Chapter contents

7 Burial

Our fear of being buried alive is illustrated by its frequent occurrence in our literature, from Sophocles' (ca. 495–406 BC) play *Antigone*, in which King Creon condemns Antigone to entombment "in a hollowed cave living," to Edgar Allen Poe's (1809–1849) macabre stories such as "The premature burial." Yet being buried alive is a common, one might even say routine, occurrence for many plants and benthic animals found in wetlands.

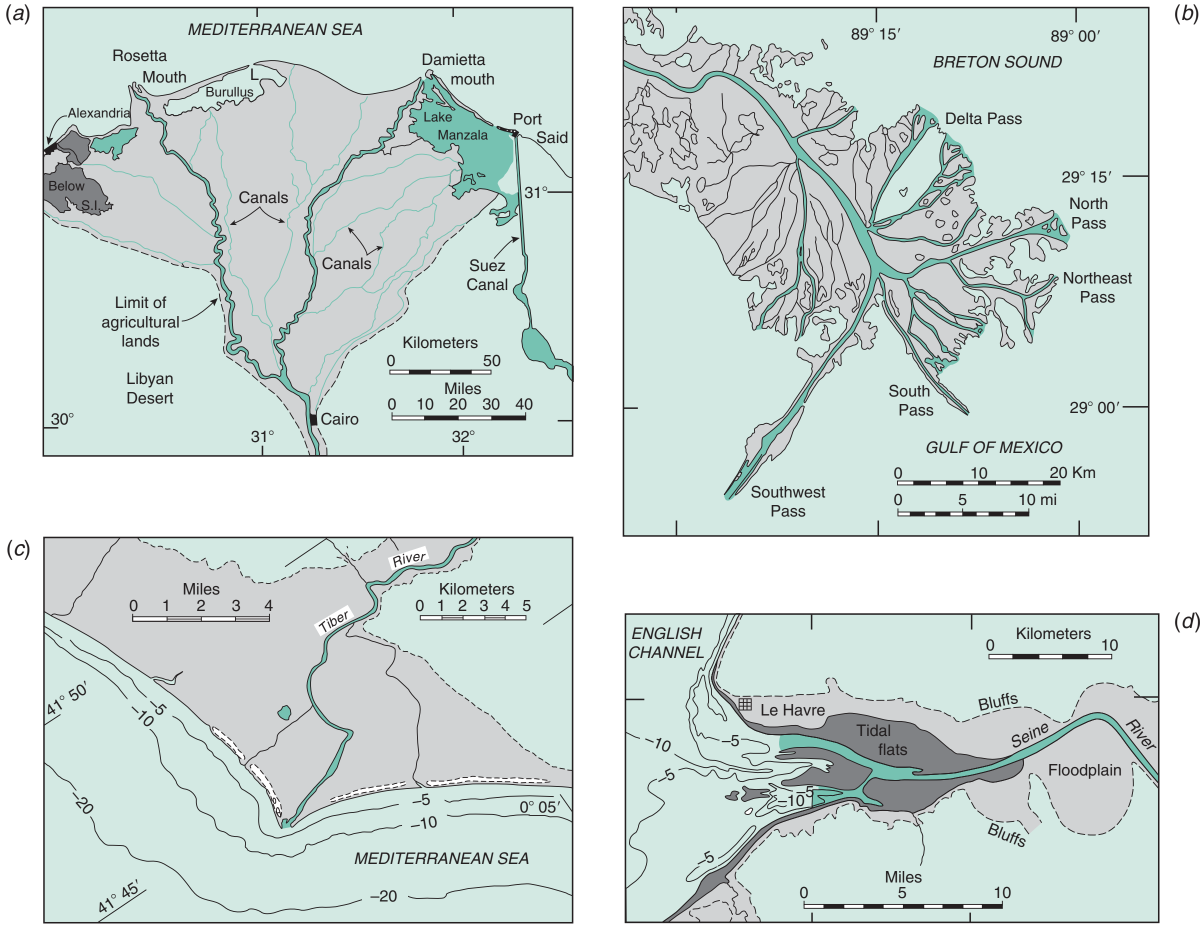

FIGURE 7.1 Although they vary greatly in size and shape, the world's deltas illustrate the amounts of sediment that are transported and deposited by rivers. Here are four examples: (*a*) Nile, (*b*) Mississippi, (*c*) Tiber, (*d*) Seine. (From Strahler 1971.)

Constant burial is one way in which wetlands differ from most terrestrial ecosystems. Many of the other factors that affect wetlands occur in terrestrial communities: disturbance, competition, and herbivory, for example. Terrestrial communities are rarely subject to burial, an exception being catastrophic events such as volcanic eruptions or landslides (e.g. del Moral *et al.* 1995; Grishin *et al.* 1996) or chronic deposition of wind-deposited sand (e.g. Maun and Lapierre 1986; Brown 1997). Such events may be dramatic and conspicuous, but they are also infrequent enough that they are rarely significant factors. Most books on terrestrial ecology would not have a chapter on burial. In contrast, rivers continually erode the land's surface and carry sediments that are deposited in wetlands as water movement slows (Figure 7.1). It is estimated that the world's rivers deliver in the order of 10^{10} tons of sediment per year to their deltas (Figure 7.2). Burial is clearly a routine experience for riparian wetlands.

The amount of sediment varies among rivers (Figure 7.3). In your own travels, you may have seen rivers that are nearly clear and rivers that seem muddy because of the amount of sediment

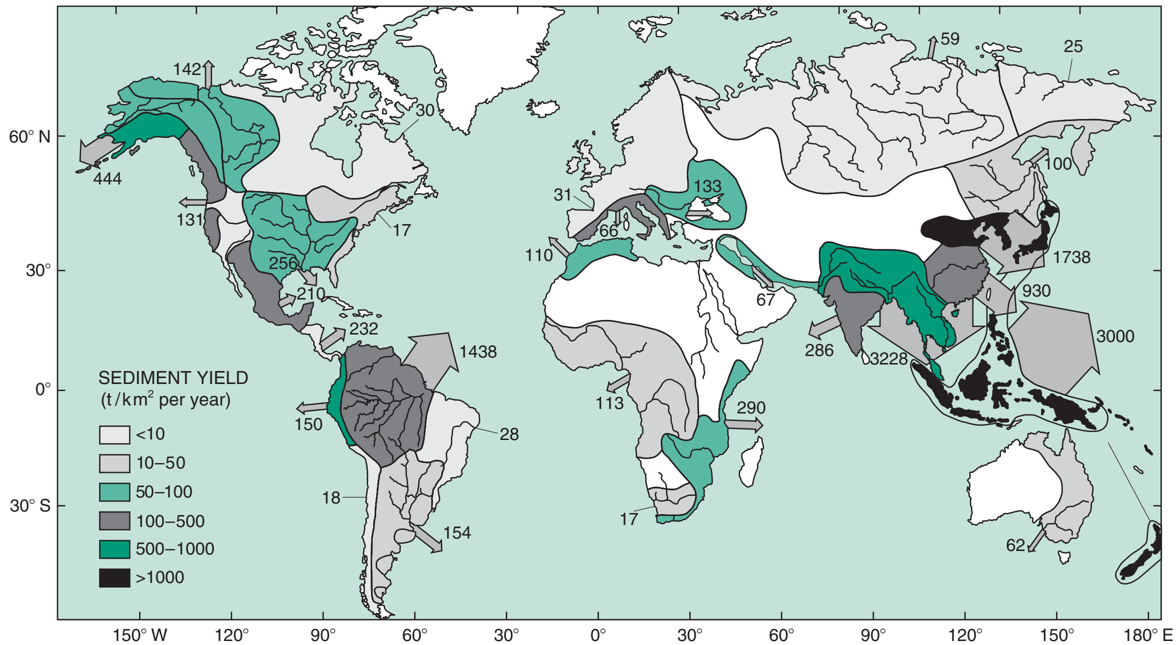

FIGURE 7.2 The annual suspended sediment load in major drainage basins; arrow width corresponds to relative discharge, numbers give average annual input in millions of tons. (From Milliman and Meade 1983.)

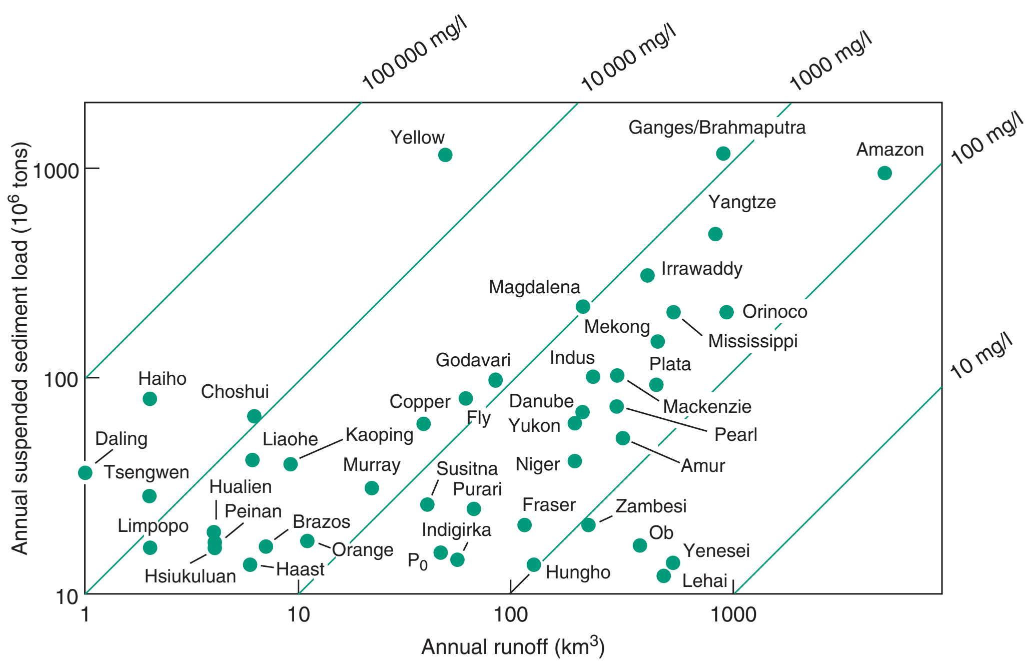

FIGURE 7.3 Annual discharge of suspended sediment from major rivers plotted against total runoff. Diagonal lines show equivalent sediment concentrations. (From Milliman and Meade 1983.)

they are carrying. The Ganges/Brahmaputra River apparently carries the largest load of river sediment in the world (Milliman and Meade 1983). It produces the delta that largely comprises the nation of Bangladesh, as well as the Sundarbans, one of the world's largest mangrove swamps (Section 8.5, Figure 8.18). Asian rivers, in general, are among the most prodigious producers of sediment. Taiwan, for example, an island of 36 000 km^2 (roughly half the size of Ireland or the same as Indiana), produces nearly as much sediment as the entire coterminous United States (Milliman and Meade 1983). The Yellow, Ganges/Brahmaputra, and Amazon have the highest annual suspended sediment loads in the world (Figure 7.3, top). In the Amazon River, the suspended particles include "fine-grained marine and volcanic rock fragments from the Andes, silt and clay from the intensely weathered lowlands and organic particles" (Richey *et al.* 1986). On the coast of China's Jiangsu province, sediment from the Yellow River has accretion rates exceeding 40 cm/yr (Lu 1995). These rivers are building coastal wetlands.

Of course, reading about the sediment moving down rivers is different from actually seeing it. Some sediment is transported as particles suspended in the water column. But larger particles bounce along the bed of the river, a process both witnessed and vividly described by a salvage operator named James Eads who, in the mid-1800s, lowered himself to the bottom of the Mississippi River in a self-made diving bell. Here is what he saw:

> The sand was drifting like a dense snowstorm at the bottom ... At sixty-five feet below the surface I found the bed of the river, for at least three feet in depth, a moving mass and so unstable that, in endeavoring to find a footing on it beneath my bell, my feet penetrated through it until I could feel, although standing erect, the sand rushing past my hands, driven by a current apparently as rapid as that on the surface. (Quoted in Barry 1997, p. 26)

Not all burial results from sediment carried into wetlands. Some burial is the result of organic matter produced within the wetland itself. It is therefore helpful to distinguish between **autogenic** burial (burial by locally produced organic matter such as occurs in peat bogs) and **allogenic** burial (burial by externally produced materials carried by water, as Eads saw for himself). Much of this chapter will focus on allogenic burial, if only because rates of burial are generally much higher in this category. Also, the process of autogenic burial has already been introduced earlier in this book (Section 1.5.1). Both can cause changes in plant and animal communities, but with autogenic burial, this may occur on timescales of 10^3 to 10^4 years, whereas allogenic burial typically requires 10^0 to 10^2 years. The terms autogenic and allogenic are easy to confuse in my experience; try to remember that auto (originally from the Greek *autos*) means self (as in *auto*graph or *auto*mobile). There are other names – Brinson (1993a, b) uses the terms "biogenic accumulation" and "fluvial deposition."

Let us continue this topic by looking more closely at rates of burial.

7.1 Exploring rates of burial

We have seen that there are two principal sources of material that bury wetlands: sediment carried in from other locations (allogenic), and organic matter produced locally (autogenic). Either can dominate, depending on location. Deltas, for example, are buried largely by sediment carried from upstream. Peat bogs are buried largely by organic matter produced by the plants. Generally speaking, burial in deltas is much faster.

7.1.1 A brief introduction: rates of burial are usually only millimeters per year

One way to measure rates of burial is to examine cores taken from wetlands. Here are some examples for you to consider, generally arranged from low to high. Deposition rates of 0.1 to 0.7 mm/yr have been found in interdunal ponds (Wilcox and Simonin 1987). In boreal and subarctic peatlands peat accumulates at rates from 0.2 to 0.8 mm/yr (Gorham 1991). Burial rates of wetlands in the English landscape are slightly higher, in the order of 0.2 to 2 mm/yr, with a majority in the lower range (e.g. Walker 1970). Higher rates of 3–6 mm/yr appear to be more typical of salt marshes (Niering and Warren 1980; Stevenson *et al.* 1986; Orson *et al.* 1990) and mangrove swamps (Ellison and Farnsworth 1996). Burial rates of 10 to 20 mm/yr occurred in the eutrophic Norfolk Broadlands (Moss 1984), while even higher rates occur in deltas. Cores record 20 mm/yr for the Atchafalaya River in Louisiana (Boesch *et al.* 1994), while other information sources document up to 51 mm/yr in the Yangtze delta (Yang *et al.* 2003) and the Ganges/Brahmaputra delta (Allison 1998).

Often, large amounts of sediment arrive in a single pulse. Floods and storms can deposit 10 or more cm of sediment in a single year (e.g. Robinson 1973; Zedler and Onuf 1984; Rybicki and Carter 1986; Lui and Fearn 2000; Turner 2006). Historical records show too that the arrival of humans in a landscape will often lead to a pulse of sedimentation. For example, annual rates of deposition in a floodplain in eastern North America were below 0.l mm prior to this century, but then accelerated by about a factor of ten to approximately 1 cm/yr with increasing human populations (Rozan *et al.* 1994). In rapidly eroding watersheds of Asia, deposition rates can exceed 40 cm/yr (Lu 1995). Sediment accumulation can be very rapid in deltaic areas. Continuing with east Asia, the Yellow River is second only to the Ganges/Brahmaputra in sediment load (Figure 7.3). More than 30% of its sediment discharge occurs during August floods. In contrast, January accounts for less than 1% of the total. With this volume of sediment arriving, the shoreline has been moving outward into the ocean at about 1.5 km/yr (Schubel *et al.* 1986).

Once the sediment is deposited it may not stay in one location. In deltas, rivers frequently change location and sediment is eroded and moved. Historical records emphasize the dynamic nature of these deposits. Conveniently, the historical duration of Chinese civilization gives us historical records that would be unavailable elsewhere. For example, in 1128 the Yellow River suddenly shifted its course southward, and from 1128 to 1855 the river mouth moved eastward by 90 km, adding an area of some 15 700 km^2. In 1855, the Yellow River again shifted northward. As river inputs decreased in southern areas, waves eroded these older deposits. About 1400 km^2 of land has now been reclaimed by the sea (Chung 1982). Now that dams are trapping sediment, the delta is shrinking. The edge of the Yellow River delta has been moving inland at 20 to 30 m annually and tidal land has sunk at rates of 5 to 10 cm/yr over the past 50 years (Chung 1982).

Although large floods are the major source of sediment, hurricanes can also deposit sediment in deltas. Sediment cores taken out of deltas record such events. At the mouth of the Pearl River on the Gulf of Mexico, cores reveal an accumulation of 8.5 m of material over a period of some 6000 years (Figure 7.4). Much of the material is organic, combining peat produced in the estuary with organic debris carried downstream. Layers of inorganic material show where hurricanes hit the marsh. In the Pearl River, Hurricane Camille (1969) left a layer of clay; in nearby Mississippi, closer to the eye of the hurricane, there is a layer of sand. At least nine distinct layers of clay or silt appear to mark the impacts of hurricanes within the last 4000 years – roughly a hurricane adding sediment to the marsh once every 400–500 years. The reworking of sediment by storms is an important process in producing typical coastal wetlands (Figure 7.5). For a longer-term view of sediment redistribution in deltas, revisit Figure 4.18.

7.1.2 Sediment loads increase with rainfall and deforestation

In general, the amount of sediment in rivers, and therefore the amount of burial downstream, is

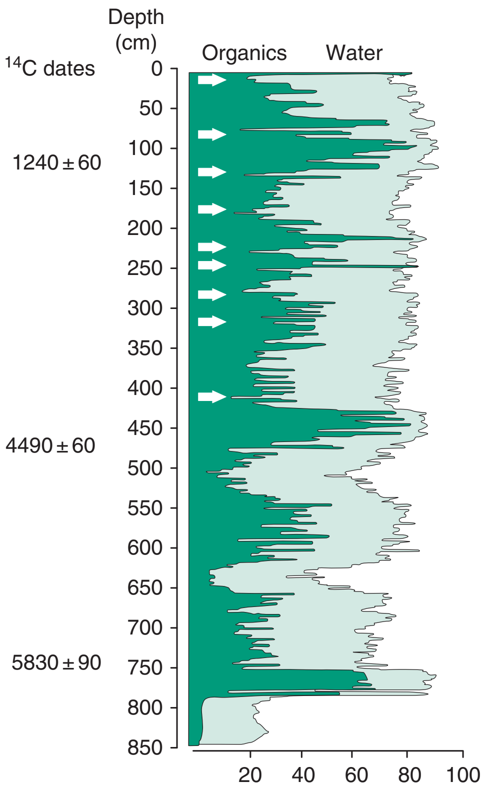

FIGURE 7.4 This sediment core from the mouth of the Pearl River on the Gulf of Mexico shows how more than 8 m of material accumulated over about 6000 years. Periods of organic accumulation from peat (organics) were interrupted by pulses of storm-deposited material (white arrows) attributable to hurricanes. (From Liu and Fearn 2000.)

determined by rainfall and vegetation cover. Cultivated watersheds have sediment loading rates orders of magnitude higher than forested watersheds (Figure 7.6). This is consistent with the results of studies on eutrophication (Section 3.5.2) where the clay content of the soil and amount of land in row crops are the best predictors of phosphorus loadings to watercourses. Although larger rivers can be expected to carry larger volumes of sediment, rainfall and human disturbance to vegetation can play equally important roles in determining sedimentation rates in watersheds.

Rainfall and vegetation cover can be broken down into a number of subcategories for making predictive models. In one such model (Howarth *et al.* 1991) soil erosion was predicted with an equation containing the following elements: area of the land type, a soil erodibility factor, a topographic factor, vegetation cover, agricultural practices, and rainfall erosivity. Each of these terms can then be estimated from technical manuals (Haith and Shoemaker 1987; Howarth *et al.* 1991). For example, rainfall erosivity (RE_t) includes assessments of storm energy and intensity, modified for dormant periods as opposed to the growing season. The specific parameters will, of course, vary with climate, soil type, and other features of the landscape. For those having limited patience with such models, the patterns are simple. In terms of time, most sediment is produced during short periods of intense rainfall. In terms of space, most sediment comes from areas of easily eroded soil on steep slopes where the natural vegetation is continually perturbed by humans.

7.1.3 Sediment produces a diverse array of wetland types

Let us move to a tropical example of burial by sediment. The entire Amazon basin is a vast display of kinds of wetlands produced by different amounts of sedimentation (Figure 7.7). Sedimentation in the west, the near-Andes area, is extremely high, reaching levels of almost 1000 tons/km^2 per year, leaving 100-m thick deposits downslope. Floodplains in the eastern Brazilian lowlands are greatly influenced by sea levels. The main valley of the Amazon River has seen both periods of erosion during low sea levels, and deposition during periods of higher water. These rising (and falling) sea levels appear to have substantially influenced the entire development of the Amazon basin.

Some 80 000 years BP, during the Glacial Maximum, sea levels may have fallen more than 100 m below recent levels (Irion *et al.* 1995), initiating a period of erosion that deepened the Amazon by some 20–25 m (Müller *et al.* 1995). After 15 000 BP, sea

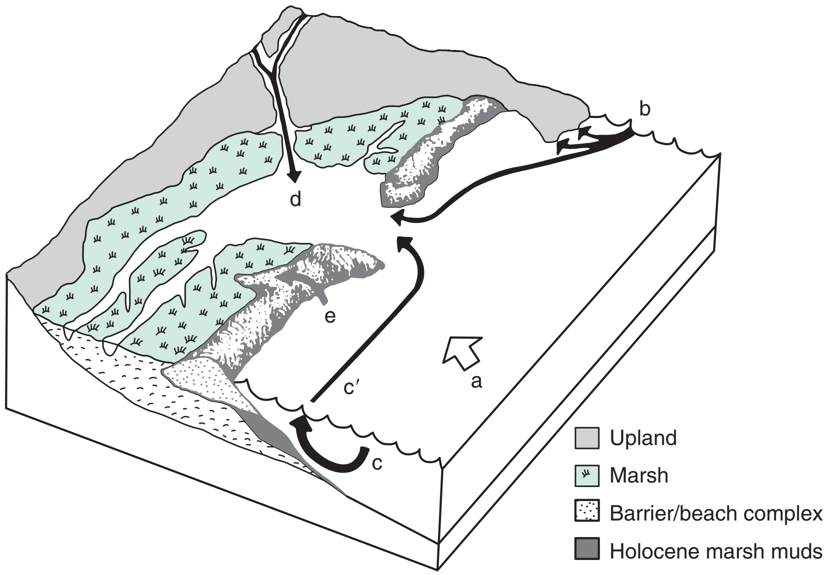

FIGURE 7.5 There are many sources of sediment in coastal marshes: (a) resuspension of offshore shelf or lagoonal muds with landward transport during storms; (b) erosion of headlands or abandoned deltas with transport to marsh via longshore currents; (c) wave cutting of marsh muds exposed in lower shore face with transport to the marsh via longshore currents (c′); (d) riverine input; and (e) overwash redistribution. (From Michener *et al.* 1997.)

levels rose about 2 cm per year and the Amazon valley was drowned because sedimentation rates were not high enough to balance rates of rising seas levels (Irion *et al.* 1995). During this period, a large freshwater lake about 1500 km long and up to 100 km wide may have extended from the mouth of the Amazon inland to about 65° W. The maximum size of this lake appears to have been reached around 6000 years BP. Sediment cores recovered from the deep-sea fan of the Amazon in the Atlantic Ocean suggest that, during this time, large quantities of continental detritus no longer reached the sea, being deposited instead in the sediment trap created by this lake. As sediments were deposited here, ridges, swales, and levees would have formed in the middle Amazon area. Superimposed upon these large-scale processes are the ongoing processes of erosion and deposition producing large meander complexes and the shallow lakes known as *várzeas* (Salo *et al.* 1986; Junk and Piedade 1997).

7.1.4 Sediment loads decrease when dams are constructed

The deposition of new sediments is an essential part of the formation of coastal wetlands and deltas. Large dams have another enormous effect on wetlands: they form huge settling basins which store the sediment that would otherwise have traveled downstream to build coastal wetlands. The suspended load in the Mississippi River decreased by about one half from 1963 to 1982 (Boesch *et al.* 1994). Over and over again, it appears that the results are clear and obvious: build large dams on a river, and watch the coastal wetlands disappear. It has happened over and over again in human history. Even so, it is remarkable how many people do not appreciate that land is being lost in Louisiana simply because large dams upstream are trapping sediment. And the Three Gorges Dam in China is now starting the same process, with wetlands being lost at the mouth of the river as the sediment inexorably fills the reservoir behind the dam. The southern Yellow River delta has already sunk at rates of 5–10 cm/yr over the past 50 years (Chung 1982). Of course, at large timescales, eventually the dams will fill with sediment and become wetlands; when, inevitably, the dam breaks, the wetland will erode, and the sediment will move downstream. The disappearance of coastal wetlands due to dams is therefore a temporary effect from the point of view of a geologist. However, humans who have built their homes in coastal wetlands, or who depend upon fish

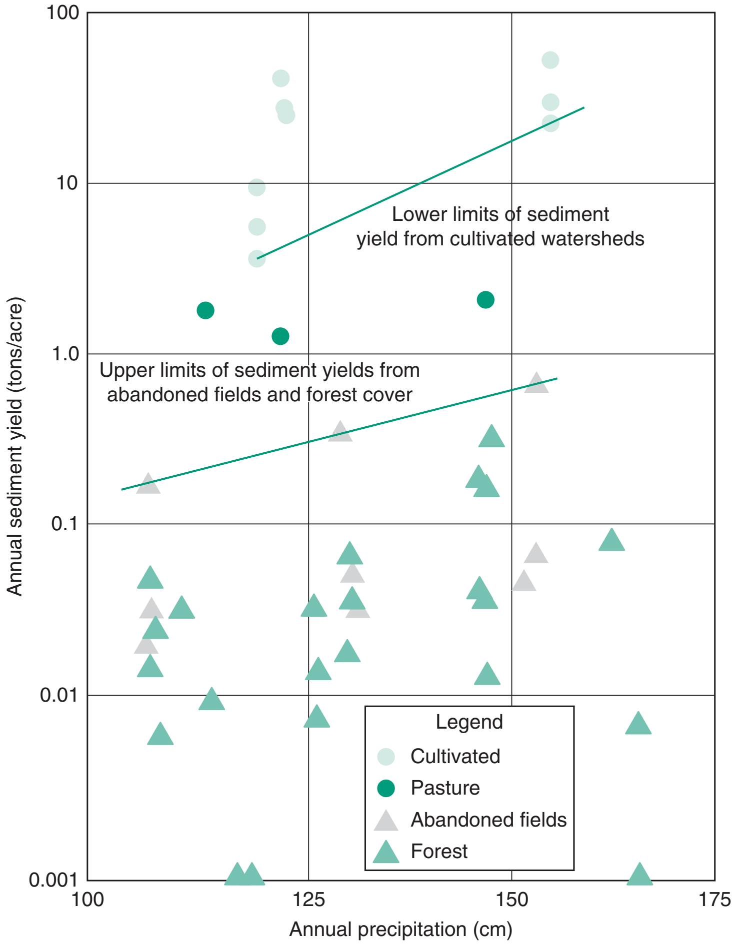

FIGURE 7.6 The annual sediment yield of a watershed is affected by annual precipitation and land use. (After Judson 1968.)

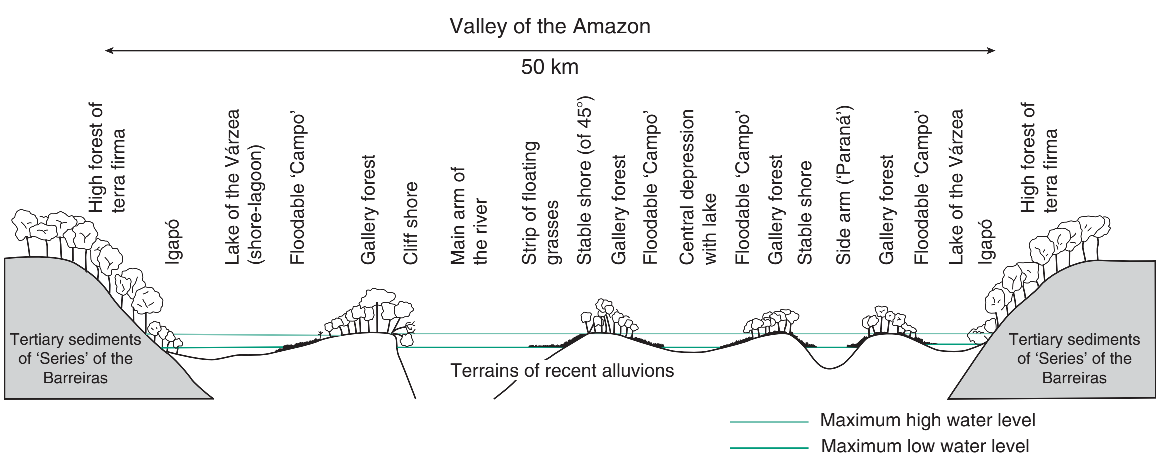

FIGURE 7.7 Much of the diversity of wetland types in the Amazon basin arises from different depths of sediment and from the erosion and redeposition of the sediment. (From Sioli 1964.)

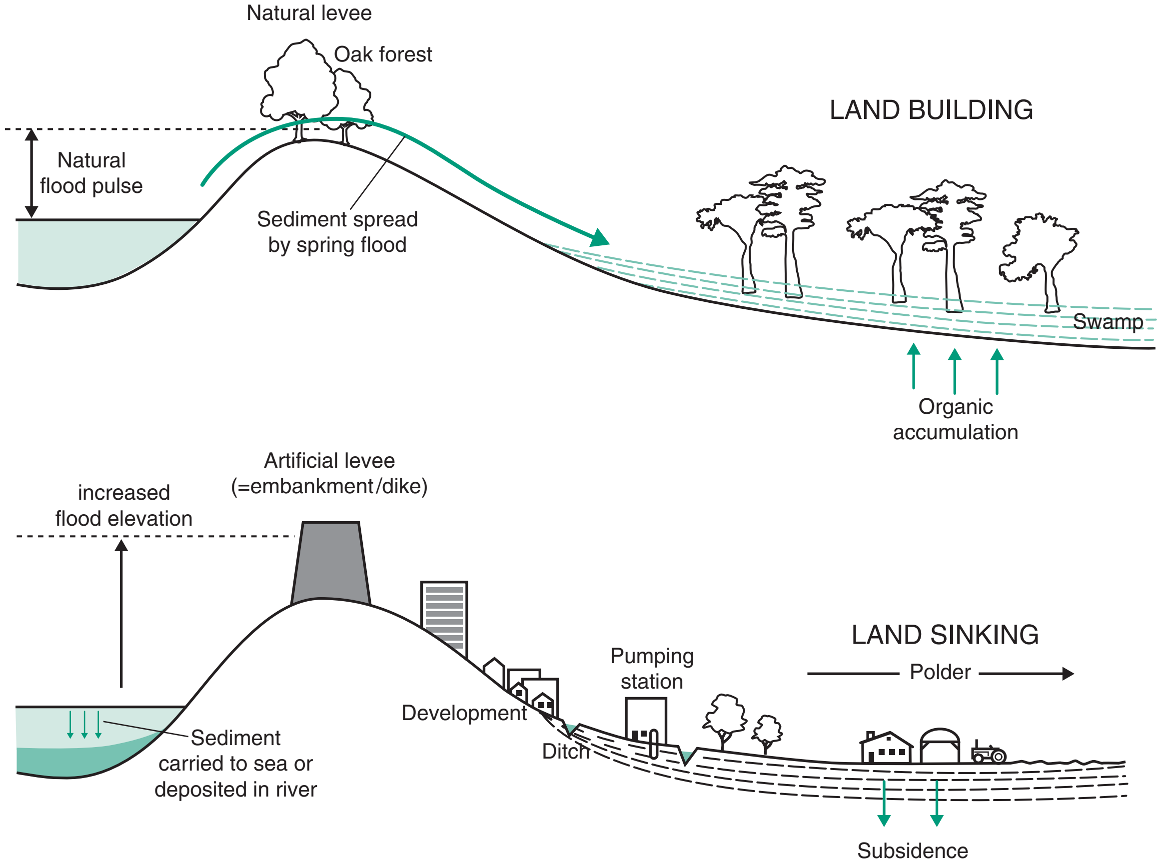

FIGURE 7.8 Recurring spring floods produce natural levees along many natural watercourses. The land is actually higher near the river, and vast wetlands occur at lower elevations, where they are sustained by annual flooding and sediment deposition (top). When humans build artificial levees, they shut off the process of annual flooding. Not only does the process of burial (deposition) stop, but decomposition often leads to further subsidence in the land surface (bottom). Hence, in the long run, artificial levees make flooding increasingly dangerous.

growing in coastal wetlands, cannot afford to take such a long-term view.

7.1.5 Sediment deposition is prevented by artificial levees

There are levees and then there are levees. The first, which we might call "natural levees," are built by the river itself. The second, which we might better call "dikes" or "embankments," are much taller and are built by humans to control flooding. For some reason, we continue to use one word to describe two very different features.

We need to understand the difference.

Natural levees are built by the river itself as it deposits new layers of sediment along its banks. It is these annual deposits of new soil, in part, that make floodplains ideal for plant growth. Since the sediments settle out of the water when the river begins to spill over its banks, the *deepest* layers of sediment are actually deposited *closest* to the river. In this peculiar way, the river builds a wall of sediment, known as a levee, along each side of the watercourse (Figure 7.8, top). Thus, when you want high land, you generally walk toward, not away from, the river. Since the levees are the highest and driest regions of the floodplain, the river often flows through the highest rather than the lowest land. Behind the natural levee walls, drainage into the river is impeded, and extensive swamps can form where water ponds. Streams may even develop on the floodplain parallel to the main river and flow for miles until they are able to traverse the natural levee and connect with the river. During floods the river will occasionally cut through the levee and deposit new layers of sediment in fan-shaped deposits of sediment known as crevasse splays (Saucier 1963; Davis 2000).

Humans who settle in such landscapes usually want to be able to prevent flooding in the spring. In the case of the Mississippi River, the story of human-built levees goes back to New Orleans (which was founded on a natural levee) which by 1726 had built artificial levees 1.2–1.8 meters (4–6 feet) in height to provided protection for the city. Levees were gradually extended upstream and downstream from New Orleans, and then to the opposite bank. As the levees grew in length and height, the water was confined to narrower areas, and so naturally, the water began to rise higher. Some engineers thought that the added rate of flow would scour the river deeper and thereby compensate for the narrowing of the floodplain. But there were unintended consequences – the desired scouring did not occur and building one set of levees merely forced the construction of longer and higher levees. Moreover, when the soil became drier, rates of decomposition increased, so the ground actually began to fall (Figure 7.8, bottom). In some areas of the world, drained land has subsided by many meters.

Returning to the Mississippi, by 1812 there were more than 250 km (150 miles) of levee on each side of the river. In 1858 the total of the two sides exceeded 1600 km (Barry 1997). In some cases these levees rose to a height of nearly 12 meters. Today 3635 km of levee have been built to corral the Mississippi waters – 2652 km along the Mississippi itself and 983 km along the banks of the Red and Arkansas Rivers and in the Atchafalaya basin (recall Figure 2.25). While the levees along the Mississippi are a well-known example, they are also rather new. The construction of levees for flood control and irrigation has been a prominent feature of human development in deltas around the world, particularly those of Asia, Mesopotamia, and Europe, where they may date back not just hundreds, but thousands of years.

7.1.6 Autogenic burial is usually rather slow

Autogenic burial means burial by locally produced organic matter. We have already seen (Chapter 1) how peat, composed largely of *Sphagnum*, may accumulate and in doing so cause changes in the water table. Further, as peat accumulates, plants become increasingly isolated from the mineral substrate, so that distributions are controlled both by water levels and nutrient gradients produced by the peat itself (Chapter 3). The general outline of how *Sphagnum* buries the underlying substrates has been understood for at least a century (Gorham 1953, 1957; Gore 1983; Zobel 1988), and Figure 7.9 shows how the underlying substrate becomes blanketed in peat, with small depressions becoming forested, and larger depressions going through a longer period ringed by floating bog vegetation. Eventually, the peat accumulates to such a depth that the vegetation is little affected by the underlying topography, and instead becomes largely controlled by climate (Foster and Glaser 1986; Zobel 1988). If, however, the topography has sufficient relief, runoff can then continue to control the peatland, with areas of comparatively rapid drainage remaining as fens, and those isolated from moving water developing into ombrotrophic raised bogs. Some idea of the time required for the transformations in Figure 7.9 is available, since many areas now dominated by peatlands were deglaciated less than 10 000 years ago.

Radiocarbon dating and intensive study of individual bogs give a deeper understanding of

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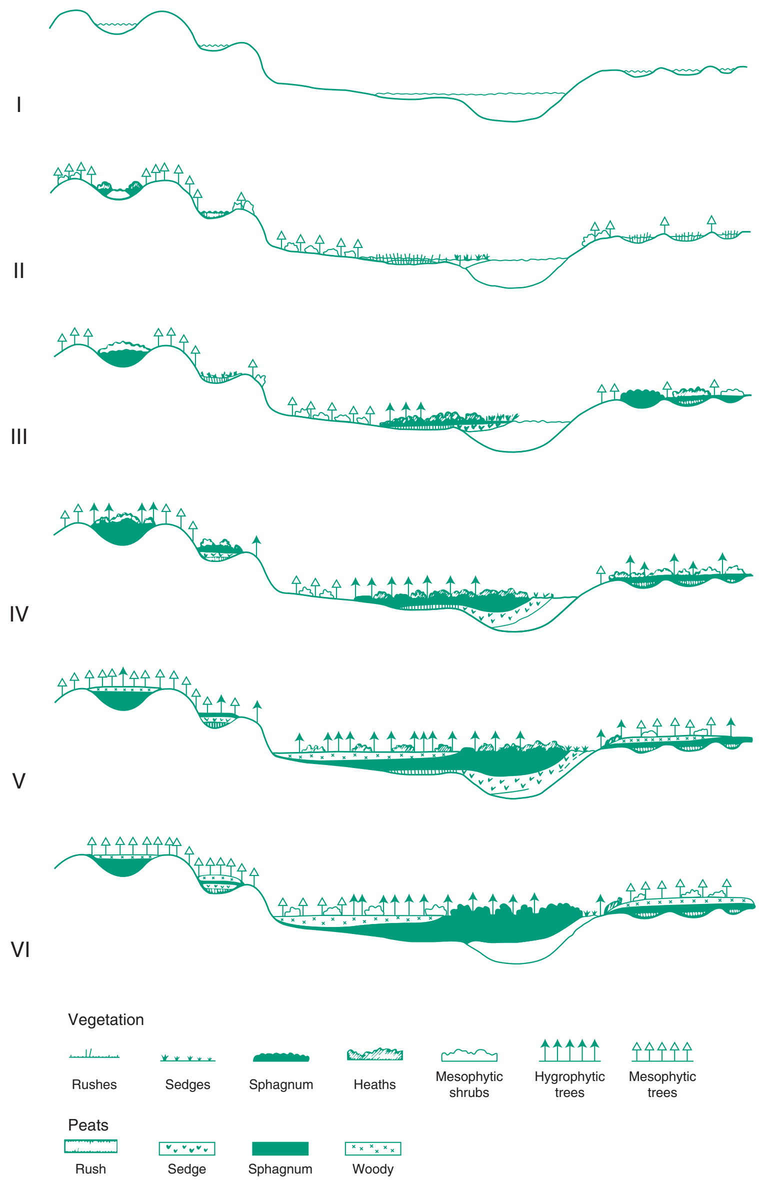

FIGURE 7.9 The development over time of peatlands on landscapes on the Precambrian shield. (From Dansereau and Segadas-Vianna 1952.)

how a landscape becomes buried in peat. One can recognize three hypotheses that might explain how large ombrotrophic bogs form. There could be initiation of peat accumulation across a broad area, with steady accumulation of peat but no lateral expansion, in which case the area of the bog would remain unchanged but the depth would increase steadily through time. Another possibility is that peat could begin to accumulate at a number of individual sites followed by expansion and fusion of the separate peat islands into one large bog. Peat might also begin to accumulate at one site and gradually increase both in depth and area. This process has been explored in the Hammarmossen bog in the Bergslagen region of central Sweden; this bog developed on a broad flat outwash plain and has been

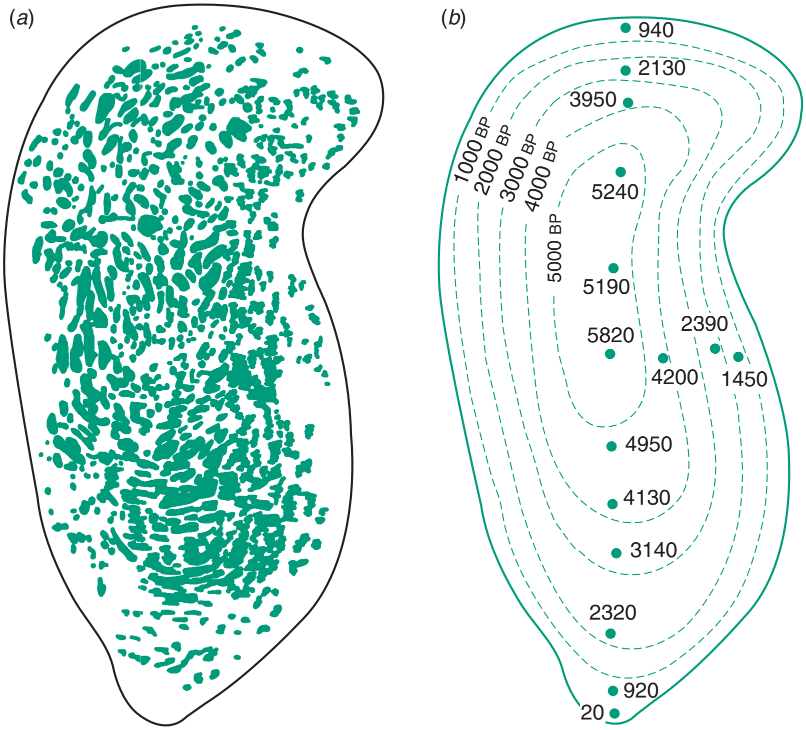

FIGURE 7.10 A top view of the Hammarmossen bog in central Sweden, showing (*a*) the distribution and size of open-water pools, and (*b*) basal radiocarbon dates with interpolated isochrones for bog expansion. The peat is 4 m thick at the center of the bog. (From Foster and Wright 1990.)

well studied by European scientists. To discriminate among the three models for bog formation, Foster and Wright (1990) took peat cores from a series of locations in this bog and obtained radiocarbon dates from the bottom of each core near the mineral soil. Figure 7.10 shows the general outline of this bog, with the open-water pools covering its surface; the adjoining sketch gives contours of bog age as determined by radiocarbon dating. The bog began forming some 6000 years BP, with growth initiated near the center under what is now the deepest peat. It seems clear that in this case, the bog has not only grown upward by peat accumulation (the peat depth near the middle is some 4 m, for a rate of accumulation of 0.67 mm per year), but it has also expanded laterally at a rate of some 200 m per 1000 years.

The careful dating of pools also allowed Foster and Wright to study the process by which pools form on the surface of raised bogs. They conclude that "pool development is the result of biological processes under hydrological control." Pools apparently begin as small hollows on the relatively steep slopes covered by shallow peat. As the peat accumulates, these turn into pools. Presumably the rate of peat accumulation in the hollows is less than that of the adjoining ridges, so that over time the peat rises around the depression. At the same time, the water table rises. The plants near the center of the depression are gradually killed and replaced by open water. Adjoining pools may coalesce to produce larger pools.

Peat cores taken from five peatlands in boreal Canada were also examined to study processes of peat formation (Kuhry *et al.* 1993). All five cores were initially dominated by wetland plants such as *Typha* and *Carex*. These were replaced by fen mosses, leading to inferred pH of about 6.0 and a water table at 5–15 cm below the vegetation surface. Subsequently, *Sphagnum*-dominated peatlands developed at each site, in which case pH levels apparently fell to 4.0–4.5. This transition from fen

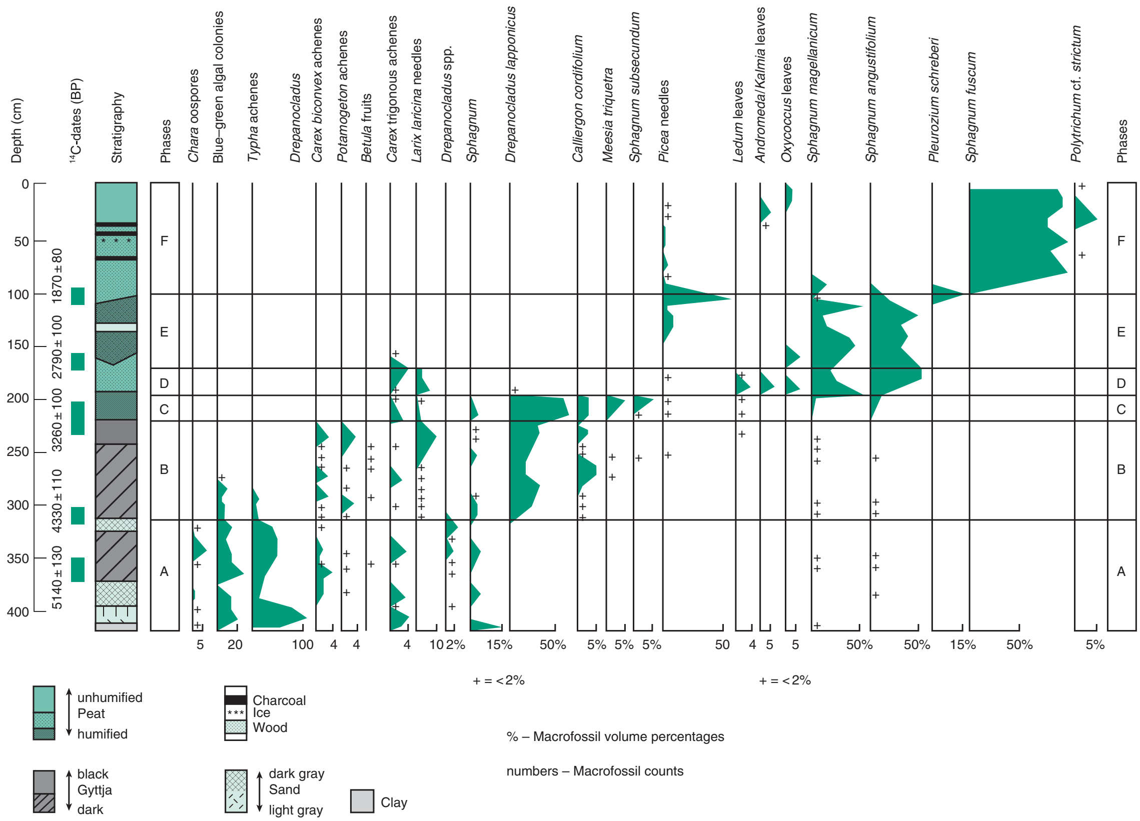

FIGURE 7.11 The vegetation history of a site in boreal Saskatchewan reconstructed from macrofossils. Note the vegetation zones A–F, beginning (A) with *Typha* and *Carex* and ending (F) with *Sphagnum fuscum*. Further, note the comparatively rapid transition from fen (*Drepanocladus*: B, C) to bog (*Sphagnum*: D, E, F). (From Kuhry *et al.* 1993.)

to bog was rapid (Figure 7.11). The overall sequence from marsh to fertile fen to infertile fen to *Sphagnum* bog took place over >2000 years in southern sites, but <1500 years in northern sites.

7.2 Burial changes the species composition of wetlands

We have learned how burial can occur in wetlands and how rates can differ, but what effects does it have on wetland ecosystems? Let's begin by considering how it changes the species found in wetlands.

7.2.1 Evidence from plant traits

We could start the biological consideration of burial by examining the morphology of wetland plants. Many wetland plants have well-developed rhizomes and pointed shoots (Figure 7.12). Examples include genera such as *Carex*, *Juncus*, *Phragmites*, *Scirpus*, and *Typha*. Pointed shoots and underground storage structures are considered to be adaptations for penetrating accumulations of leaf litter (Grime 1979), and it is likely that the same traits also are adaptations for penetrating accumulations of sediment. Sediment deposition will often be

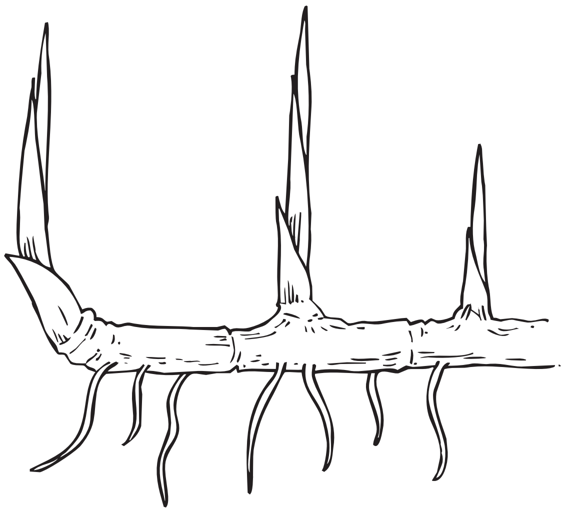

FIGURE 7.12 Rhizomes and pointed shoots allow buried plants to re-emerge.

correlated with litter deposition. Litter also influences the species composition of a wide array of plant communities (Sections 6.3.6, 9.4). Litter contributes, of course, to peat formation. If deep enough, it can kill patches of plants (Section 4.4.2). And large amounts of big litter or coarse woody debris also may be deposited (Section 8.3) in wetlands.

In contrast to plants with large shoots, small evergreen rosette plants are intolerant of burial, and this may in part be why they are largely restricted to eroding shorelines (Pearsall 1920) or to infertile conditions with low primary productivity. At a larger scale, this may also explain, in part, why such plants are often restricted to oligotrophic lakes. Eutrophic lakes and bays with high sedimentation rates are generally occupied by larger rhizomatous plants. So are many coastal wetlands. While we can explain such patterns in part by differences in relative competitive abilities (Chapter 5), differing tolerances to burial may also play a role.

7.2.2 Evidence from experimental studies

Experimental studies show that burial can change the composition of plant communities. Here are three examples; many more could be cited.

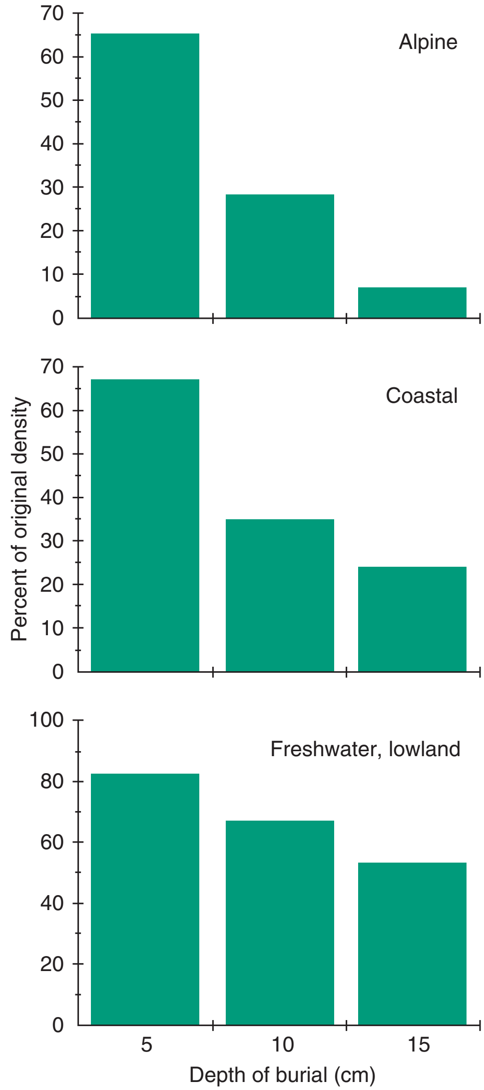

FIGURE 7.13 Effects of burial (measured as percent of original shoot density) plotted against depth of burial in three wetland vegetation types. (From data in van der Valk *et al.* 1983.)

In one study, three wetland types were experimentally buried: alpine, freshwater lowland, and coastal (van der Valk *et al.* 1983). In general, the alpine wetlands were most sensitive to burial (Figure 7.13). This was likely because many of plants were short species with slow growth rates (e.g. *Oxycoccus microcarpus*, *Parnassia palustris*). The freshwater lowland wetlands, in contrast, had taller species (e.g. *Eleocharis palustris*, *Equisetum fluviatile*). After a further year of growth, the coastal wetlands showed most recovery and the alpine wetlands the least. In general, regeneration from buried seeds was marginal; most recovery was from buried rhizomes.

In a second study, salt marsh vegetation near San Francisco was covered with 10 cm of sediment dug out of nearby tidal channels (Allison 1995). Overall, vegetation cover returned to control values after only 2 years. Species such as *Salicornia virginica* and *Distichlis spicata* recovered quickly. Other species such as *Frankenia grandifolia* and *Jaumea carnosa* recovered only when the burial occurred early in the growing season. In general, plots were revegetated by ingrowth from adjoining plants, or else from buried rhizomes. There was very little seedling establishment. Recovery was relatively rapid because the buried areas were only 1-m^2 circular plots; since most recovery was from adjoining areas, larger areas of spoil or sediment would presumably take much longer to recover.

Individual species have also been studied. *Valisneria* is a widespread aquatic plant. The tubers and rhizomes provide reserves for shoots to re-emerge after burial, and also provide food for waterbirds. Yet as little as 20 cm of sediment killed more than half the tubers (Figure 7.14). Burial by sand was more damaging than burial by silty clay; only 15 cm of sand caused as much mortality as 20 cm of silty clay. Rybicki and Carter (1986) conclude that, since *Valisneria* tubers normally grow under 10 cm of sediment, storms carrying as little as 10 cm more can damage stands of aquatic plants.

These selected studies emphasize an important point in the ecology of burial. The effects of burial on a particular wetland or species are likely to depend upon the depth of burial and the degree to which burial is a common feature of the habitat. Deltaic wetlands are regularly buried by allogenic sediment, so it would not be surprising if they were relatively resilient to small annual accretions of

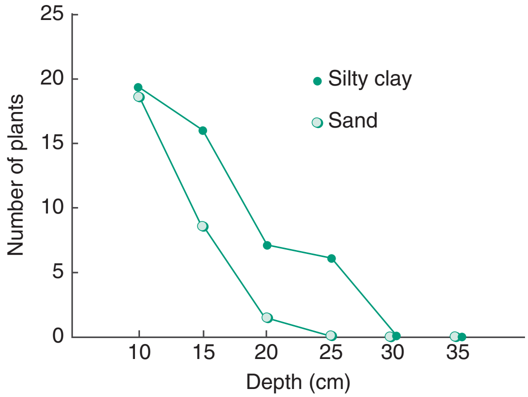

FIGURE 7.14 The number of viable *Valisneria* plants decreases with depth of burial. (From data in Rybicki and Carter 1986.)

sediment. The effects would obviously be different if the plants were buried more deeply. The deeper the burial, the more likely that the plant composition will change, since deeper burial will increase mortality, will change elevation, and will require re-establishment from seeds dispersed with the sediment.

To put such studies in context, let us look at one extreme case of burial from the Mississippi River delta. In 1849, levees near Bonnet Carré were broken by a breach nearly a full mile wide. The river poured into the landscape and laid down a deposit of sediment that covered 91 km^2 (35 square miles) (Saucier 1963). The total volume was calculated at 142 million m^3 (5 billion cubic feet). We can put this into more familiar terms. If we assume generously that one large truck load of sediment is 7.6 m^3, and if we hired full trucks to arrive at the rate of one per minute, dumping 24 hours per day and 7 days per week (some half a million trips per year), it would still take more than 35 years to spread this much sediment. Note that an event like this is not necessarily uncommon in coastal wetlands, and that it would include the full range of burial effects. Near the breach, the 2 m of sediment would have likely killed all the herbaceous plants. Further away from the breach, the burial would decline, until at the fringes of the deposit, less than 1 cm would have been typical, and the primary effect may have been the augmented

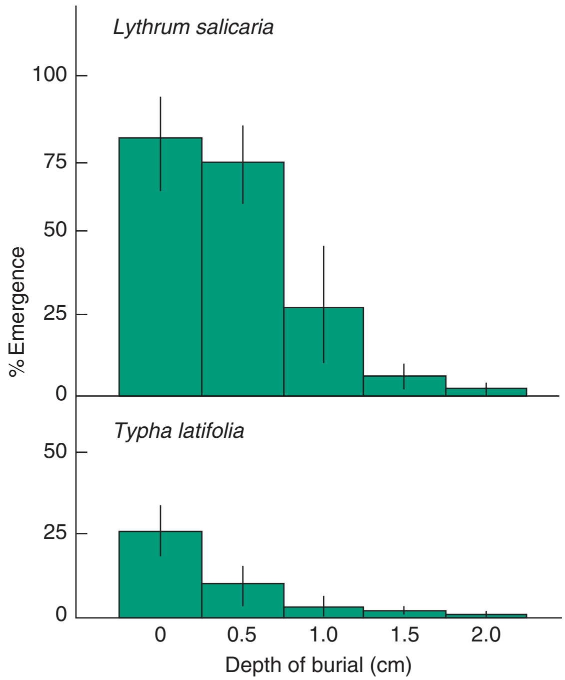

FIGURE 7.15 Burial decreases emergence of *Lythrum salicaria* and *Typha latifolia*. (F. Terillon and P. A. Keddy unpublished data.)

Table 7.1 **Effects of contaminated meltwater upon percent germination of five wetland plant species ($n = 5$ replicates of 36 seeds each)**

	Snowmelt concentration (%)		
Species	0	20	100
Aster umbellatus	5.8	2.0	0
Dulichium arundinaceum	11.6	3.4	0
Scirpus cyperinus	14.2	10.2	0
Typha latifolia	13.2	7.2	1.0
Lythrum salicaria	30.0	19.2	9.0

Source: From Isabelle *et al.* (1987).

fertility. Each flood and the sediment, then, can create a wide array of effects from outright death to just increased fertility. The details depend upon the type of plants present at the start, the depth of burial, and the type of seeds present in the sediment.

7.2.3 Seedlings are particularly sensitive to burial

Seedlings are likely to be much more sensitive to burial. A survey of 25 wetland plant species revealed germination was frequently above 80% in the light but many of the same species had 0% germination in darkness (Shipley *et al.* 1989). One could therefore assume that relatively small amounts of sediment would therefore prevent many species from even germinating. Even 1 cm of sediment is sufficient to reduce emergence by more that 50%; 2 cm of burial reduces emergence to negligible levels (Figure 7.15).

Similar results are reported by Galinato and van der Valk (1986) and Dittmar and Neely (1999). Therefore, even small amounts of sediment can change the species composition of wetlands. Not only does germination of individual species decline, but diversity as a whole decreases significantly with depth (Jurik *et al.* 1994). Species with larger seeds are less sensitive to burial (Jurik *et al.* 1994).

There is a confounding factor in such work. Sediment may also contain a variety of toxic substances, particularly if the sediments originate in agricultural fields or urban areas (e.g. Reynoldson and Zarull 1993). The foregoing studies by Jurik *et al.* (1994) used sediment collected from a sediment trap in a ditch draining several soy bean and corn fields. This has the advantage of being a relatively natural treatment, since these sorts of habitats are a major source of sediment for wetland ecosystems. However, these sediments may also have contained herbicides or fungicides which could affect germination quite independently of burial. Sediments washed from urban areas are likely to contain contaminants, particularly salts from road de-icing (Field *et al.* 1974; Scott and Wylie 1980). In cold climates, contaminated snow is routinely dumped directly into rivers, or else allowed to melt in vacant lots which drain directly into storm sewers. To test for effects of such contaminants upon the establishment of wetland plants, Isabelle *et al.* (1987) watered pots containing standard seed mixtures of five wetland plant species with meltwater from snow removed from urban streets. Both the biomass and richness of the experimental plant communities were reduced by increasing concentrations of snowmelt (Table 7.1). Meltwater alone significantly reduced germination. The only two species growing at high concentrations were *Typha latifolia* and *Lythrum salicaria*, two widespread plant species that are common in ditches and roadside wetlands.

7.3 Burial has impacts on many animal species

Sedimentation is regarded as one of the three leading threats to freshwater aquatic ecosystems, the other two threats being exotic species and impoundments (Richter *et al.* 1997). As a consequence of these threats, Richter *et al.* observe that there is “a quiet crisis taking place beneath the surface of the world’s rivers and lakes,” conservative estimates suggesting, for example, 20% of the world’s freshwater fishes are extinct or in serious decline. Aquatic organisms seem to be disproportionately at risk of extinction; in the United States of America, for example, between 14% and 18% of terrestrial vertebrates are considered to be at risk, whereas the figures for aquatic life are two to four times higher (some 35% for amphibians and fishes, 65% for crayfish, and 67% for unionid mussels). The primary cause of the altered sediment loads is agricultural non-point pollution, a factor already seen to be a major cause of increases in nutrient levels in wetlands (Section 3.5.2). Road construction is another major source of sediment in watersheds (Section 8.2).

Burial by sediment has two main consequences for wetland animals. First, aquatic invertebrates and fish eggs are smothered by fine layers of silt and clay (e.g. Cordone and Kelley 1961; Ryan 1991; Waters 1995). Second, aquatic plants can be stimulated by the nutrients in the sediment, and when these plants decompose under the ice during the winter, they can reduce oxygen to levels where aquatic life is killed (e.g. Vallentyne 1974; Wetzel 1975). Lemly (1982) studied the effects of both nutrient loading and sedimentation upon aquatic insects in an Appalachian mountain stream (Figure 7.16). The Plecoptera, Trichoptera, and Ephemeroptera

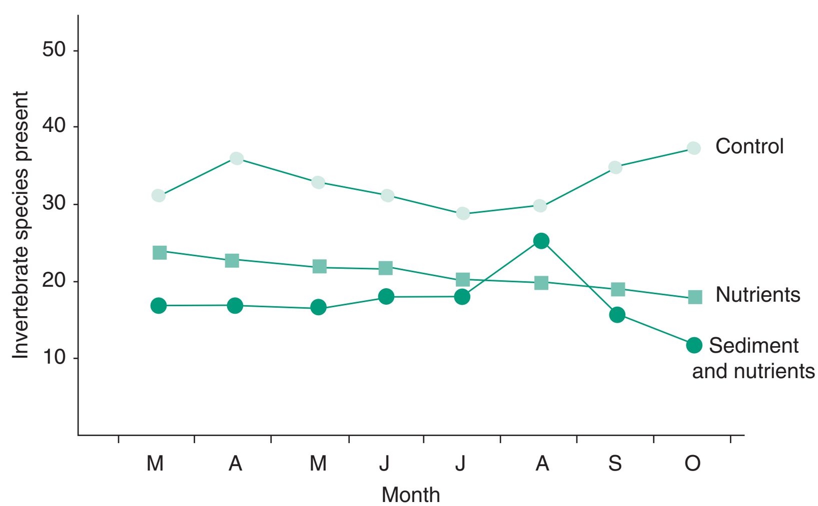

FIGURE 7.16 Changes in the number of invertebrate species with nutrient and sediment loading to a stream. (After Lemly 1982.)

all declined in richness, density, and biomass with increased sedimentation. Many of the insects collected had their respiratory structures clogged with soil particles. Moreover, fine sand and organic silt adhered to their body surfaces. The groups most sensitive to sedimentation were the filter feeding Trichoptera and Diptera. Sediment loading appeared to be more detrimental than simple eutrophication. Other effects of sediment may be more indirect; in aquatic communities, suspended clay may shift competitive dominance from cladocerans to rotifers by interfering with feeding by the cladocerans (Kirk and Gilbert 1990).

Sediment yields for forested watersheds typically are 3–12 tons/km^2 per year. This leaps to ca. 300 for a clearcut watershed and to ca. 3600 for clearcutting followed by farming and pastures; a construction site yielded ca. 49 000 tons/km^2 per year (Bormann and Likens 1981, Table 2–4). These changes are also evident in Figure 7.6, and appear to have been a consequence of human activity for millennia (e.g. Hughes and Thirgood 1982; Binford *et al.* 1987); even Plato complains, in his *Dialogues*, that humans have caused extensive soil erosion in Attica.

In the study above by Lemly (1982), logging, residential construction, and grazing were the sources of inorganic silt, and cattle were the source of nutrients. In the case of streams, the effects of deforestation are even more serious because there are two further consequences. First, the water becomes warmer, thereby reducing concentrations of dissolved oxygen for fish and invertebrates. Second, tree leaves are the base for stream food webs. For all these reasons, the amount of riparian forest is considered to be an important predictor of the biotic integrity of streams (Figure 7.17). As the amount of urban land use in a watershed increases, increased amounts of riparian forest are needed to compensate. As Figure 7.17 shows, excellent biotic integrity values are only possible if riparian forest exceeds 75% and urban land use is less than 20%. We will return to this topic in the next chapter, when we address the impacts upon wetlands of roads in particular, and adjacent land use in general.

FIGURE 7.17 Biotic integrity of streams can be predicted from two watershed properties: percentage of land that is urban and percentage of riparian forest remaining. (After Steedman 1988.)

7.4 Sedimentation, sediment cores, and plant succession

Nearly every introductory textbook in ecology uses the example of hydrosere succession, or pond succession, to illustrate how ecological systems change progressively through time. We will set aside this topic, and the possible connections between wetland zonation and ecological succession, for Chapter 10. But since we are exploring burial, we should emphasize the importance of sediment cores taken from wetlands (e.g. Figure 7.4), and the information that can be gained through the examination of pollen and macrofossils in sediment cores (e.g. Figure 7.11). These cores document long-term changes in vegetation that can counter too much short-term thinking. Once one has a set of such cores, one can try to put together a larger narrative about how landscapes have changed through time. Here is one example. Walker (1970) studied sedimentation rates in a set of 20 sediment cores from across England, trying to reconstruct changes in wetland vegetation type through time. Although the accumulation of sediment was associated with a gradual change from open water to floating-leaved plants to reeds to bog, the sequence of changes in vegetation was not so constrained as one might expect. In all, he recorded 71 vegetation transitions. Of these, 17% showed reversal of this sequence, most short-lived, which he attributes to local changes in lake level, temperature, or trophic status of the lake water. In a second stage he extracted 159 transitions and concluded: "The most impressive feature of these data is the variety of transitions which have been recorded and which must reflect the flexibility of the succession." For example, "significant numbers of transitions to bog take place directly from reed swamp, fen and swamp carr." Many of these vegetation types or seral stages last 1000 years or longer.

Such data do suggest we should be cautious in drawing too many conclusions about plant succession and sediment accumulation, unless we simultaneously consider factors that can counter succession, including fire, flooding, erosion, burial, or changing climate (Walker 1970; Yu *et al.* 1996). The persistence of individual vegetation types for 1000 years or longer emphasizes that ecological communities may possess some resilience when faced with either allogenic or autogenic forces of change.

7.5 Ecological thresholds: burial, coastlines, and sea level

Burial, like fire, has two apparently contradictory effects. In the short term, it may cause immediate death. It damages many plant and animal individuals and species. And it may extinguish wetlands by filling them with sediment. In the long term, however, sedimentation may create new habitat for the same organisms that were killed. This is particularly important in coastal areas, where newly deposited sediment builds enormous deltas (Figure 7.18). So rather than one general rule about burial in wetlands, the impacts of burial depend upon the species, the location, and the timescale. Let us look at the longer timescale issues here.

Sedimentation becomes vital to wetlands when sea levels are rising, since if the total of allogenic and autogenic burial does not keep up with sea level, the land will disappear. Global sea levels have risen at 1.8 mm/yr for the past century (Figure 7.19). Thus, any wetland in which accretion is less than this rate will disappear under water (Nuttle *et al.* 1997). This is already happening along the Louisiana coast, where rates of loss are given at something like 65 km^2 of wetlands per year (Boesch *et al.* 1994). A simple explanation for the situation in Louisiana, the many hectares of vanishing wetlands, is that the sum of allogenic and autogenic burial is less than the rate of sea level rise. Hence, factors that increased burial would seem to be beneficial. There would not, you think, be much room for debate about the future of coastal ecosystems. The objectives should be clear: increase rates of burial.

In practice there are problems. There are other factors that also must be considered. An important one is the subsidence of sediments deposited in previous years. Humans perturb the process of sedimentation in multiple ways, from logging cypress swamps to building levees to digging coastal navigation canals to using boats that generate shoreline-eroding wakes. All of these factors, and more, have to be put together to decide whether a wetland is rising fast enough to keep up with sea level. Overall, the principal factor seems to be reduced sediment input, largely as a result of artificial levees (Boesch *et al.* 1994), but there

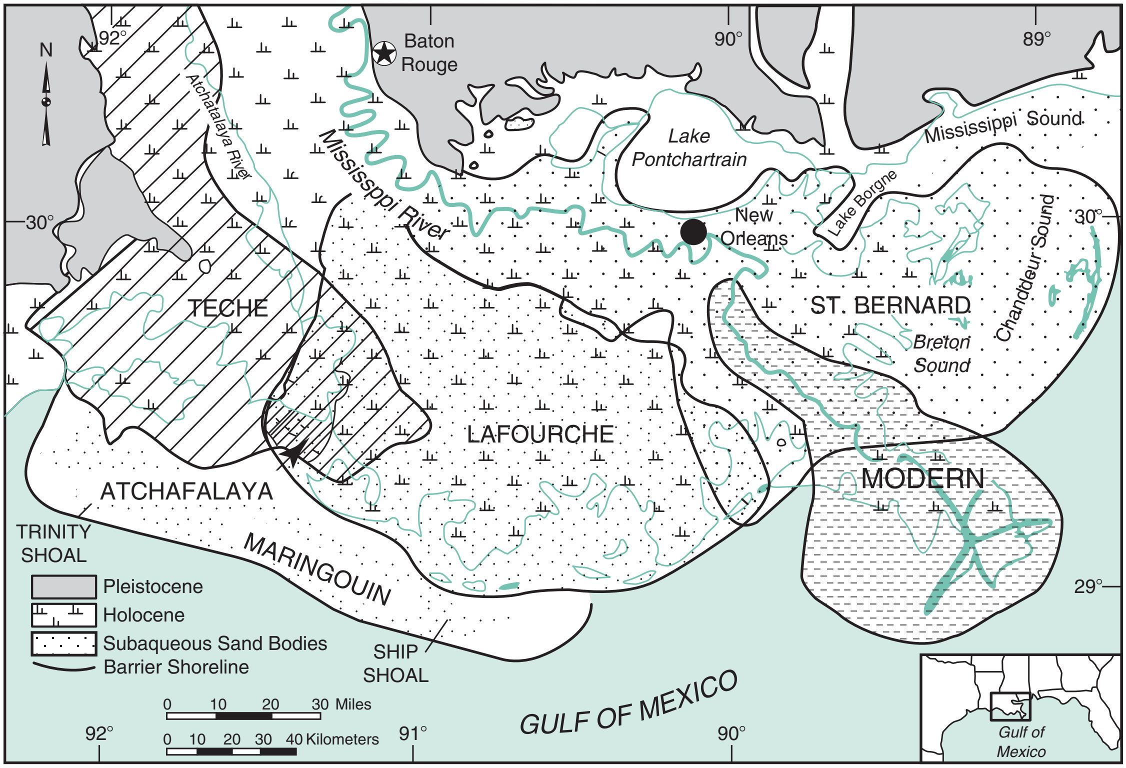

FIGURE 7.18 The Mississippi River delta is a composite of six distinct delta lobes produced by different courses of the Mississippi River over the past 7000 years. If the delta is to grow, rates of sedimentation must exceed the combined effects of subsidence and sea level rise. (From Boesch *et al.* 1994.)

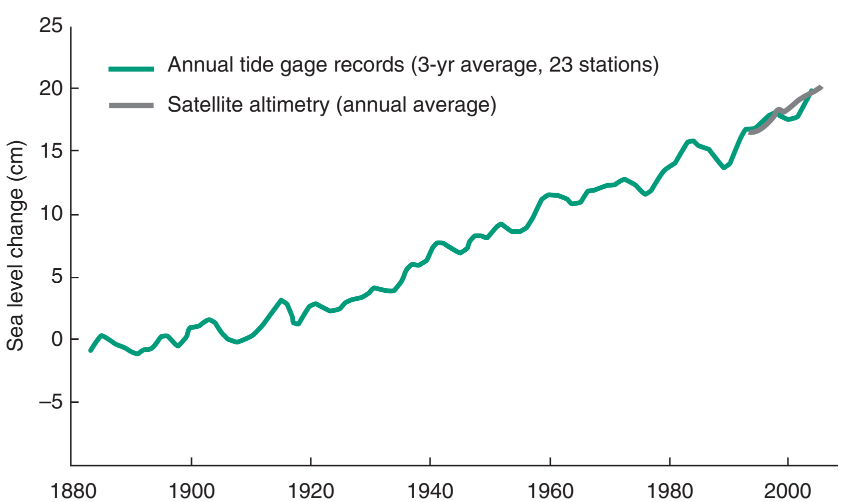

FIGURE 7.19 Global sea levels, averaged over many locations, have risen at 1.8 mm/yr for the past century. (Douglas 1997; adapted from R.A. Rohde at www.globalwarmingart.com.)

are also other important factors including construction of canals (Turner 1997) and grazing by nutria (Wilsey *et al.* 1991; Grace and Ford 1996; Keddy *et al.* 2009a). And then, of course, there is the difficulty of measuring the rates at which sea levels rise and fall, particularly when glaciers far away can produce enormous volumes of water over short periods. The most difficult issue is that the rate of burial may just about balance the rate at which sea level is rising. If the forces are almost equally balanced, then rather minor factors or rather small differences in process rates might decide whether land is lost or gained. That is what makes work with thresholds (popularly termed "tipping points") (Gladwell 2002) so tricky: the consequences may be enormous (for example, the loss of millions of hectares of coastal wetlands), but the threshold (or tipping point) may result from what appear to be minor issues.

More generally a **threshold** arises when a small change in a causal factor produces an unexpectedly large change in the response factor. A familiar example (and one that greatly affects wetlands) is temperature: at just above 4 °C, there is fluid water; at just below 4 °C, there is ice. Beyond the region of the threshold, significant changes in temperature have much less impact. Another familiar example is flooding – when there is just enough water to fill soil pores, the soils shifts from oxidized to reducing, two very different ecological states. Another example comes from peatlands. When just enough peat accumulates that plant roots cannot reach mineral soil beneath the peat, the wetland changes rapidly from a fen to a bog.

Now let us consider examples that are important for coastal management. First, if global carbon dioxide levels increase, it is likely that rates of photosynthesis will also increase. At the same time, rising temperatures will cause glaciers to melt and sea levels to rise. You can read opinions that since coastal plants will grow faster, coastal marshes will keep up with rising sea levels. The problem is that such simplistic opinions ignore rates of decomposition. Rising temperatures will also likely increase rates of decomposition. As you saw in Chapter 1, the world's largest peatlands occur not in areas where production is high, but in colder areas where decomposition is slow. There is a threshold where rates of accumulation just balance rates of rising sea level – pass this point, and the coastal wetland disappears. To continue with this example, if there is added production from higher photosynthesis, the added production may simply be consumed by herbivores. Higher plant growth rates might simply make more nutria. And, if the coastal wetlands have top–down control, alligators, by feeding on nutria, might reduce nutria populations just enough to tip the balance toward accretion of new land from autogenic accumulation. Or not. In a finely balanced system, such effects are not improbable, but they are difficult to measure. Enormous populations of microorganisms and invertebrates consume a lot of litter that could become peat. Millions of nutria can eat a lot of organic matter too. The resulting balance is critical, and it would be easy for coastal wetland to slip over the threshold.

Now an exception. Lest you assume that you can assume this of all coastal wetlands, you should be aware of exceptions. Along the Hudson Bay lowlands of Canada, extensive areas of salt marsh occur on a shoreline that is rising some 1.5 cm/yr (Glooschenko 1980) due to post-glacial rebound (also termed isostatic rebound). The marshes here are similar in composition to those of Alaska and northern Europe (e.g. *Puccinellia phryganodes*, *Triglochin maritimum*) but as the land rises, salinity falls, and freshwater marsh species (e.g. *Carex palacea*, *Typha latifolia*) invade. Further inland are extensive bogs and fens interspersed with raised beach ridges. These wetlands are all very young, not because of newly deposited sediment, but because deglaciation occurred only some 8000 years ago, and new marshes continually form as land rises from beneath the sea. Emerging coastlines with salt marsh vegetation are also found in other areas including Alaska, Scandinavia, Australia, and South Africa (Stevenson *et al.* 1986) as well as around the Great Lakes (Baedke and Thompson 2000; Johnston *et al.* 2007).

In summary, over larger timescales of centuries and millennia, then, the balance among erosion, sedimentation, subsidence, and emergence produces much of the physiographic diversity of coastal wetlands (Figure 7.5). These changes can be slow and gradual, or, if a threshold is involved, rapid. Beware of simplistic generalizations about cause and effect. And plan for the worst.

7.6 So is sediment bad or good?

Sometimes the books about wetlands appear to contradict themselves. In some books you can read that wetlands are important for their role as filters that prevent suspended solids from entering watercourses. One assumes, therefore, that these solids must be accumulating in the wetlands. Indeed, if sediment is accumulating, then it is only a matter of time until that wetland disappears – coastal wetlands being an exception of sorts. Too often this simple issue of logic is ignored. For example, Hutchinson's (1975) treatise on limnological botany has only one relevant index reference "rate of accumulation, supposed effect" which refers to Pearsall's views in the 1920s. Another even longer compendium (Sharitz and Gibbons 1989), 1265 pages dealing with wetlands and wildlife (roughly twice the length of Hutchinson), has not a single main reference to sedimentation effects. The single subreference (Richardson 1989) occurs in a section titled "wetlands as filters" and refers to a series of studies that document the effects of wetlands as filters of suspended solids. One can only look at images like Figure 7.1 and wonder.

Much of the literature on sediment, and most if not all of the models, implicitly assume that sediment is undesirable. This is reasonable for heavily populated watersheds where humans have greatly increased rates of erosion by stripping forests and ploughing fields (e.g. Figure 7.6). This assumption, however, still has to be put into perspective. Certainly, abnormally high levels of sediment are undesirable for vegetation types such as fens, or fish species such as salmon and trout. At the same time, fresh alluvial sediments are necessary for building deltas, the establishment of tree species on floodplains, and therefore for all the plant and animal species that require alluvial forests. It is therefore necessary to think carefully about the timescales and the location. The rates of sediment deposition that would destroy small fens and wet prairies in the upper watersheds of rivers could be necessary for the deltaic wetlands farther downstream.

CONCLUSION

Sediment carried by rivers is deposited in wetlands as water movement slows and thus burial is a common event in riparian wetlands. Rates of allogenic burial (by material carried into wetlands) are generally more rapid than rates of autogenic burial (resulting from organic material produced in wetlands). Both the amount of rainfall and the degree of vegetation cover that occur in a watershed affect the amount of burial that occurs in wetlands. Many wetland plants are adapted to burial, having pointed shoots and spreading by rhizomes. Experimental studies of burial have shown that the amount and type of sediment affects both plants and community composition and that seedlings and filter-feeding animals are particularly sensitive. While burial may cause the immediate death of wetland organisms, it also can create new habitat for them. In assessing the costs and benefits of burial, species, location, and timescale must be taken into account. The role of sediment in wetlands, and its management, is likely to grow with importance in the coming years, as dams continue to alter sediment supply rates, and changing climate causes sea level to rise.