i \neq c}^m \frac{F_o}{V_c} \cdot SS_o + SS_{c,t} - ESS$$

where:

(ss) , = Concentration of inorganic suspended sediments ($mg.L^{-1}$) in polygon c at time t.

m = The number of polygons that share an interface with polygon c.

F_i = The input of water into polygon c as m^3 per d(t).

V_i = The water volume (m^3) of each polygon with flow (F_i) into polygon c.

SS_i , = Suspended sediment concentration ($mg.L^{-1}$) of each polygon with flow (F_i) into polygon c.

F_o = The output of water from polygon c to all m polygons as m^3 per d(t).

V_c , = The water volume (m^3) of polygon c.

SS_c , = Suspended sediment concentration

(mg.L⁻¹) of polygon c with flow (F_o) to polygons i to m.

The case when suspended sediments enter the study area from pump water or Lake Pontchartrain was calculated as F_i·kss_{pump} and F_i·kss_{lake}, respectively. Where, kss_{pump} and kss_{lake} are constants (0.008 g/l and 0.12 g/l, respectively).

Results

Water

The hydrologic forcing functions RUNOFF and LAKE (Fig. 3) were repeated annually producing a steady state water level variation in each polygon. The impact of this hydrologic averaging on the water levels in each polygon are shown in Fig. 5. Seasonal water level variations were stable over the 28 years that the PBS model was run. However, differences between areas were significant. The Walker polygon had relatively large annual water-level variations (14.9 ± 5.5 cm). The Marksville polygon had the smallest waterlevel variations (7.2 ± 1.8 cm). The Trapagnier, LaBranche and Piquant polygons were all similar with moderate variations(10.7 ± 3.4, 10.0 ± 3.1, and 10.6 ± 3.4 cm, respectively).

Sediments

The average seasonal deposition of suspended sediments was compared with average suspended sediment concentrations over the course of the 28-year PBS simulation (Fig. 6) and as expected, greater suspended sediment loads leads to larger depositions. Although suspended sediment loads can have a relatively rapid seasonal oscillation within an annual cycle, the rate of deposition tends to be constrained (*i.e.*, is a more moderated process) by the lack of suspended sediments during Summer and Fall and high flow rates (resuspension and erosion) during Winter and Spring.

We conducted a sensitivity analysis to see how the seasonal variation of suspended sediment con-

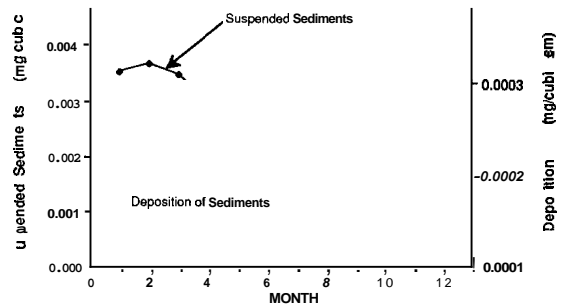
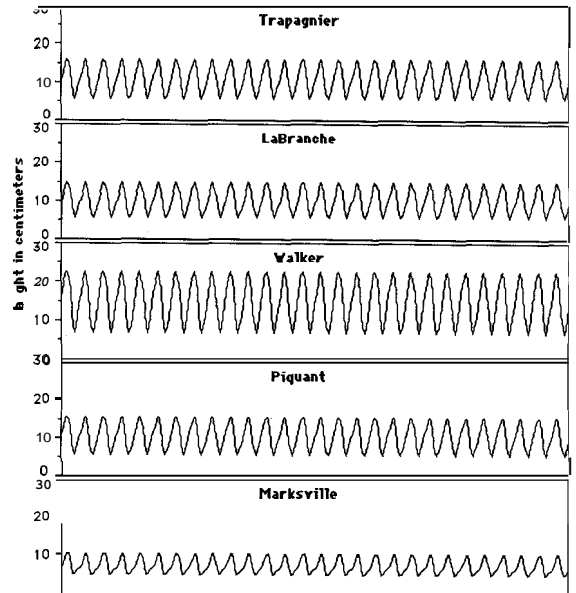


Fig. 6. Average concentration of suspended sediments and the rate of deposition of these sediments is seasonal with maximum deposition occurring in the spring (month 2 = Feb, month 4 = April, etc.)

centrations (SS), after deposition, varied as a function of changing sedimentation rates and found that the rate of sedimentation had different impacts within different polygons (Fig. 7A). A high Ksed of 1.0 cm/g/l resulted in suspended sediment loads of zero in all polygons except the Walker polygon. A low Ksed parameter of .01 cm/g/l led to high suspended sediment loads in all polygons, with the highest daily concentrations found in the Walker

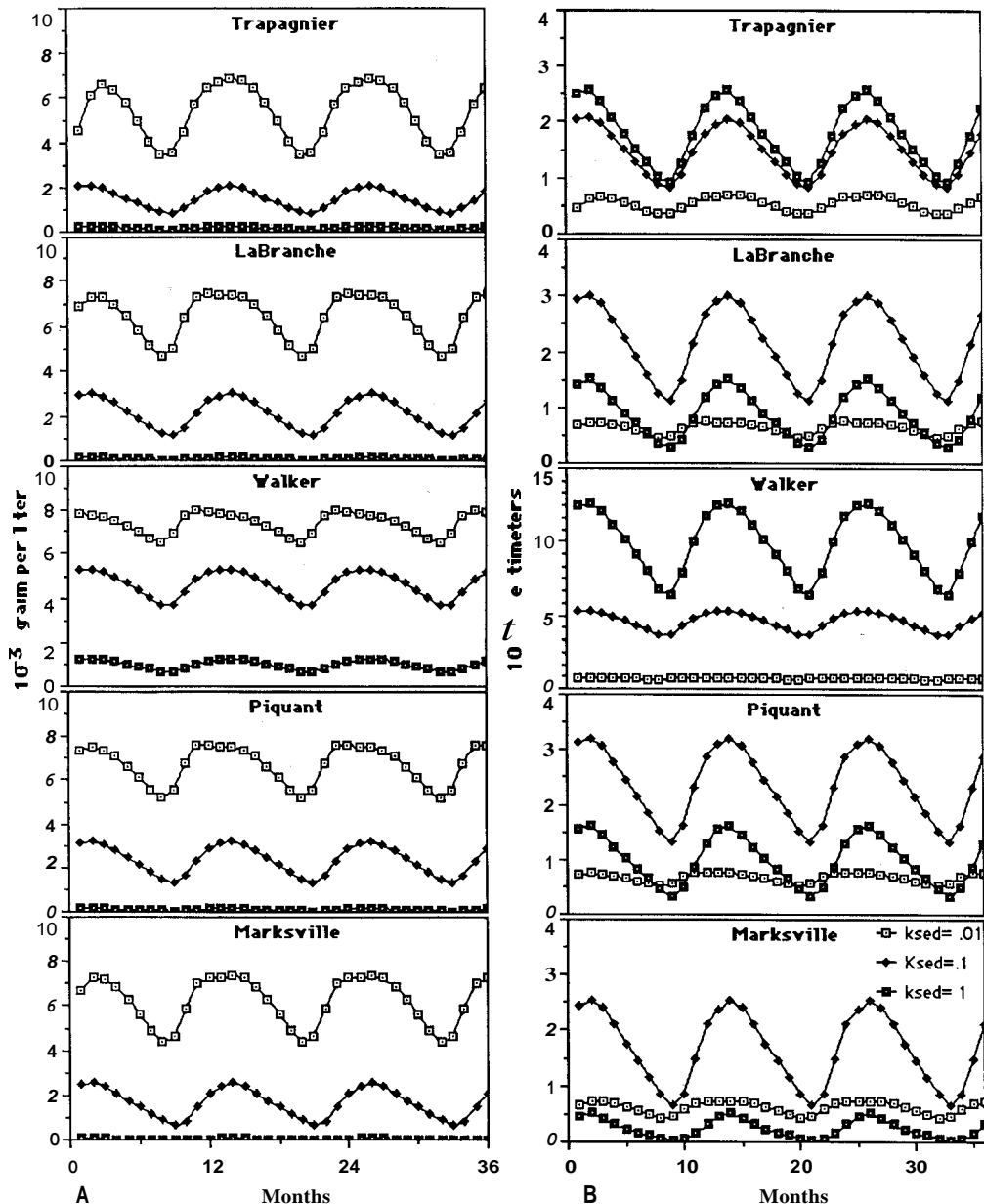


Fig. 7. Sensitivity of the PBS model to changing K_{sed} , the sedimentation parameter. (A) Daily suspended sediment loads, after deposition, during 3-year runs of the PBS model. (B) Daily deposition of suspended sediments, as elevation measurements, during 3-year runs of the PBS model.

polygon (.008 g/l) and the lowest suspended sediment concentrations found in the Trapagnier polygon (0.0035 g/l). With a K_{sed} value of 0.1 cm/g/l, the value used to run the PBS model for 28 years, the daily suspended sediment concentrations varied from a maximum of 0.0053 g/l in the Walker polygon to a minimum of 0.0007 g/l in the Marksville polygon.

The contribution of suspended sediments to the maintenance of wetland elevations (*i.e.*, accretion) was estimated by multiplying K_{sed} by the daily changes in suspended sediment concentrations (Fig. 7B). A comparison of the model's response to different K_{sed} values indicated that the most accretion occurred in the Walker polygon when sedimentation K_{sed} was set at the maximum value

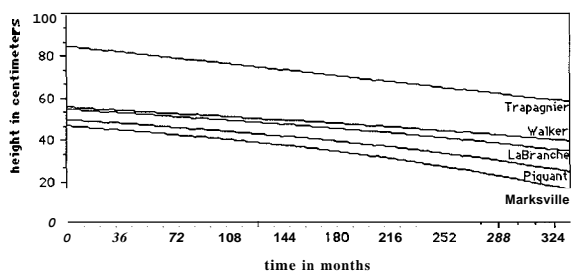


Fig. 8. Decrease in wetland elevations for each of the five polygons simulated by the PBS model from 1952 to 1980 (daily time steps over a 28-year period).

of 1.0 cm/g/l. The accretion in the Walker polygon varied seasonally, going from a high of 12.7×10^{-4} cm/d during winter to a low of 6.4×10^{-4} cm/d during summer. Interestingly, with a high K_{sed} the least amount of accretion occurred in Marksville when in reality, we have observed high sedimentation potential in this area as evidenced by the formation of several flood deltas. This difference occurs because the PBS model is only simulating the past net landloss trends while current trends appear to be reversing due to increasing lake water levels and sediment inputs. When the K_{sed} value was set very low (*i.e.*, 0.01 cm/g/l), the higher values for deposition (0.8×10^{-4} cm/d) occurred in the Piquant polygon while the lower values occurred in Trapagnier (0.3×10^{-4} cm/d). Our selection of a final K_{sed} value of 0.1 cm/g/l resulted in moderate accretion rates with seasonal deposition ranges between 5.3×10^{-4} cm/d and 3.7×10^{-4} cm/d in the Walker, Piquant and Marksville polygons, and between 2.1×10^{-4} cm/d and 0.8×10^{-4} cm/d in the Trapagnier and LaBranche polygons.

The PBS model predicted a significant decline in elevations for each polygon after 28 years (Fig. 8). The rate of the decline in wetland elevations was found to be inversely related to the degree of water level fluctuations. The Spearman Rank Correlation Coefficient between water level fluctuations and elevations was -0.90 with a significance level of $.05$ (one-tailed test). The Walker polygon had the greatest water level variations and the smallest decrease in wetland elevations (16.9 cm/28 years) while the Marksville polygon had the smallest water level variations and the largest decrease in wetland

elevation (31.2 cm/28 years). The Trapagnier, LaBranche and Piquant polygons had moderate decreases in wetland elevations in comparison to the other two sites (27.0, 20.9, and 25.7 cm/28 years, respectively) but were still sensitive to the degree of water level fluctuations.

The wetland elevations decreased in each polygon as a linear function of time (Table 2). The slopes of the regression lines indicate the rates of land loss in each polygon (Elevation) and the relative deposition rates of organic matter (EBM). Table 2 also summarizes the long term elevation trends predicted by the PBS model as a function of three different K_{sed} values. It is significant to note that for a degrading wetland the PBS model predicts very little build up of land as a function of biomass accumulation (EBM). Only the LaBranche and Walker polygons showed a positive contribution to wetland elevation due to bioproductivity. According to the PBS model, the Piquant and Marksville polygons have been slowly losing their ability to produce organic matter.

Although the Trapagnier polygon, with its high elevations and its high percentage of swamp habitat, managed to maintain a steady input of organic matter (*i.e.*, 3.1×10^{-3} cm/day), it was insufficient to keep up with subsidence. The slope of the landloss curve for Trapagnier (-0.081) was greater than for any other polygon. Suspended sediments reach Trapagnier via pump water but this water is relatively devoid of sediments. Increasing the sedimentation parameter (K_{sed}) had little effect upon the land loss slopes shown in Table 2. This implies that there must be an increase in sediment loading if Trapagnier is to reverse the current trend.

Succession

Each polygon in the PBS model was initialized with a different mix of habitat types based upon differences seen in aerial images (Pierce *et al.* 1985). These initial values for swamp, marsh, and water can be seen at year one in Fig. 9. The predicted habitat changes in each polygon indicate which areas were most susceptible to decreasing wetland elevations, suspended sediment supplies, and or-

Table 2. Linear regressions of 3-year runs of the PBS model showing the change in wetland elevations and the buildup of wetland elevations due to biomass accumulation in the sediments as a function of three sedimentation parameter values.

Polygon	Ksed	Elevation		EBM*	
		intercept (cm)	Slope (cm/d)	intercept (cm)	Slope (cm/d)
Trapagnier	.01	85.00	-.084	3.1×10^{-3}	0
	.1	85.01	-.081	3.1×10^{-3}	0
	1	85.00	-.080	3.1×10^{-3}	0
LaBranche	.01	54.98	-.058	3.8×10^{-3}	3.0×10^{-6}
	.1	55.00	-.053	3.8×10^{-3}	3.0×10^{-6}
	1	54.99	-.057	3.8×10^{-3}	3.0×10^{-6}
Walker	.01	55.97	-.059	3.7×10^{-3}	5.8×10^{-6}
	.1	55.99	-.048	3.7×10^{-3}	5.5×10^{-6}
	1	56.00	-.033	3.7×10^{-3}	4.9×10^{-6}
Piquant	.01	50.00	-.059	3.9×10^{-3}	-2.3×10^{-6}
	.1	50.02	-.054	3.9×10^{-3}	-2.1×10^{-6}
	1	50.02	-.058	3.9×10^{-3}	-2.2×10^{-6}
Marksville	.01	47.01	-.063	3.8×10^{-3}	-3.6×10^{-6}
	.1	47.02	-.060	3.8×10^{-3}	-3.4×10^{-6}
	1	47.02	-.064	3.8×10^{-3}	-3.6×10^{-6}

*EBM = Wetland elevation buildup (accretion) due to biomass production.

ganic matter accumulations (Fig. 9). Trapagnier, the cell with the most swamp area, was stable for 25 years. After 25 years the wetland elevation of Trapagnier dropped rapidly and was affected by the water level fluctuations in Lake Pontchartrain. At this point in time swamps began to flood and were replaced by marsh. This replacement by marsh proceeded very rapidly. It took only three years for the simulated swamp area to decrease by 25 percent. Although this is probably an unrealistic rate of decline for any individual tree it was realistic at this landscape level model because we assumed that loss of viability was sufficient for reclassification (*i.e.*, persistent flooding prevents cypress regeneration), that time-delay mortality was unimportant (*i.e.*, it was not a component of the May-MacArthur equations) and that landscapes are sensitive to critical threshold values (*i.e.*, catastrophe theory).

The Walker and LaBranche polygons were the only areas to show an initial increase in simulated marsh area. During the first 6 years of the simulation the amount of marsh hectares in LaBranche in-

creased from 1209 ha to 1289 ha. After these first 6 years the marsh area dropped from 1289 ha to 925 ha while simulated swamp area dropped from 748 ha to 344 ha and water area increased from 100 ha to 789 ha. During the first 9 years of the simulation the amount of marsh in the Walker polygon dropped from 1294 ha to 1095 ha, the swamp area dropped from 856 ha to 454 ha, and the amount of open water increased from 92 ha to 518 ha.

The most dramatic changes in habitat distributions within any of the polygons predicted by the PBS model occurred in Piquant and Marksville. There was a steady decrease in swamp and marsh area and a very steep increase of water area. After 28 years of simulation, the swamp area in Piquant dropped from 660 ha to 146 ha, the marsh area decreased from 1409 ha to 624 ha, and water area increased from 191 ha to 1490 ha. In the Marksville polygon, swamp decreased from 255 ha to 20 ha, marsh dropped from 564 ha to 166 ha, and open water increased from 112 ha to 746 ha.

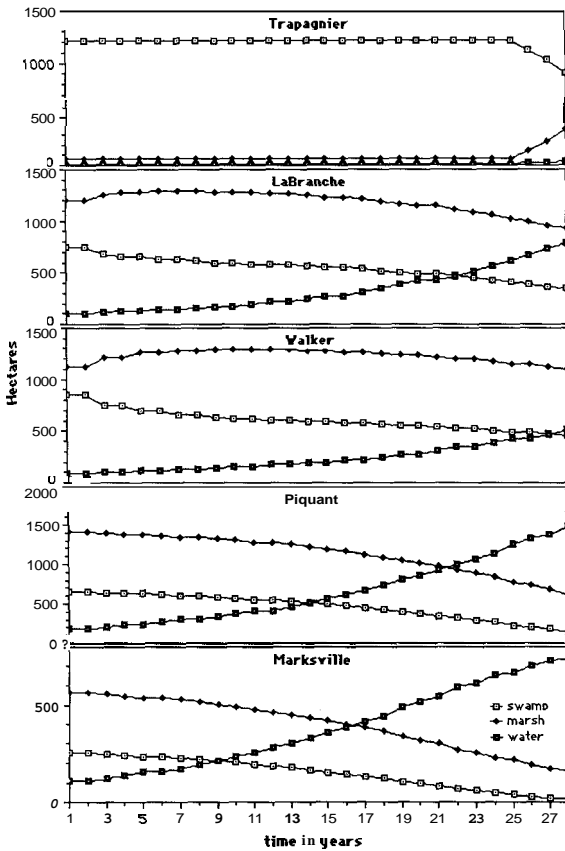


Fig. 9. The change in community structure in each polygon as predicted by the PBS model from 1952 (year one on the x-axis) to 1980.

Discussion

The PBS model was designed to examine marsh succession at the landscape level and to evaluate the utility of the polygon design for landscape simulation. For what it was designed for, the PBS model does a reasonably good, but not an outstanding job. A regression analysis, used as a measure of the goodness-of-fit between predicted and actual habitat change (Costanza and Sklar 1985), resulted in an r^2 of .56 with a $p < .01$. Decomposed into its separate habitat components, the r^2 indicated that the PBS model could account for 62.6%, 50%, and 41.9% of the spatial variation over time for swamp, marsh, and open water, respectively.

Pearson product-moment correlations, in terms of hectares, suggest that the PBS model captured the observed temporal habitat and landloss trends

(Table 3). For each habitat type, large positive correlations were found between the number of hectares simulated and the number of hectares observed. There were significant negative correlations between swamp and water hectares indicating that landloss or landgain in St Charles is a dynamic exchange between swamp habitats and open water areas. The PBS model also found that swamps can appear relatively stable for long periods of time, when they could in fact be experiencing degrading environmental conditions which can result in rapid habitat changes after a tolerance threshold is exceeded. Has the threshold been reached for this landscape? The negative correlation matrix implies that it has. Personal observations in 1988 indicate that hardwood swamps in this area, especially in the Trapagnier polygon, are being quickly replaced by marsh and open water habitats. However, photo interpretation of recent aerial photographs is necessary to validate the predicted forest decline.

The problem with this PBS model is its simplicity. This model mostly describes general ecological processes for simple spatial distributions and is not well equipped for predicting short term occurrences. The use of a constant K_{sed} for the entire area does not reflect the true spatial dynamics of deposition and erosion, and although further study is necessary, K_{sed} should be made dependent upon habitat distributions and vegetation density. Other problems include the use of generalized forcing functions and a one parameter (*i.e.*, elevation) determination for habitat succession. The May-MacArthur model of succession appears to over-simplify complex processes and should be enhanced to include more variables. Other improvements should include measurements of elevation gradients in each polygon to better relate elevations to flood duration and synoptic measurements of sediment concentrations in the water to validate assumptions on suspended sediment loads.

Despite all its shortcomings, a polygon-based simulation model has some real validity and utility. The regression data indicated that the PBS model for the St Charles wetland landscape simulated the subsidence, accretion, wetland productivity, and habitat dynamics reasonably well. As a result, we can discuss the significant ecological patterns which

Table 3. Correlations matrix comparing hectares of swamp, marsh, and open water habitats as predicted by the PBS model and as measured by Pierce *et al.* (1985).

	PBS Swamp	PBS Marsh	PBS Water	Swamp	Marsh	Water
PBS Swamp	1					
PBS Marsh	-.184	1				
PBS Water	-.736	.054	1			
Swamp	.754	-.111	-.518	1		
Marsh	-.314	.723	.341	-.075	1	
Water	-.747	.081	.691	-.555	-.413	1

emerged. That is, accretion from suspended sediment deposition is proportionally more important in those areas where biomass deposition is lowest (Table 2), suspended sediment deposition is non-linear (Fig. 6), and habitat change is a function of spatial differences in the apparent subsidence rates (Fig. 9). These simulated relations shed light on what we observe in nature. For years, local fishermen and hunters have noticed that the marsh plants in the Marksville area died very early in the fall while other marshes stayed green through December. According to The Soil Conservation Service (1987), this phenomenon is the result of salt water intrusion. However, why is salt water intrusion occurring? According to the PBS model, the Marksville polygon sedimentation rates are not keeping up with subsidence (increasing Ksed had little impact). This means that during the Fall dry period, when runoff is at a minimum (Fig. 3), the hydrologic head on the marsh (*i.e.*, elevation) is not maintaining the height needed to keep brackish lake water (Lake Pontchartrain increases in salinity each Fall, Stone and Hinchee 1980) from moving up into the marshes. To compensate for salt water intrusion there must be more pumping of urban and river waters to increase fresh water, or there must be more deposition to increase the elevation. There is a project now to increase the deposition factor of the suspended sediments by building brush fences (Boumans *et al.* 1987; Day *et al.* 1988; Kamps 1962; Verhoeven and Akkerman 1967) on mud flats and by planting marsh grasses (Woodhouse *et al.* 1974; Webb *et al.* 1984; Knudson and Woodhouse 1983; Joenje 1978). It will be interesting to see if these techniques can reverse current trends.

Our model found little movement of suspended sediments out of the lake and into the study area. Suspended sediment concentrations followed the upland runoff function and not the function simulating the lake water head. During the 28-year runs of the PBS model the elevations in each of the polygons stayed high enough to keep lake water out of the area. In reality, wind induced tides make the lake water head fluctuate around the average lake water level (Stone and Hinchee 1980; Wang and Scarlatos 1982; Baumann 1987), so that during high winds and high tides the lake water has more of a chance to enter the area. Although the incorporation of wind into our model would increase its realism and its validity, it was not included because the positive effects of wind (*i.e.*, the resuspension and redeposition of sediments up onto higher ground, Baumann *et al.* 1984), is to a degree balanced by the negative effects of wind (*i.e.*, the erosion and export of sediments downwind, Mentha 1984). Even with wind induced tidal inundations it appears from our results that the polygons dominated by swamps (Trapagnier and LaBranche) will continue to degrade because they are either too far from Lake Pontchartrain or they are cut off from the lake due to man-made impediments (*e.g.*, spoil levees and railroads).

The elevations decreased at different rates in the different polygons. The polygons with the most marsh area (LaBranche and Walker) decreased the least. The polygons with the most water area (Piquant and Marksville) decreased the most. The marsh dominated polygons were able to compensate for subsidence better than the other areas because the higher productivities of marsh grasses

added to the elevation as organic deposition (EBM). For this marsh dominated landscape, the correlation between elevation change and biomass deposition (EBM), in three year runs of the model, was found to be more significant ($r = 0.825$, $p < 0.01$) than the correlation between elevation change and elevation built by suspended sediments (ESS) ($r = .681$, $p < .03$). It seems that as marshes disappear the landscape's ability to compensate for subsidence is significantly reduced.

Elevation change was also related to water level fluctuations. The greater the annual water level variation the smaller the decline in the elevation curve (Fig. 8). This is consistent with the subsidy-stress hypothesis of Odum *et al.* (1979) which states that the benefits of energetic processes such as tides, waves, and sunlight to an ecosystem can be plotted as a normal distribution. Maximum subsidy occurs in the midrange of the bell-shaped curve while stress occurs at the two extremes. Impoundments, levees, and roads decrease the annual water level variation (Wang 1987; Swensen and Turner 1987). Decreasing the hydrologic subsidies by partial or complete impoundment of wetlands has lowered tree growth (Conner *et al.* 1981) and animal density (Sklar 1983) in other Louisiana wetlands.

The PBS model is a potential tool for the exploration of generalized wetlands processes at the landscape level. Simulating long term trends using a polygon-based spatial model, has management and ecological utility because the model can address cumulative impacts (Gosselink and Lee 1987; Dijkema *et al.* 1985). Point and non-point forcing functions (*i.e.*, perturbations) can be easily incorporated to evaluate impacts and management plans at a regional scale.

There are only a few spatial models of ecosystem processes (Costanza and Sklar 1985). The complexity associated with simulating both spatial and temporal trends with a mechanistic model has deterred its development. Our own experience with the CELSS model of Sklar *et al.* (1989) is a case in point. The CELSS model has over 2400 cells, 2000 lines of programming code, and over 100 parameters controlling only eight state variables. In general, an increase in the number of cells and parameters will increase the degree of uncertainty if

the data requirements are not met. On the other hand, the PBS model has only 130 lines of code, five polygons and 20 parameters controlling five state variables (*i.e.*, water, suspended sediments, primary production, habitat type, and elevation). The PBS model required a small desktop computer. The CELSS model required a Cray II supercomputer. The difference was a better goodness-of-fit between the real and simulated data for the CELSS model (Costanza *et al.* 1986) than for the PBS model (0.89 and 0.56, respectively). The trade-off appears to be more rapid simulation time at the expense of model accuracy and realism. Although the correlation and regression results for the PBS model were not as high as those reported for the CELSS model they did however, indicate that the long term trends and spatial ecological processes in a wetland can be captured by a relatively simple program based on exchanges across polygons. This is a significant finding because it opens the door to the development of dynamic GIS (geographic information systems).

GIS's are rapidly developing throughout the world at local, regional, and global scales. They are polygon-based spatial databases which, theoretically, could be directly accessed by a dynamic simulation model to predict spatial changes. We believe that the true potential of a GIS will be fully realized when it is somehow linked to a simulation system. The PBS model is only a first step in this new direction.

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