Perspectives on Louisiana Land Loss Modeling

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Abstract: Louisiana's coastal wetlands are changing rapidly. Although some areas are accumulating new land, the deltaic plain of the Mississippi River is losing an estimated 39.4 mi^2 (102 km^2) per year (Gagliano et al., 1981). This paper describes models that have been used to analyze the temporal and spatial patterns of habitat change in coastal Louisiana. Early attempts at understanding wetland loss used areal data for only two points in time. Later, additional time periods were included, giving a better understanding of how these rates change. Next, simple linear models were used to relate land loss to factors such as canal density, and multiple regression models were used to examine the interactions of factors associated with wetland loss. Our most current knowledge of wetland loss is based on digitized, high-resolution, aerial photographs from different time periods, along with new forms of spatial statistics. Using distance measures and proximity analysis, these data indicate a decrease in land loss with increased proximity to natural waterways and an increase in land loss with increased proximity to artificial channels. The most complex of the wetland loss models to date is a dynamic simulation model of the coastal marshes of the Atchafalaya River, which attempts to replicate the historical spatial pattern of habitat change and project into the future the implications of various management options. Although each modeling approach to wetland loss has led to greater complexity, it has also led to a better understanding of the land loss problem. With future growth in spatial data bases and analytical tools, we will come to understand better how to minimize Louisiana's land loss problem.

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INTRODUCTION

Louisiana's coastal zone, which contains 40% of the contiguous United States' coastal marshes (Turner and Gosselink, 1975), developed from Mississippi River depositional sediments over the last 6000 years (Frazier, 1967). The ecological and economic importance of the coastal marshes is considerable: the deltaic plain of the Mississippi River, with its vast wetlands, is the nation's top volume producer of fisheries (U. S. Department of Commerce, 1982). This large production is tied directly to wetlands; for example, landings of Gulf shrimp in Louisiana are related to area of intertidal vegetation (Turner, 1977). The Louisiana coastal zone also produces North America's largest fur harvest (Larson et al., 1980). In addition, 70% of Louisiana's $8 billion oil and gas production comes from Louisiana's coastal parishes (Maruggi and Hartl, 1981).

It has been known for some time that the area of Louisiana's coast is decreasing (Adams et al., 1976; Craig et al., 1979; Gagliano and van Beek, 1970; Gagliano et al., 1981), a loss that could have dire economic and social consequences. Gagliano et al. (1981) predict that the remaining 185,000 ha of Plaquemines Parish will be converted to open water within 50 years. Turner (1982) predicted that a reduction in wetland area of 1% per year could cause a revenue loss of one billion dollars over the next 20 years from the commercial fishing industry alone.

Many factors, both natural and human-induced, have been suggested as a cause of Louisiana's land loss problem. Natural factors include storm erosion, eustatic sea level rise, subsidence caused by isostatic adjustment or compaction of alluvial sediments, and loss of sediment due to natural abandonment of river deltas (Gosselink and Baumann, 1980; Mendelssohn et al., 1983; Morgan, 1967). Human-induced factors include subsidence caused by the extraction of water, oil, gas, and other minerals; direct conversion of land to water through construction and subsequent erosion of oil and gas access canals and pipelines; the impoundment and draining of marshes for agriculture and development; and the loss of riverine sediments to deep Gulf of Mexico waters because of the leveeing of the Mississippi (Cleveland et al., 1981; Craig et al., 1979; Gosselink and Baumann, 1980; Mendelssohn et al., 1983). It has also been hypothesized that Louisiana's ubiquitous oil and gas canals are indirectly causing much of the land loss by altering the area's natural hydrology (Craig et al., 1979; Deegan et al., 1984; Scaife et al., 1983).

Our understanding of land loss and the processes causing it has grown as the tools to study it have evolved. The earliest studies estimated land loss rates using point estimates of land and water on U. S. Geological Survey (USGS) topographic quadrangle maps from different periods (Gagliano and van Beek, 1970; Gagliano et al., 1981). Later studies calculated land loss rates by measuring total land and water area at various sites using USGS maps in combination with black and white or color infrared aerial photography and then calculating the change over time (Adams et al., 1976). Combining the data sets of Gagliano and van Beek (1970) and Adams et al. (1976) with information on canal density, Craig et al. (1979) were able to produce regressions showing that land loss in the Louisiana coastal zone is related to density of canals. The next advance in the study of land loss came about through the development of a computerized data base containing information from habitat maps summarized by quad sheet and by parish, Louisiana's equivalent of a county (Wicker, 1980, 1981). While these data contained no spatial information within the quad sheet, they did allow regression analyses to be performed for large portions of the coastal zone (Deegan et al., 1984; Scaife et al., 1983).

These previous studies used data that either covered a limited area or were aggregated and therefore lacked spatial detail. Without this detail, site-specific management options to reduce or reverse land loss cannot be studied. The need for large coverage and high spatial resolution has led to the application of spatial proximity analysis and spatial simulation modeling. Proximity analysis uses digitized habitat maps and software developed for image processing applications to analyze the spatial patterns of a landscape, whereas spatial simulation modeling attempts to replicate the landscape's spatial dynamics (Costanza et al., 1986; Sklar et al., 1985). These two techniques are currently being used to analyze the processes involved in land loss. In this paper, we discuss these two methods in detail and provide a general review of the evolution of Louisiana wetland loss models.

DATA BASE DESCRIPTIONS

Several different types of spatial data have been used to study land loss in Louisiana. In this section we describe four of the more commonly used sources: USGS quadrangle maps, photomosaics, quad sheet summaries, and digitized habitat maps.

Quadrangle Maps

In the period between 1890 and 1914, the first USGS maps of Louisiana's coast were produced through field studies. These early maps, which covered a total coastal area of 7,300 mi^2 (18,907 km^2; Gagliano et al., 1981), are unreliable, however, as many of the small aquatic areas that are typical of land loss were either stylized or omitted. Thus, these initial maps underestimate water area (Gagliano and van Beek, 1970). Beginning with the 1930s, the first USGS maps based on aerial photographs were produced (Gagliano et al., 1981), leading to a substantial increase in spatial detail.

Photomosaics

The acquisition of aerial photography for large portions of the state's coastal zone has increased the level of detail included in land loss studies. Photomosaics of a large area are usually obtained during a short time, whereas producing USGS maps of a similar area can require a number of years (Craig et al., 1979). Early photomosaics were compiled from black and white photography. Later, color infrared photography proved to be a far superior medium for the analysis of vegetation and habitat types. Areal measurements of land and water have been made from both USGS quad sheets and photomosaics in two ways: (1) by determining the percentage of land and water points in a sample grid and then multiplying by total area (Gagliano and van Beek, 1970), and (2) by direct measurement with a manual or electronic planimeter (Adams et al., 1976; Craig et al., 1979).

Quad Sheet Summaries

Habitat maps of the entire Louisiana coastal zone have been produced by Coastal Environments, Inc., of Baton Rouge, by photointerpreting black and white photography from the 1950s and color infrared photography from 1978 (Wicker, 1980, 1981). These maps, which were produced on 1:24,000 USGS base maps, were coded using the Cowardin habitat classification system (Cowardin et al., 1979). Total area of each habitat type was obtained through planimetering and then summed by quad sheet and by parish. These data summaries were then stored on computer tape. The resulting data base is thus highly amenable to statistical analysis. It has the advantages of complete coverage over two time periods, uniform interpretation, and computerized format. The major disadvantage is that these data contain no spatial information within the quad sheet. This data set is therefore more suited to studies of global causes of land loss, which occur over large areas, rather than local factors.

Digitized Habitat Maps

Wicker's habitat maps have been digitized more recently by the National Coastal Ecosystem Team of the U. S. Fish and Wildlife Service. Digitizing is a process that samples the points of a polygon and stores the X/Y coordinate of each point in a computer, whereas planimetering is a measurement that provides area only; thus, digitizing can lead to area measurements and also retains geometric information. These digitized habitat data of the entire Louisiana coastal zone are stored on computer in polygon format for two different time periods. While this represents an incredible scientific resource, the resulting data are difficult to use because (1) the quantity of data requires a large amount of storage and processing time, and (2) with polygon format data the vertices of each polygon are stored as Cartesian coordinates, and thus these data are not quickly processed by computer. To make data processing more manageable, the data base can be transformed into a cell format (also referred to as raster format). This is done by laying a grid of any arbitrary size over the polygon data, calculating the area of each habitat within each grid cell, and then assigning that cell the code of the habitat with the largest area. Increasing the cell size reduces the processing costs but also decreases the amount of spatial information that is retained. The result is a data base that can be easily manipulated using matrix operations.

STUDIES OF LAND LOSS RATES

The first comprehensive study of land loss in coastal Louisiana was performed in 1970 by Gagliano and van Beek. Although there were earlier studies of land loss in Louisiana (Treadwell, 1955; Morgan and Larimore, 1957; Peyronnin, 1962; Saucier, 1963; Kwon, 1969), these considered either areas of limited size or analyzed only certain types of land loss, such as shoreline retreat or barrier island erosion. The study by Gagliano and van Beek was the first to include all land loss, including the breakup of inland marshes, over a large study area. They looked at land loss using USGS quad maps from three time periods: the 1890s, the 1930s, and the 1950s–1960s.

Thus, an 1890s to 1930s rate could be calculated, along with a 1930s to 1950s–1960s rate. A half-mile (0.8-km) square grid was overlain on each map, producing 255 intersection points per 7½ minute quad sheet. At each intersection, it was determined whether the point was land or water, allowing the calculation of a land-to-water ratio for each quad sheet. Multiplying these percentages by the total quad area gave an estimate of land and water area for each quadrangle. Land loss was calculated by looking at the difference in total land for each quad sheet between each time period.

For the 1930s to 1950–1960 period, Gagliano and van Beek calculated that a total of 495 mi^2 (1282 km^2) had been lost, resulting in an average rate of 16.5 mi^2 (42.7 km^2) per year. They produced a land loss rate map by contouring the loss rate of each quad plotted as the center point of that quad. This map showed that the Atchafalaya basin was one of the only areas experiencing land gain and that most of the rest of the study area was deteriorating. Using the age and depth of burial of marsh clays and peats as an indicator of subsidence rates, they found that areas of greatest land loss were found in areas experiencing the highest subsidence rates.

A 1976 study by Adams et al. investigated land loss rates in the Barataria basin. They used USGS maps from 1960 to 1971 and color infrared photography from 1974 to examine land loss in 14 sample sites within their study area. These sites were chosen from each of the four marsh types within Barataria (saline, brackish, intermediate, and fresh). In addition, each study site was classified according to whether it was moderately or heavily impacted by man. Land and water area in each of the sites was obtained through planimetering. Rates were reported as annual loss, in acres, and as the annual percent of loss in land (land loss divided by total land). All study sites except one experienced a loss of land, with the highest rate being an average of 1.89% per year. The one site that gained land did so at an average rate of 0.19% per year. Losses were highest in the brackish marsh sites. One interesting finding was that heavily impacted sites experienced less land loss than moderately affected sites.

One of the most quoted land loss studies examines the trend in land loss over the period from 1890 to 1978 (Gagliano et al., 1981). This study combines the earlier work of Gagliano and van Beek (1970) with analyses performed on the Wicker quad sheet summary data. For study areas of 7,300 mi^2 (18,907 km^2) from 1890 to the 1930s, and 11,500 mi^2 (29,785 km^2) from the 1930s to 1978, Gagliano and associates found average annual wetland loss rates of 6.7 mi^2 (17.4 km^2) between 1890 and 1935, 15.8 mi^2 (40.9 km^2) between 1935 and 1958, and 28.1 mi^2 (72.8 km^2) between 1956 and 1978. Using the midpoint of the time interval to plot each of these rates, they found that land loss was increasing exponentially over time (Fig. 1). From this curve they predicted a loss rate of 39.4 mi^2 (102 km^2) per year for 1980. At this predicted rate, they estimated that Plaquemines, Terrebonne, St. Bernard, and Lafourche parishes had life expectancies of 52, 102, 152, and 205 years, respectively.

These studies documented the extent of wetland loss over the years and resulted in increased public awareness of wetland deterioration in Louisiana (Boesch, 1982). Having clearly defined the problem, attention was then focused on the factors influencing land loss, since this could allow for mitigation.

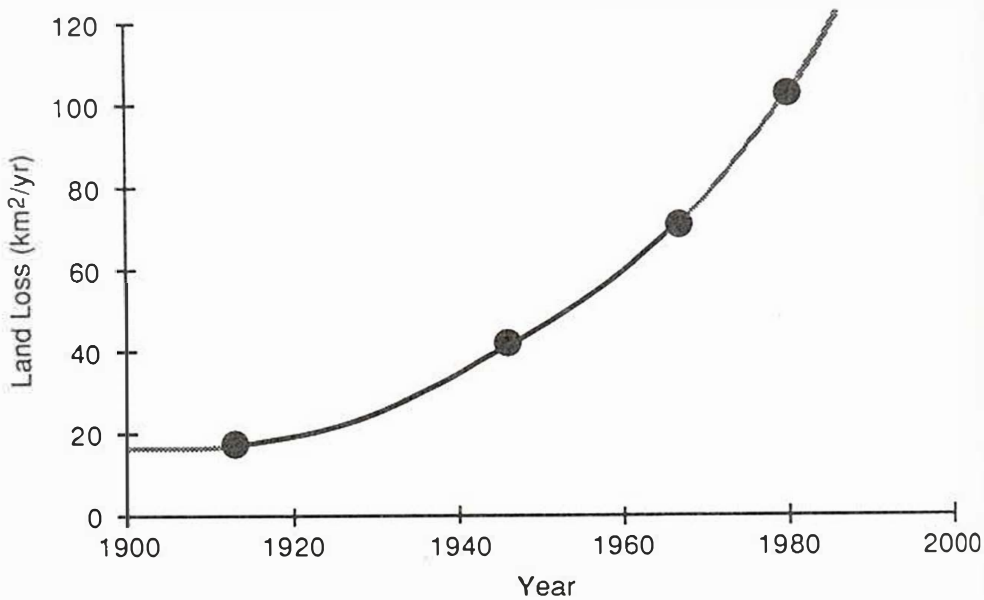

Fig. 1 Changes in the rate of land loss between 1913–1967 for the Mississippi River deltaic plain of Louisiana. Extrapolated rates are shown as a broken line (modified from Gagliano et al., 1981).

REGRESSION MODELS

The next step in the evolution of land loss studies was to use regression models to test the effects of specific factors on land loss. Combining the work of Gagliano and van Beek (1970) and Adams et al. (1976) with canal density data from Chabreck (1972), Craig et al. (1979) looked at the effect of canal density on rate of land loss. For seven of Louisiana's hydrologic units, they found a y-intercept value (i.e., zero canal density) of 0.10% per year (r^2 = 0.97). For areas in Barataria basin, the y-intercept was similar (0.07% per year) although the data did not fit as well (r^2 = 0.69). Craig and coworkers concluded that this zero canal value probably represented land loss from natural causes, i.e., changes in land elevation relative to sea level.

In another study, Scaife et al. (1983) divided Wicker's habitat maps of Louisiana's deltaic plain (those lands adjacent to the Mississippi River and therefore directly influenced by its sediment supply) into 10 subsamples based on distance from the coast, since subsidence rates generally are larger closer to the coast (Kolb and Van Lopik, 1958). The maps were also subdivided into six delta lobes, since delta systems of different geologic ages experience different subsidence rates (Frazier, 1967). Simple regressions were then run using the annual percent of land loss over each quad between 1955 and 1978 as the dependent variable and the percent of quad area that was canal in 1978 as the independent variable. The degree to which land loss is correlated with canal area is indicated by the slopes of these regressions. As expected, rates of loss were generally higher in younger deltas and in areas close to the coast. The average value for percent land loss with no canals present (i.e., the y-intercept of the regressions) was 0.091 ± 0.139% annually. For the period between 1955 and 1978, this accounted for 11% of the overall land loss. Scaife and co-workers interpreted this to mean that 11% of the land loss was caused by factors other than canals and that therefore canals might be responsible for the remaining 89%.

Two problems with this study are that (1) the size of the individual subsamples was small (5 to 20 quad sheets per subsample), and (2) many of the intercept estimates were not statistically significant (most of the slopes were, however). To address these problems, Deegan et al. (1984) performed a more elaborate multiple regression analysis using the same quad sheet data. They supplemented this data base with more accurate measurements of distance to the coast, delta age, and depth of sediment overlying the Pleistocene terrace. They also increased the number of independent variables by using data on initial marsh area in 1956, three measures of canal and spoil area (i.e., 1956 canal/spoil area, 1978 area, and change in area from 1956 to 1978), area of natural waterways, and change in urban and agricultural area between 1956 and 1978. In addition, all combinations were included, as they were using a stepwise multivariate regression technique.

Deegan and co-workers found a significant linear relationship ($r^2 = 0.72$, $P < .01$) for marsh loss per hectare with the following equation:

$$\text{LOSS} = -182.7 + (0.147 \cdot \text{IMARSH}) + (0.69 \cdot \text{DD}) + (1.46 \cdot \text{DC}) + (6.43 \cdot \text{DEPTH}) - (0.0004 \cdot \text{AGE} \cdot \text{FC})$$

where

LOSS = Loss of marsh between 1956 and 1978 (in ha)
IMARSH = Initial (1956) marsh area (ha)
DD = Change in urban and agricultural area between 1956 and 1978 (ha)
DC = Change in area of canal and spoil between 1956 and 1978 (ha)
DEPTH = Sediment depth over the Pleistocene terrace (m)
AGE = Age of delta lobe (years)
FC = Final (1978) canal and spoil area (ha)

According to this equation, the total land loss caused by canals and associated spoil banks is equal to the change in canal area (DC) multiplied by a regression coefficient (1.46). This gives an average loss of 42,327 ha, which is equivalent to 32% of the total marsh loss. Their estimate of average indirect wetland loss from canals was 13,336 ha, or 10% of the total marsh loss; this was calculated by subtracting the land actually converted to water by dredging and construction of canals (direct loss) from the total loss statistically associated with canals (42,327 ha − 28,991 ha). The incorporation of a negative AGE coefficient in the regression model indicates that canal effects generally will decrease as the age of the subdelta lobe increases. Scaife et al. (1983) reached the same conclusion by comparing the slopes of the regression equations for each of their delta basins.

The analysis by Deegan et al. (1984) removed several sources of bias that were included in the study by Scaife et al. First, Deegan et al. used a much larger sample size (139 quad sheets). Second, Scaife et al. used a qualitative method for aging delta lobes (deltas were numbered one through six in increasing order of age), whereas Deegan et al. used the actual age in years. And finally, in the Deegan et al. model more factors were included and the model was allowed to determine which of those were important, rather than determining *a priori* that only distance from coast and delta age were important.

On the other hand, including as many variables as possible into a single regression equation increases the likelihood of incorporating nonmechanistic information. For example, the independent variable that explained the most variance in marsh loss in the Deegan et al. model was the 1956 marsh area (IMARSH). The amount of marsh transformed into water obviously depends on the amount of available land. By explaining wetland loss as a function of preexisting marsh (an initial condition rather than an analytical association), the importance of more mechanistic relationships, such as hydrologic alterations by canal, was reduced; therefore this was partly responsible for the low estimates of indirect canal effects on land loss in the Deegan et al. multivariate regression model.

These statistical models demonstrated that the indirect effects of canals on land loss were at least as important as the direct effects of canals. Human intervention in the coastal zone is clearly influencing the natural processes of river delta growth and deterioration; however, the extent of this influence is still not clear. It could be that many important effects are still being missed because of the gross spatial resolution of the quad sheet data. Examining the spatial associations between land loss and features such as canals with more detailed data will reveal a clearer picture of these interactions.

SPATIAL PROXIMITY ANALYSIS

As was discussed above, the Wicker (1980, 1981) quad sheet summary data are appropriate for the study of global factors of land loss, such as canal density, delta lobe age, depth to Pleistocene, distance to coast, etc. There are serious limitations to highly aggregated data such as these, however, since summing area by habitat results in a loss of spatial detail; thus, only net changes in habitat distribution can be determined. Therefore it is possible that a large rate of land loss could be masked by land gain. This lack of detail represents a substantial source of error.

Second, it is not possible to test directly local factors with aggregated habitat data. The regression models of Craig et al. (1979), Scaife et al. (1983), and Deegan et al. (1984) give only an approximation of the effects of canals on land loss, because there is no spatial resolution within the quad map. Without spatial detail inside the quad, it is impossible to determine whether this loss actually occurs adjacent to canals or somewhere else. If canals are a cause of land loss, then land loss rates should increase with nearness to canals. The quad sheet summary data lack the detail required to test some of the more important land loss hypotheses. The following section describes how proximity analysis, when combined with high-resolution, digitized habitat maps, can allow the relation between canals and land loss to be examined more explicitly.

Digitized habitat map data of a 2550 km^2 study area in Terrebonne Parish were obtained for 1956 and 1978 at a cell size of 50 m $\times$ 50 m (Fig. 2). At this level of resolution, narrow linear features such as canals appear, although they are blocky and are not continuous (Fig. 3a). Total land area for the study area in 1956 and 1978 was 1596 and 1405 km^2, respectively.

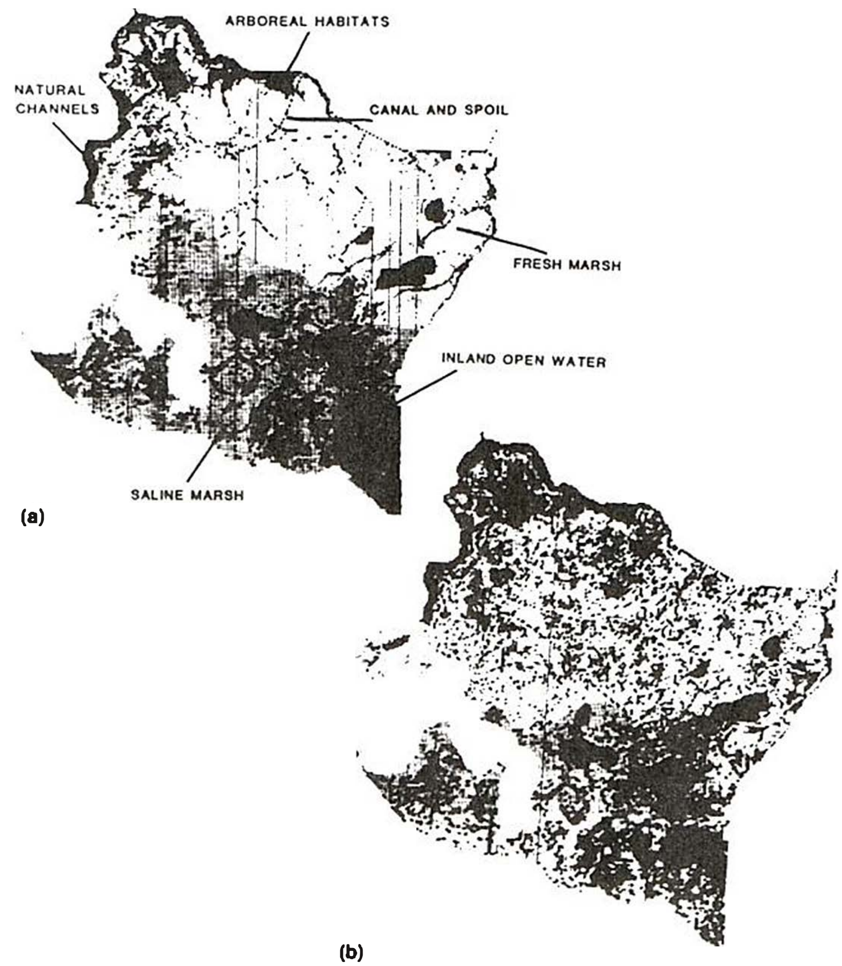

Fig. 2 The Terrebonne marsh/Atchafalaya delta study area in 1956(a) and 1978(b). Note the large amount of open water which appears in the 1978 map, as well as the emergence of the Atchafalaya delta in the midwestern section.

Thus in the 22-year period, the area lost was 191 km^2, or 12.0% of the original land area. This is equivalent to an average annual loss rate of 8.7 km^2, or 0.6%. As discussed previously, however, this represents a net land loss rate and is an underestimate of the gross loss. For example, the growth of the Atchafalaya delta between 1956 and 1978 added 13.7 km^2 of land to the study area. A gross loss rate can be calculated by counting the number of cells which were land in 1956 and water in 1978. Using this method, a loss rate of

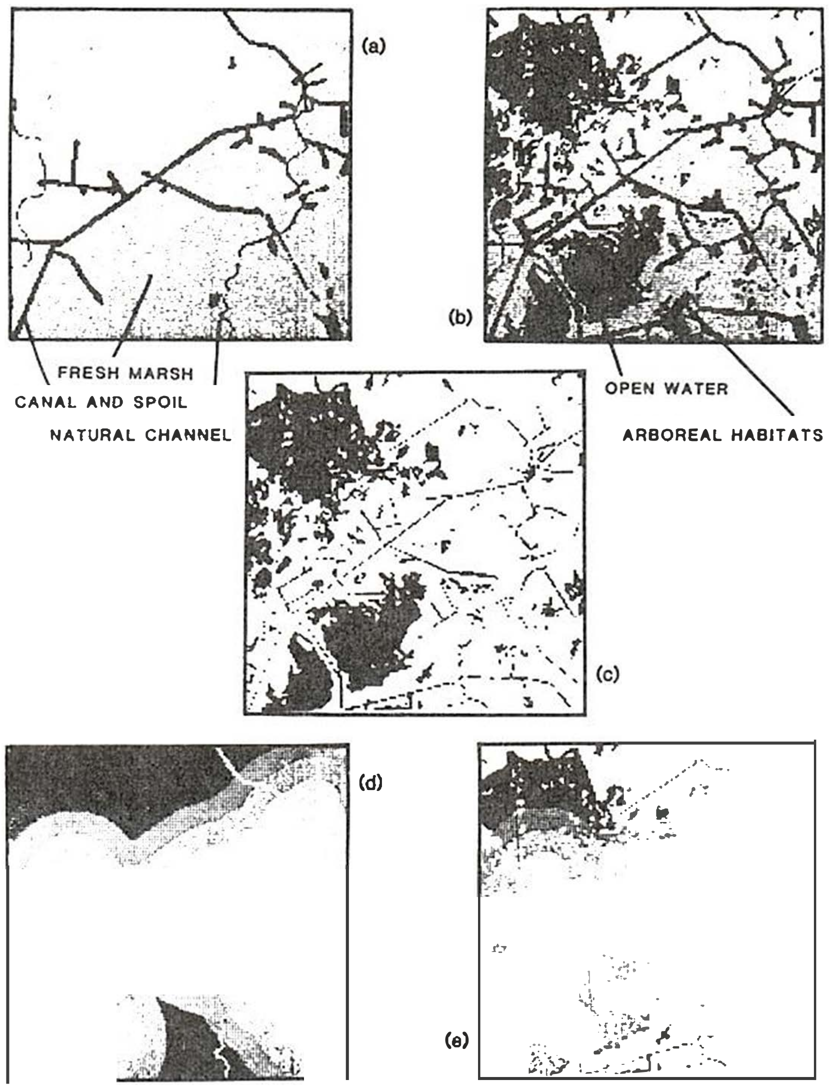

Fig. 3 A 1.125-km² subsection of the Terrebonne marsh/Atchafalaya delta study area for 1956(a) and 1978(b), illustrating the methods used to generate images for the proximity analysis. A land loss map (c) was created by highlighting all the cells which were land in 1956 but changed to water in 1978 (land loss is shown as the dark area). Grouping cells by distance intervals to the nearest canal produced an "iso-distance" contour image (d) which was used to test the effect of canal and spoil on land loss (distance contours in figure are 500 m thick). Superimposing land loss on map (d) results in an image of land loss by distance to canal or spoil (e).

233 km^2, or 14.6%, is obtained (10.6 km^2 or 0.7% per year). A transition matrix showing changes in habitats between the two time periods is given in Table 1.

Using the 22-year loss rate of 14.6%, it is now possible to test other hypotheses concerning land loss. For example, if land loss is a completely random process, then it should be independent of habitat type and, thus, loss

TABLE 1

Habitat* Transition Matrix for the Terrebonne Marsh/ Atchafalaya Delta Study Area Between 1956 and 1978†

To	Terrestrial habitats				Aquatic habitats				
From	Saline marsh	Fresh marsh	Arboreal habitats	Spoil	Canals	Natural channels	Inland open water	Gulf open water	Total (1956)
Saline marsh	408	149	3	11	7	15	54	10	657
Fresh marsh	18	590	29	22	16	7	114	0	796
Arboreal habitats	0	19	100	4	3	2	1	0	129
Spoil	1	3	1	6	3	0	0	0	14
Canals	0	1	0	2	9	3	1	0	16
Natural channels	4	5	2	1	2	61	2	1	78
Inland open water	10	2	0	0	0	2	247	0	261
Gulf open water	7	3	0	4	0	0	0	583	597
Total (1978)	448	772	135	50	40	90	419	594	2548

*Categories have been aggregated from habitat codes presented in Appendix I. Saline marsh includes salt marsh, brackish marsh, and beach. Fresh marsh includes fresh marsh and intermediate marsh. Arboreal habitats include uplands, swamp, and scrub-shrub. All other categories are as listed in Appendix I.

†Area in km^2.

rates in fresh, brackish, and salt marsh habitats should all be close to the 14.6% value. A comparison of wetland habitats in the Terrebonne marsh/Atchafalaya delta study area indicated differences in habitat susceptibility to land loss (Table 2). The saline marsh loss rate was similar to loss for the overall study area (13.1%), though the rate for fresh marsh was higher (17.3%). Arboreal habitats, found on more stable soils, had a lower rate of 4.6%, as expected. Spoil banks had the highest rates of land loss (21.4%), perhaps because of compaction or oxidation of organics or channel expansion by erosion. It is possible, however, that this high loss rate is an artifact of the 50 m × 50 m cell size, since spoil is a narrow, linear feature. Nevertheless, it is clear from this analysis that land loss is not a random process with respect to habitat.

TABLE 2

Land Loss in the Terrebonne Marsh/Atchafalaya Delta Study Area from 1956 to 1978 by Habitat of Origin

	Saline marsh	Fresh marsh	Arboreal habitats	Spoil
Area of land lost (km^2)	86	138	6	3
Total 1956 habitat area (km^2)	657	796	129	14
Percent loss	13.1	17.3	4.6	21.4

As was mentioned in earlier sections, there are several different kinds of land loss, such as shoreline erosion (land converted to Gulf open water), construction of new canals (land to canal), creation of new ponds (land to inland open water), and expansion of canals, natural channels, and lakes (land to canal, natural channel, and inland open water, respectively). The analysis of the Terrebonne data allows these different types of loss to be differentiated (Table 3). It was found that the transformation of land to inland open water is the most significant source of land loss, accounting for almost 75% of all loss. Land lost by direct conversion to canal is equal to 12.1%, while loss to natural channels is equal to 10.6 percent. Land lost to Gulf open water by shoreline retreat accounts for less than 5% of the area's total land loss.

TABLE 3

Land Loss in the Terrebonne Marsh/Atchafalaya Delta Study Area from 1956 to 1978 by Final Habitat Type*

	Canals	Natural channels	Inland open water	Gulf open water
Area of land lost (km^2)	28.3	24.8	169.9	10.4
Percent loss	12.1	10.6	72.8	4.5

*Percent is of the total area of land lost (i.e., 233.4 km^2)

If canals are having a significant effect on land loss, then rates of loss near canals should be higher than rates away from canals. Calculating the distribution of land loss according to its distance to canal and spoil is therefore one test of the impact of canals on land loss. This distribution can be compared with distance distributions from other features, such as natural channels, to see how they differ.

Figures 3a and 3b show a 1.125-km^2 subsection of the Terrebonne marsh/Atchafalaya delta study area for 1956 and 1978. A land loss image was constructed by displaying all cells that were land in 1956 and were converted to water in 1978 (the dark shading in Fig. 3c). To test the effect of canals, an "iso-distance" map (Fig. 3d) was created, which for each cell is the distance of that cell to the nearest canal or spoil. By merging the land loss and canal distance images, an image showing land loss by distance to canal or spoil was produced (Fig. 3e). The land loss within each distance contour was summed for the entire study area and then normalized by the total number of land pixels in that contour, since total land area is itself dependent upon distance to canal (Fig. 4). The result is a graph showing percent of land loss as a function of distance to canals (Fig. 5a).

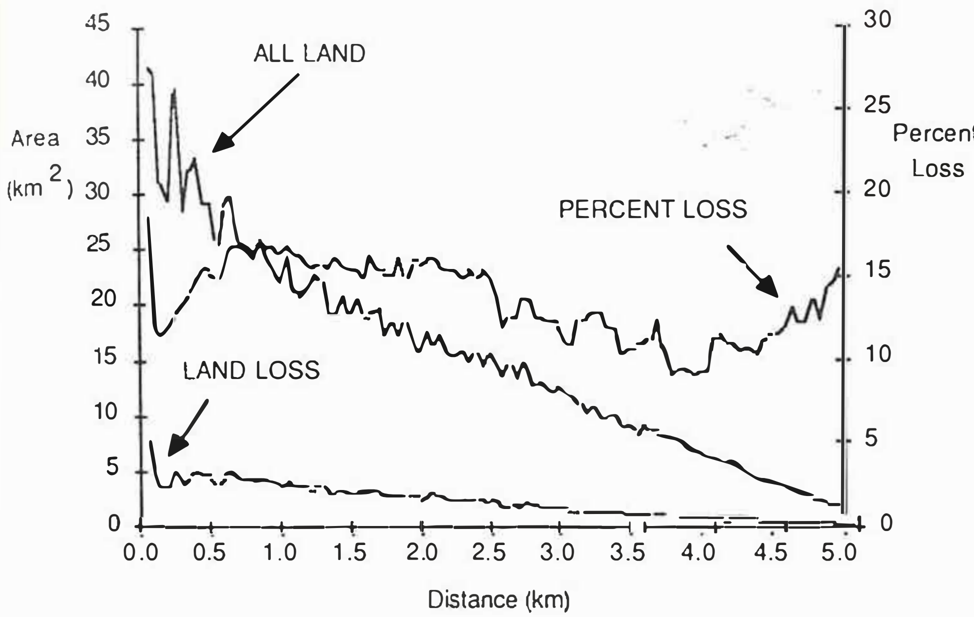

Fig. 4 Plot showing the effect of distance to nearest canal or spoil on land loss, total land (excluding water), and percent land loss (land loss per distance interval divided by total land per distance interval) for the Terrebonne marsh/Atchafalaya delta study area. The use of land loss as an index of canal and spoil effects is inaccurate, since the total amount of erodable land is itself a function of distance to canal or spoil. The percent land loss takes this into account.

Figure 5a indicates that the probability of land being converted to open water increases as distance to canal decreases. From a distance of 0.75 km to 4 km, land loss rates steadily decrease from 17% to 9% (this compares with the 14.6% rates for the overall study area). Within the first 0.75 km, loss ini-

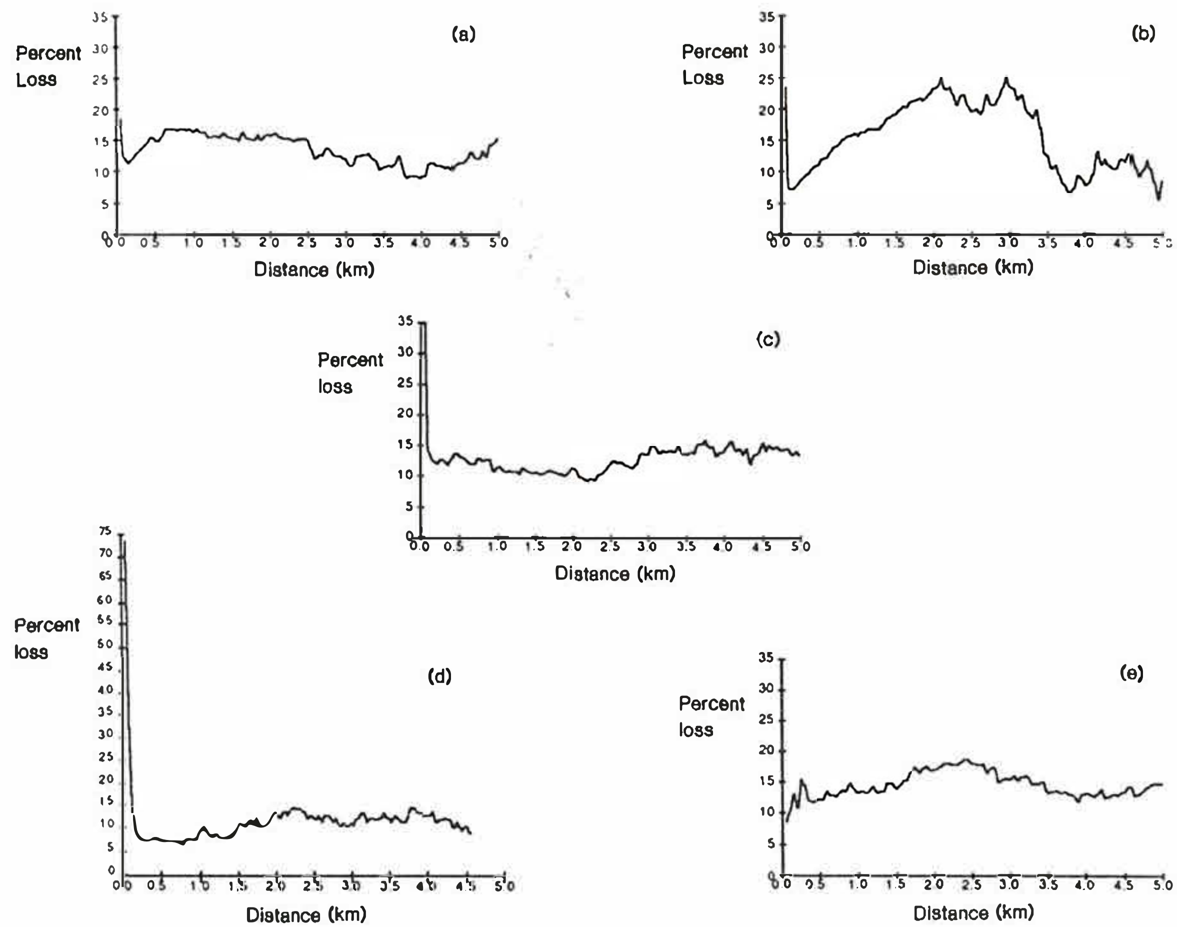

Fig. 5 Percent land loss as a function of distance to nearest canal or spoil (a), natural channels (b), inland open water (c), Gulf open water (d), and uplands (e). Distances are based on the 1956 distribution of these habitats.

tially starts at a rate of over 18%, then drops below 12%, and again rises to 17% (Fig. 5a). There could be several reasons for this initial drop in rate of loss, including more stable sediments adjacent to canals because of spoil deposition, or the possibility that the more readily eroded land near canals had already been converted to open water before 1956. It is also possible that this is an artifact of the relatively large cell size.

Whereas land loss decreases as distance to canals increases, the opposite relationship is found when comparing loss with distance to natural channels (Fig. 5b). At distances between 2.0 and 3.0 km from natural channels, high rates of land loss occur. As distance decreases from 2.0 to 0.25 km, however, the rate drops from 25 to 7%. Beyond 3 km, loss rates return to average values. The initial high rate found in the first 0.25 km may be caused by channel expansion (caused by slumping of channel walls or erosion from boat traffic), the creation of new meanders or, again, it may be an artifact of cell size.

Rates of loss were also compared with distance to inland open water (Fig. 5c) and to Gulf open water (Fig. 5d). New inland open water could be created by the expansion of preexisting ponds and lakes or by creation of new ponds. Immediately adjacent to preexisting inland open water, the rate of loss is 35%, though this quickly drops to a 14% level (Fig. 5c). As distance increases from 0.5 km, there is a slight decline from 14% to a minimum of 9% at 2.25 km; after this, the rate increases. Therefore, though pond expansion is an important factor, a large amount of loss is also occurring at a distance from preexisting open water.

The rate of loss immediately next to Gulf open water was the largest observed (Fig. 5d). Almost 75% of the land adjacent to the Gulf of Mexico was lost, indicating a significant amount of shoreline retreat. At a distance of 1.5 km, the rate stabilized to the average saline marsh rate of 13% (the curve plots loss rates within the first 5 km from the Gulf or bays, which is almost entirely within the saline marsh zone).

Whereas the plots of loss versus distance to the various water bodies all show clear trends, a plot of loss versus distance to upland habitats shows a more random distribution (Fig. 5e). Thus, the probability of land being converted to water is independent of proximity to uplands.

The preceding results demonstrate the power of proximity data for studying coastal land loss. These data clearly show how canals and natural channels are having opposite effects on land loss. While the 17% rate of loss near canal and spoil is only a few percentage points higher than the overall average of 14.6%, this statistic becomes more alarming when the rate of transformation from land to canal and spoil is considered (i.e., 63 km^2 from 1956 to 1978; Table 1). The result is that it is becoming increasingly difficult to find land located far from canals or spoil (Fig. 6). In 1956, the slope of the curve between area of land and distance to canal and spoil was relatively low, with land still occurring at distances of 5 km and beyond. By 1978, however, most of the land cells were less than 1 km from a canal or spoil, and almost no land was found at a distance greater than 4 km. Thus, construction of new canals is pushing the distribution of land closer to canals; since rates of loss increase with proximity to canals and spoil, this change in the land distribution will lead to accelerated rates of land loss.

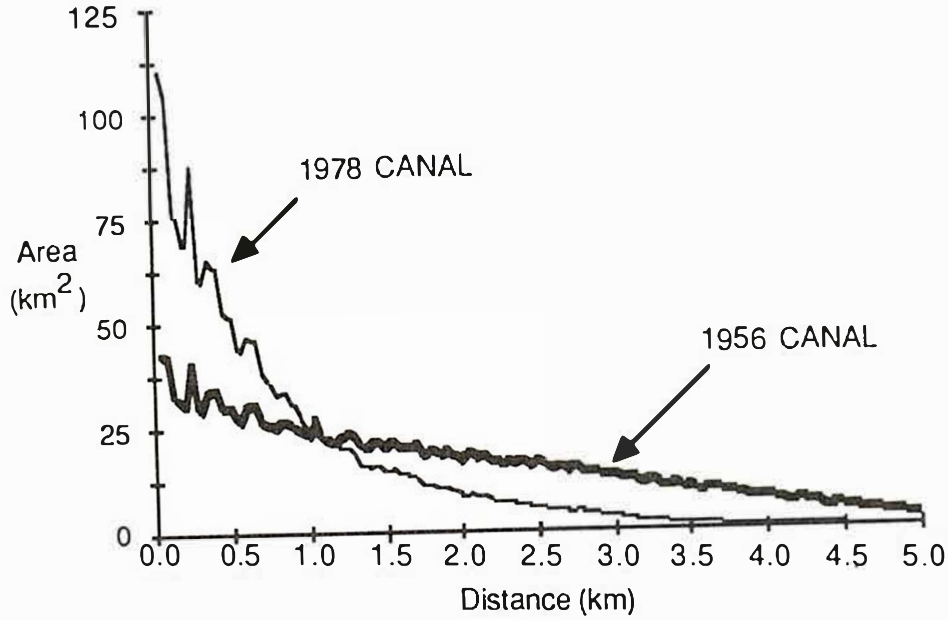

Fig. 6 Area of land (water excluded) versus distance to nearest canal or spoil in 1956 and 1978. Note that for 1978 the distribution of land has shifted much closer to the origin, due to the construction of new canals.

One limitation with the data used for this analysis is the lack of spatial detail immediately adjacent to aquatic features. This study demonstrates that smaller cell sizes are needed to determine whether the initial drops seen in Figs. 5a-5d are real or artifacts. Future analysis with 10 m × 10 m cells will address this problem.

SIMULATION MODELS

A simulation model describes the interactions between state variables (those within the system) and forcing functions (input variables outside of the system) through sets of differential equations. These differ from statistical models because simulation models attempt to mimic time-dependent processes. Like regression models, they tend to aggregate large, complex systems into a few important variables. Unlike regression models, simulation models often include nonlinear feedback loops. An example of such a model is the one developed by Cleveland et al. (1981) to assess the impacts of canals on land loss in Barataria basin.

The Cleveland et al. (1981) simulation model has four salt marsh variables (streamside marsh, inland marsh, open water, and canal area) that change with time as a function of riverine sediment input, growth of canals (i.e., 2% per year), subsidence (1.3 cm/yr), and sedimentation (1.2 cm/yr). Starting the model in 1970, the model predicted that 72% of the salt marsh disappeared after 100 years when run without canals (i.e., natural erosion only); with canals, 100% of the salt marsh disappeared after 70 years. This model could have been validated simply by comparing its estimate of land loss at one point in time with the actual salt marsh land loss at that same point in time. Unfortunately, the data bases are only now becoming available for this kind of validation. The Cleveland et al. (1981) model demonstrated a mechanism where diversion of riverine sediments from the Mississippi River into degrading marshes could reverse the loss of land and revert the wetland system back to a prograding marsh.

The most ambitious land loss modeling effort to date is the Coastal Ecological Landscape Spatial Simulation (CELSS) Model being developed at the Center for Wetland Resources, Louisiana State University, in cooperation with the U. S. Fish and Wildlife Service. This model simulates spatial processes with equations for each km^2 of marsh, swamp, water, or land. Details of the model structure are given in Sklar et al. (1985) and Costanza et al. (1986). Here we give only a brief sketch with some sample results.

CELSS is a two-dimensional, finite difference model using a 1-km^2 grid. The grid approach has been used to model global, general atmospheric circulation with some success (Kasahara and Washington, 1967; Williams et al., 1974). The square cells have exchanges across their four sides. Each cell in the model potentially is connected to adjacent cells through the exchange of water and materials. Inputs were specified as boundary conditions in the form of time series over the simulation period (1956 to 1978). Weekly values of Atchafalaya and Mississippi River discharge, riverine sediment and nutrients, runoff, rainfall nutrients, Gulf salinity, sea level, temperature, and air movement were supplied to the simulation (Costanza et al., 1986).

The volume of water crossing from one cell to another is a function of water storage (W) and connectivity (K), such that unidirectional water flow across a single boundary is KW. Water head differential is proportional to differences in water volumes in cells of equal size. The location and characteristics of the major waterways and levees were also supplied to the model. These features are very important in determining water flow and the distribution of sediment and nutrients. Thus, in addition to overland flow, water exchange with adjacent cells can occur via canals or natural bayous, though exchange may be prevented by the presence of levees. The model begins with the waterway and levee structure of 1956 and ends with the 1978 structure (Fig. 7). The habitat-specific water flow connectivity parameter is adjusted to reflect the presence and size of waterways or levees. If a waterway is present at a cell boundary a large connectivity value is used, increasing with the size of the waterway. If a levee is present, a connectivity value of 0 is specified until water level exceeds levee height. The model's canal and levee network is updated each year during a simulation run. Man-made canals and levees are added to the model's hydrologic structure at the beginning of the year they were built.

Figure 8 shows diagrammatically all the state variables of the model for a typical cell. Changes in abiotic material concentrations (salt, suspended sediments, and elevation) were modeled as a function of water flow between cells and concentration of materials in the cells (the state variables), along with internal deposition (flows 8 and 9), resuspension (flow 7), and subsidence (flow 10). Biotic materials (detritus and primary productivity) in the model respond to the abiotic characteristics of a cell and the habitat type of

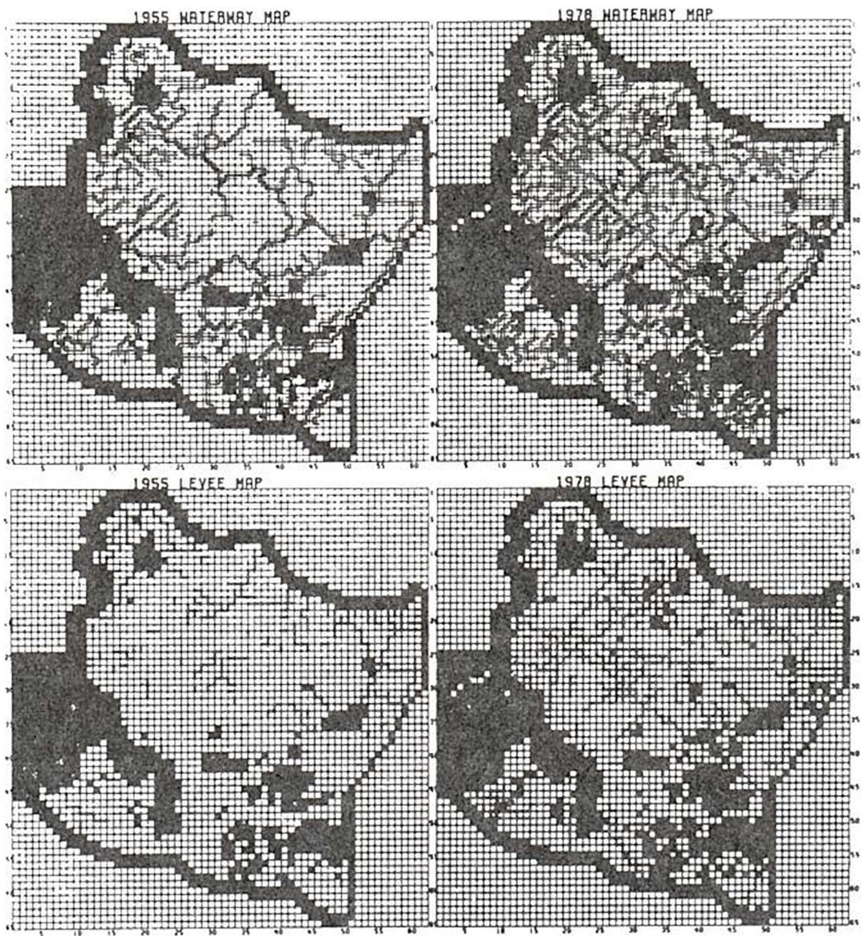

Fig. 7 Maps of the major waterways (top) and levees (bottom) in the Terrebonne marsh/Atchafalaya delta study area for 1955 (left) and 1978 (right). Waterways include canal and natural channels, while levees are equivalent to spoil banks. Line widths in the waterway maps are indicative of the relative size and flow coefficients of the waterway. Maps are based on data obtained from the Louisiana Department of Natural Resources and were converted to a 1-km^2 grid.

that cell. For example, a Gaussian equation describes the response of the primary producers for each habitat to each abiotic state variable. This acts to maximize productivity under ideal conditions and lowers productivity as conditions deviate from optimal. The response to different nutrient concentrations, on the other hand, was simulated with the Michaelis-Menten rate equation (i.e., $V = [V_{max} \times S]/[K_m + S]$), as recommended by Dugdale (1967) and Parsons and Takahashi (1973). Values for V_{max} and K_m were estimated based on knowledge of the study area and published literature and then adjusted for optimal model fit.

The complex interactions between primary production and the supply of nutrients (in this case, nitrogen) are also shown in Fig. 8. Factors influencing dissolved inorganic nitrogen (DIN) include denitrification (flow 3), nitrification (flow 6), Michaelis-Menten uptake (flow 4), deposition

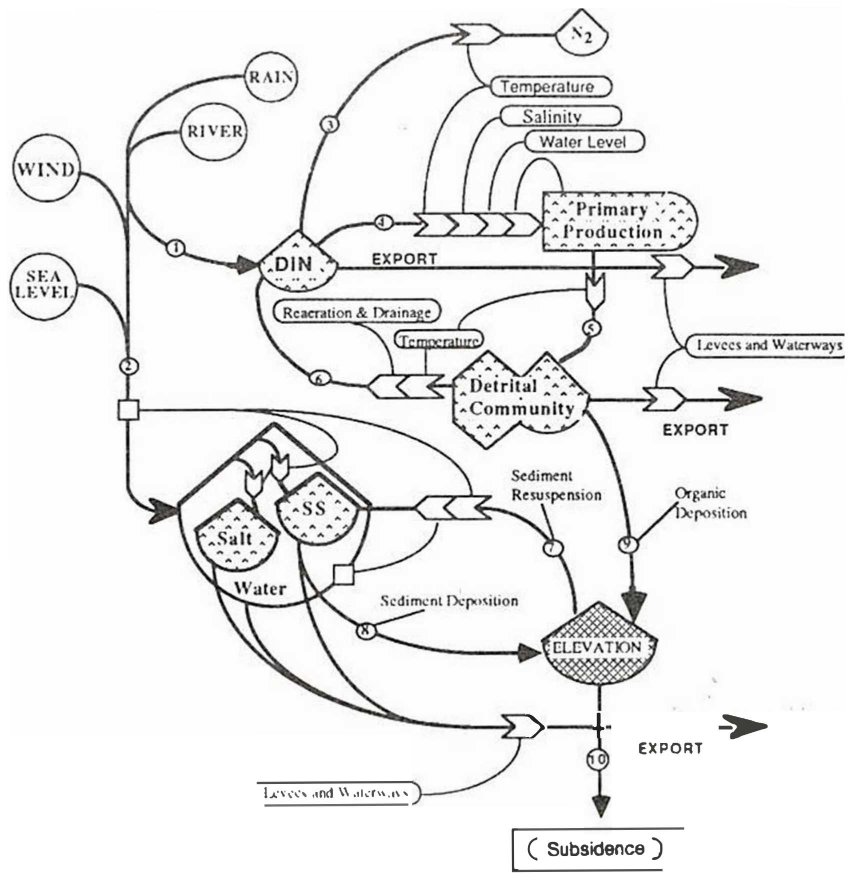

Fig. 8 Conceptual model of the processes occurring in each cell of the dynamic spatial simulation model. Physical and biological processes control the storage (tanks) and exchange rates (lines and arrows) of all state variables in each cell. DIN = dissolved inorganic nitrogen; SS = suspended sediments. Fluxes of nitrogen, suspended sediments, and detritus between cells are proportional to water flow. Forcing functions are shown as variables in circles.

(flow 5), rain and river inputs (flow 1), and hydrologic exports. Under optimal conditions, primary production is maximized and large quantities of organic matter accumulate in the sediments. This, in turn, helps maintain the elevation of the land by balancing the loss from subsidence. The land elevation is also maintained by riverine input of sediment and organic matter. The synergism between plants and marsh elevation thus results in a feedback that enhances the stability of the marsh. Breaking this feedback by diverting suspended sediments from the marsh causes an acceleration of land loss.

Habitat succession occurs in the model, after a certain time lag, when the environmental conditions in a cell of one habitat type become more like the environmental conditions of a different habitat type. A subroutine monitors the state variables in each cell and checks to see if the "environment" (salinity, elevation, productivity, etc.) is stable. If the values of the state variables change to the extent that the cell's environment is inappropriate for its designated habitat type, then the cell habitat type and all the associated parameter settings are switched to a new set of parameters that are more representative of the new environment.

The model produces a large amount of mapped output for all state variables plus habitat types for each week of the simulation. The model was run for 35 years (1820 weekly iterations) starting in 1955 and ending in 1990. The best way to appreciate the model's dynamic spatial behavior is to view a video display of the mapped variables over time. In a paper we can show only a few examples of simulated habitat changes (Fig. 9). This series shows the gradual intrusion of salt and brackish marsh into the system from the southeast sector of the study area with a concurrent freshening in the northwest sector. It also illustrates a loss of freshwater marsh and an increase in open water habitats in the north. These trends are indicative of the movement of river water and sediments farther south in recent times and a lack of connectivity with the northern fresh marsh areas.

The resulting simulated 1978 habitat map was compared with the actual 1978 habitat map in order to calibrate the model. This was then evaluated in two different ways: (1) a cell-by-cell comparison was made between the real and simulated maps to determine the percent of accurately predicted cells, and (2) a comparison of the aggregated habitat statistics was made to see how well the habitat areas matched (i.e., without considering their spatial distribution). The cell-by-cell comparison resulted in an 85% fit. The calibration of this model is continuing, and therefore this fit should improve over time. Nevertheless, the model does a good job at predicting the spatial distribution of the habitat changes.

As for the second method of evaluation, the actual amount of open water increased by 137 km^2 between 1956 and 1978, whereas the area of fresh marsh decreased by 98 km^2 in the same 22-year period (Table 4). The corresponding areas predicted by the simulation were 114 and 147 km^2, respectively. A regression of the actual habitat areas versus the predicted areas gave an r^2 of 0.961 ($.01 < P < .05$), which is significantly better than the cell-by-cell comparison mentioned earlier. Thus, the model is depicting accurately the temporal changes these habitats are undergoing. The spatial distribution should improve with the further calibration of the model.

The benefits of a spatial simulator like CELSS are great because it gives management agencies the ability to predict where and when land loss will occur. For example, specific plans to divert sediments to areas of high land loss potential could first be studied and then be implemented with minimum effort. Although CELSS is still being developed, it appears to have the potential to be the first land loss model capable of testing various management solutions to the Louisiana wetland loss problem.

DISCUSSION

The processes controlling wetland loss in the Mississippi River deltaic plain are not unique to Louisiana. Coastal wetland succession throughout the world is the interaction of many related factors, such as (1) the subsidence rate, caused by sediment compaction, (2) land slope, (3) hydrology, (4) distri-

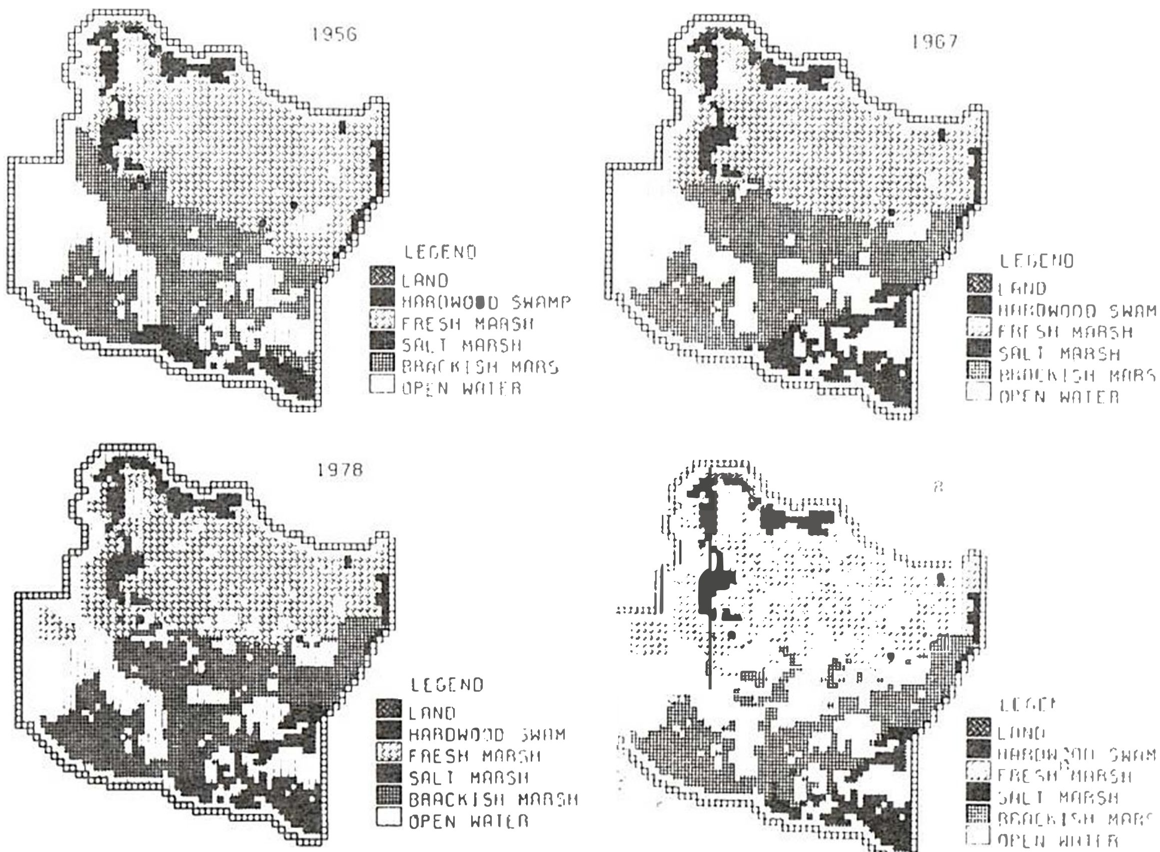

Fig. 9 Output of the dynamic spatial simulation model for the Terrebonne marsh/Atchafalaya delta study area for 1956, 1967, 1978, and 1989. Data represent the average habitat type for each 1-km^2 cell. After 1985, forcing functions were approximated with the data from the previous year. The percent correspondence, on a cell-by-cell basis, between the simulated 1978 map and the actual 1978 habitat map (see Fig 2b) was 85%.

TABLE 4

Simulated and Actual Change in Area of Major Habitat Types from 1956 to 1978 in the Terrebonne Marsh/Atchafalaya Delta Study Area

	Area (number of 1-km² cells)				
	Real			Simulated	
Habitat type	1956	1978	Change	1978	Change
Fresh marsh	864	769	−98	717	−147
Swamp	130	113	−17	118	−12
Brackish marsh	632	554	−78	647	15
Salt marsh	98	150	52	128	30
Open water*	742	879	137	856	114
Upland	13	14	1	13	0
Total	2479	2479		2479	

*Includes natural channels, inland open water, and Gulf open water (see Appendix I).

bution of sediments and nutrients, and (5) production of organic matter. All of these factors are affected by economic and environmental resource utilization. Even without subsidence or channelization, coastal habitats face an increased chance of deterioration from rising sea levels (Gornitz et al., 1982; Nummedal, 1982). It has been predicted that the increasing concentrations of atmospheric CO_2 (Siegenthaler and Oeschger, 1978) could cause global temperatures to increase from 1.5 to 3.5°C over the next 50 years (Hansen et al., 1981; Gornitz et al., 1982), which, in turn, can affect wetland habitats worldwide. For Louisiana, this global warming could cause a eustatic sea level rise of 1 cm/yr between 1980 and 2020 (Nummedal, 1982). Coastal marshes can act to buffer the impacts of this rising sea level if their terrestrial supplies of sediment and nutrients are not interrupted, allowing the marshes to maintain themselves by accumulating peats. If effective wetland management is not implemented soon, most of Louisiana's wetlands may be irreversibly destroyed. Data bases and computer techniques such as those described in this paper to model the spatial and temporal dynamics of wetland succession can decrease the uncertainties of proposed land loss mitigation projects, as well as increase our basic understanding of coastal and wetland ecology.

The next logical step in the study of wetland deterioration would be to incorporate the empirical findings of the proximity study into the simulation model. This would allow spatial distributions to be predicted more accurately. In the not-too-distant future, two additional developments should improve our modeling efforts. First, faster computers will allow spatial data of higher resolution to be processed at faster rates, as well as allow hundreds of parameter adjustments to be tested at high speed and relatively low cost. Second, the acquisition of new habitat data from high altitude, color infrared photography for 1983 and 1985 will add to our understanding of how spatial processes change over time. The current generation of satellite systems obtain highly detailed imagery over short time intervals. The Thematic Mapper on Landsat has a 30 m × 30 m cell resolution (Malila et al., 1984) and France's SPOT satellite obtains imagery with a 20 m × 20 m resolution (Welch, 1985). The availability of these data will be invaluable in the future for understanding and managing our coastal systems.

The current trend of continued habitat loss will inevitably lead to severe wetland degradation unless something is done. Each oil access canal, levee, and dredge-and-fill activity that is permitted may seem small and unimportant on a case-by-case basis, appearing only as an insignificant localized impact. However, we have shown that when spatial processes and cumulative impacts are considered, the effects are greatly magnified. We believe that the proximity and simulation models are superior analytical tools that give both scientists and coastal managers the best means to deal with regional problems such as land loss.

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APPENDIX I

Table of Cowardin Code Categories Used for Habitat Classification in This Paper*

Habitat type	Cowardin codes
	Terrestrial
Salt marsh	E2EM, E2EM5N4, E2EM5N4D, E2FL3, E2UB34
Brackish marsh	E2EM5P5, E2EM5P5D
Intermediate marsh	E2EM5P6, E2EM5P6D
Fresh marsh	PEM, PEMD
Beach	E2BB2
Swamp	PDV, PFO12, PFO123, PFO13, UDV2E
Scrub-Shrub	E2SS2, E2SS3, PSS1, PSS123, PSS13
Uplands	UDV, UDV1, UDV1O, UDV2, UFO12, UFO13, USS, USS13
Spoil	UDV3, UFO1S, USS1S, USS13S
	Aquatic
Natural channels	E1OWT, R1AB2, R1AB5, R1FL3, R1OW, R2AB5
Canal	E1AB5O, E1OWO, E1OWX, L2OWO, POWO, POWX, R1ABO, R1AB5O, R1AB5X, R1OWO, R1OWX
Inland open water	E1AB2, E1AB5, E1OW, L2AB, L2AB2, L2AB2H, L2AB5, L2AB5H, L2OW, L2OWH, PAB2, PAB5, POW, POWH
Gulf open water	E1OWG

*Habitat maps were coded by Wicker (1980, 1981) using the Cowardin code classification (Cowardin et al., 1979). It was necessary to distinguish between open water in the Gulf versus inland open water; therefore, the E1OW category was split into E1OW (inland) and E1OWG (Gulf).

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FRESHWATER WETLANDS AND WILDLIFE

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