Chapter contents

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8 Other factors

We have so far explored the six most important factors that control wetlands. If you understand these six factors, and how they affect wetland composition and functions, you have done well. Hydrology is certainly the most important, with fertility next. In spite of this you would be surprised at the number of books published on wetlands that do not even have entries for words like "nutrients" or "fertility" in the index! It is important that we put our knowledge of wetlands into the big picture – first things first.

At the same time, there are other factors that do not fit neatly into any of these six categories. As with a statistical analysis, we have extracted six main effects, but sources of variance remain. We can either ignore the rest of the variation, or consider some of the sources. The goal of this chapter is to examine a few "other factors." Although their occurrence in this chapter means that they are regarded as being generally less important than the preceding six factors, there are local conditions where these "other factors" may become very important indeed.

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8.1 Salinity

The ocean is a vast pool of saline water which has enormous effects on coastal wetlands, and produces distinctive types of wetlands (Figure 8.1). Salinity is normally measured as the conductance of water, and expressed in parts per thousand, with normal oceans having ca. 35 ppt. The major dissolved elements are sodium, chloride, sulfur, and magnesium. Higher salinity areas occur where freshwater inputs are low and evaporation is high (e.g. Mediterranean Sea, 38 ppt) while lower salinity areas occur where freshwater inputs are high and the climate is cooler (e.g. Baltic Sea, as little as 1 ppt).

Some people will be shocked to see salinity listed here, as merely another factor. You could, as I said in Chapter 1, divide the entire world of wetlands into freshwater wetlands and saltwater wetlands, or interior and coastal wetlands. Indeed, some books restrict themselves to only freshwater or only saline wetlands. From one perspective, this is quite reasonable. But it creates problems, too. It tends to make us overlook the many processes that freshwater and saltwater wetlands share. It also breaks scientists into groups that sometimes hardly seem to talk to one another. In this book

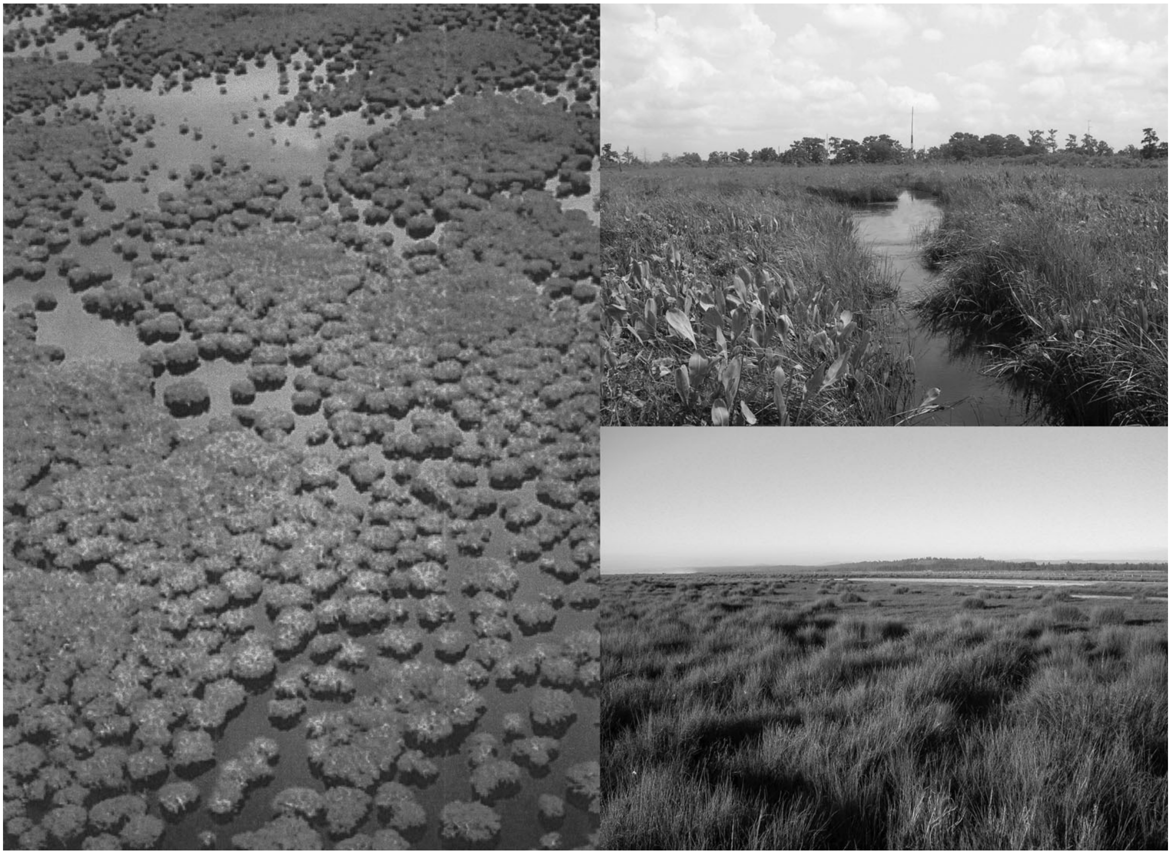

FIGURE 8.1 Salinity changes the species composition of wetlands from mangrove swamp (left, Florida Keys, USA; courtesy G. Ludwing, U.S. Fish and Wildlife Service) to salt marsh (bottom right, El Yali, Chile; courtesy M. Bertness) to oligohaline marsh (top right, Gulf of Mexico, Louisiana). (See also color plate.)

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I wish to to emphasize how all wetlands share many common features, species, processes, and problems. All wetlands experience flooding, all wetlands are affected by fertility, all wetlands are affected by disturbance, and so on. There is much we can learn from emphasizing commonality. We can think of saltwater wetlands as freshwater wetlands with another causal factor imposed.

So how does this new causal factor affect the group of wetlands we call coastal wetlands? There are two main ways. First, salinity is harmful to many species, even many species that normally occur in wetlands. Second, salinity changes the pool of species that can form a habitat. Let us look at them in turn, first using plants, and then expanding to macroinvertebrates.

8.1.1 Salinity depresses the growth of many species

The negative effects of salinity arise because of the added stress that salinity puts on plants. It requires added energy, and often specialized mechanisms, to deal with the salinity. Hence, plant growth rates are depressed (Pezeshki *et al.* 1987a, b; McKee and Mendelssohn 1989). Figure 8.2 shows the responses of four marsh species to five different salinity regimes over 3 months. The salinity regimes used were (1) 0 g/l salinity, (2) final salinity of 6 g/l reached in 6 weeks, (3) final salinity of 6 g/l reached in 3 days, (4) final salinity of 12 g/l reached in 3 weeks, (5) final salinity of 12 g/l reached in 3 days (Howard and Mendelssohn 1999). In all cases, higher salinity reduced growth. Seedlings are sensitive to

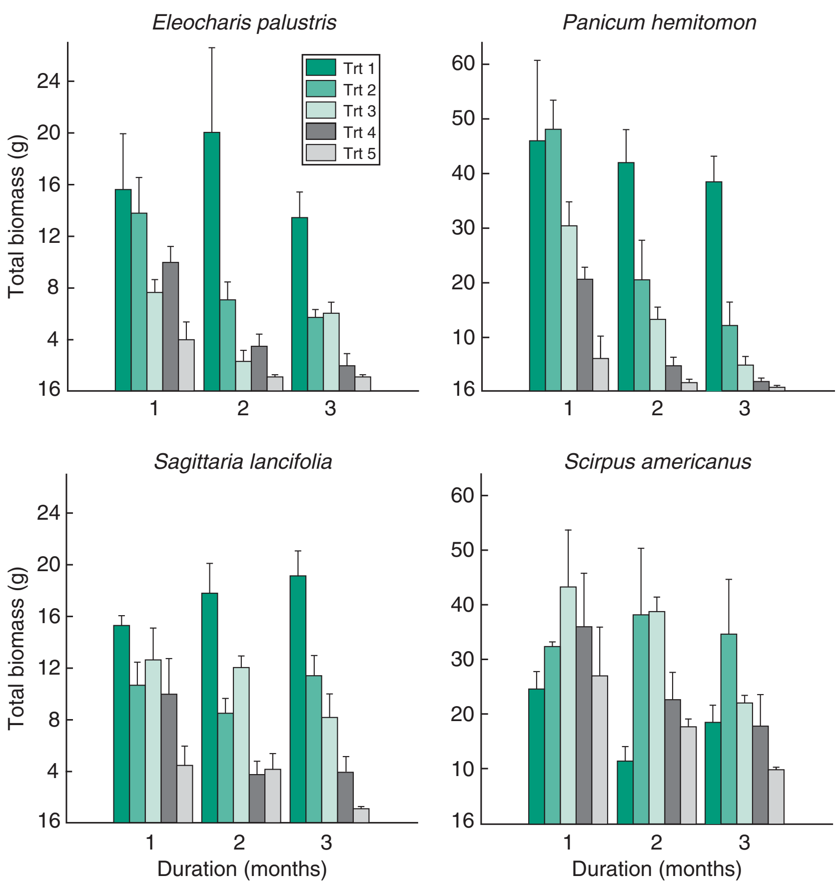

FIGURE 8.2 The effects of salinity upon plant growth. Four common coastal species show decreased growth with increased exposure to salinity. The five salinity treatments simulate pulses such as might be caused by storms. (1) 0 g/l salinity, (2) final salinity of 6 g/l reached in 6 weeks, (3) final salinity of 6 g/l reached in 3 days, (4) final salinity of 12 g/l reached in 3 weeks, (5) final salinity of 12 g/l reached in 3 days. (From Howard and Mendelssohn 1999.)

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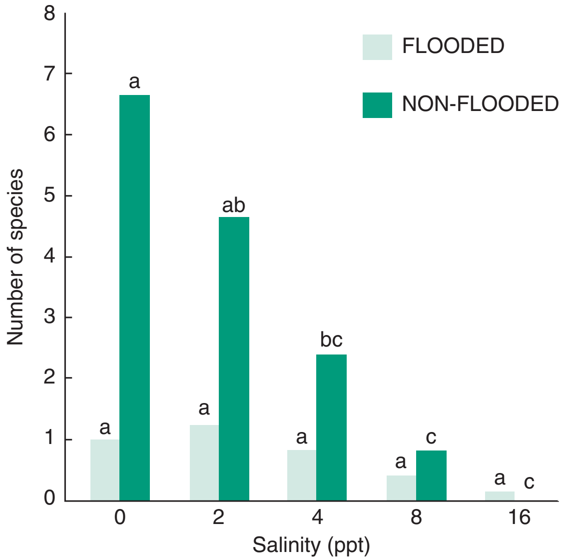

FIGURE 8.3 The number of species of marsh plant emerging from soil samples taken in Louisiana and exposed to flooded and non-flooded treatments over five salinities. Flooding reduces germination (as you would expect from Chapter 2). Salinity also reduces germination, until at 16 ppt, flooded and non-flooded samples have negligible emergence. (From Baldwin *et al.* 1996.)

salinity as well. When marsh soils are exposed to saline water, the number of species germinating decreases with increasing salinity (Figure 8.3)

The most likely cause of depressed growth is the difficulty of obtaining water. The plants may be flooded daily at high tide, but they may still not have access to soil water. Normally, water uptake occurs because evapotranspiration creates osmotic gradients within plant tissues. The water deficit is transmitted down the plant through the xylem, thereby causing water to diffuse into roots (Salisbury and Ross 1988; Canny 1998). The greater the salinity, the stronger this osmotic gradient must be to extract water from the soil. One can measure these water deficits in photosynthetic tissues using a pressure bomb (Scholander *et al.* 1965), which yields readings of xylem tension in megapascals. Plants growing in salt water have a much more negative tension in their xylem (Figure 8.4), reflecting the difficulty in withdrawing water from saline solutions. In addition, there are likely physiological stresses from the ionic composition of the water, and ionic accumulations in the plant tissues (Howard and Mendelssohn 1999). A more detailed exploration of the consequences of salinity can be found in standard reference works (e.g. Chapman 1974; Tomlinson 1986; Adam 1990).

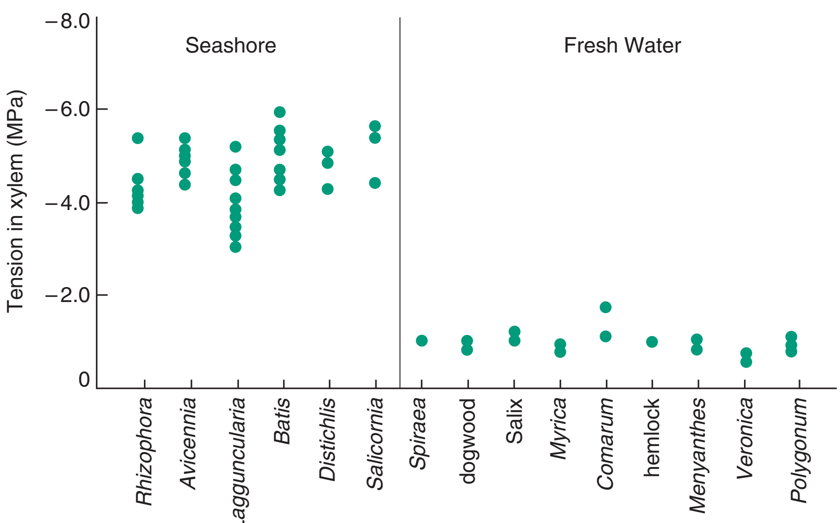

FIGURE 8.4 Xylem tension in plants of two contrasting wetland habitats. (After Scholander *et al.* 1965.

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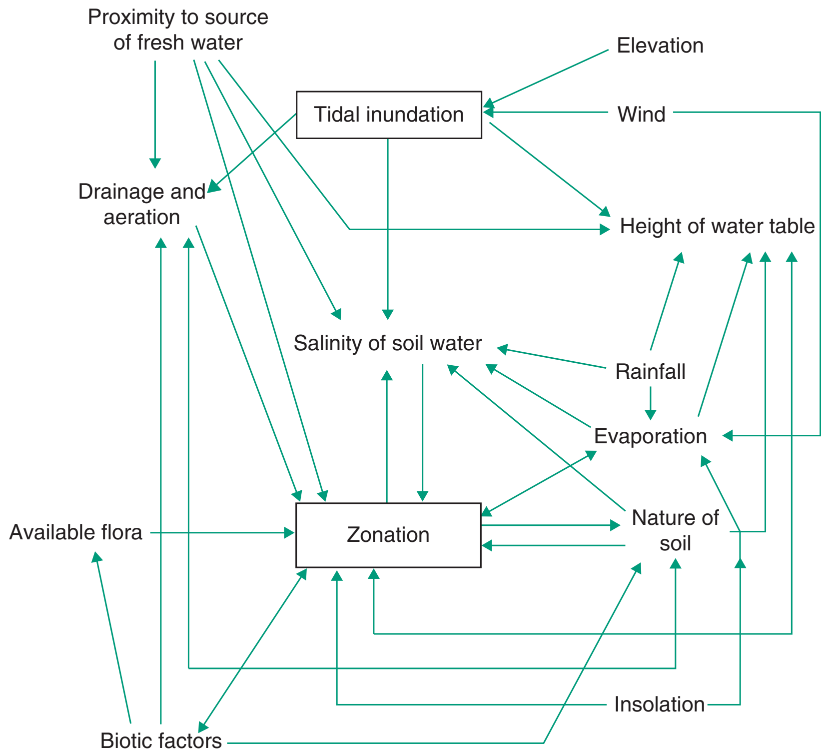

FIGURE 8.5 Environmental factors influencing salt marsh zonation. (Modified from Adam 1990 and Clarke and Hannon 1969.)

Of course, salinity is just one of many factors affecting coastal wetlands. You have already seen examples of fertility and disturbance and burial affecting coastal wetlands too. These produce a complex network of cause and effect (Figure 8.5). One other important factor is climate – cool periods with lots of rain can reduce salinity, whereas hot periods of drought can increase it. Indeed, evaporation from shallow pools can create salinity higher than the ocean – hypersaline conditions. Hence, as Figure 4.23 showed, wetland plants may germinate only during cool wet periods where salinity remains low enough for seedlings to establish.

Overall, you can think of salinity as an added cost that a plant has to bear to grow in a coastal environment. The added cost may become critical when the plants are already struggling to cope with other forces like grazing and hypoxia. Here is one example which tested for possible interactions of salinity with two factors discussed earlier in the book, flooding and herbivory. Grace and Ford (1996) focused upon a common marsh plant, *Sagittaria lancifolia*. Pieces of turf containing this species were exposed to factorial combinations of salinity, flooding, and simulated herbivory. Here is the critical point – none of these factors alone significantly affected the test plants (Figure 8.6) – but all three factors combined produced negative effects on the plants. Hence, if one did only the work in the first four histograms – each factor alone – one could conclude that salinity, flooding, and herbivory were unimportant. But the last two histograms tell a rather different story. When these three factors are combined (hsf: herbivory + salinity + flood), plant size falls significantly. If fertilizer is added to this combination to try to compensate for the damage (hsff: herbivory + salinity + flood + fertilizer), there is no benefit. Of course, plants in Louisiana coastal marshes are exposed to herbivory, salinity,

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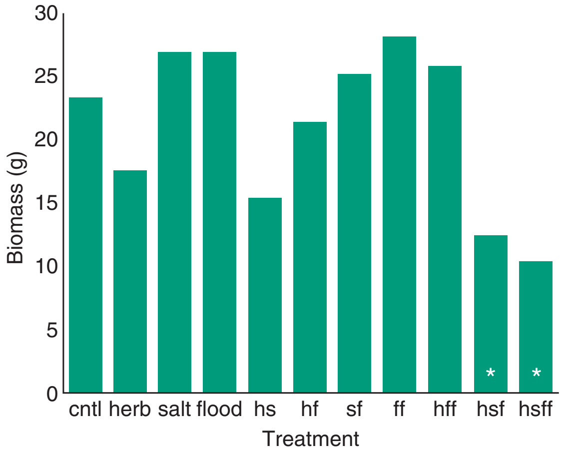

FIGURE 8.6 The response of one common marsh plant, *Sagittaria lancifolia*, to simulated herbivory (herb), salinity (salt), and flooding (flood). Although the effect of each factor or each pair of factors is insignificant relative to controls (cntl), when all three factors are combined (hsf: herbivory + salinity + flooding), plant size falls significantly. If fertilizer is added to this combination to try to compensate for the damage (hsff: herbivory + salinity + flooding + fertilizer), there is no benefit. (From Grace and Ford 1996.)

and flooding simultaneously. This illustrates how multiple factors interact to produce coastal wetlands, and demonstrates the general principle of multiple interacting factors emphasized in Chapter 1.

8.1.2 Salinity reduces the size of the species pool

Saline environments appear to pose a nearly insurmountable obstacle to plant adaptation. The other primary consequence of high salinity is reduced plant diversity. When wetland plants are exposed to increasing salinity, they eventually die. Only a small proportion are able to tolerate the salinity of the ocean (Figure 8.7).

In tropical areas, woody plants can occupy saline wetlands, producing intertidal forests (Tomlinson 1986); the tree species are referred to as **mangroves**, whereas the vegetation is called **mangal**. Tomlinson reports that there are only 9 major genera of mangroves and some 34 species in the world, with 11 minor genera contributing a further 20 species. Including the associates of mangroves, this list can be extended by a further 60 species. To put these figures into perspective, some 90 woody plant species have been found in a single 500-m^2 transect in a tropical riparian floodplain of central America (Meave *et al.* 1991) – that is, one small section of freshwater forest has the same number of species as all of the world's mangal flora. A few more examples – there are some 200 genera and 2600 species in the palm family, but only four are commonly found in mangal (Tomlinson 1986, pp. 30, 295). The family Myrsinaceae has over 1000 species in about 30 genera distributed throughout the tropics and subtropics, but only four species occur in mangal (p. 284). The question as to why so few plants have evolved salt tolerance remains an open one. We may nevertheless conclude that one of the major effects of salinity is to reduce the number of plant species present.

This means that coastal wetlands can look very different, since they have species that are different from interior wetlands. When only a few species dominate a coastal wetland, say in the case of the grass *Spartina alterniflora*, the study of coastal wetlands can easily become the study of that single species. Similary, when the coastal wetland is dominated by mangroves, wetland ecology can easily be confused with the study of mangrove ecology. In these cases, it is easy to become so wrapped up in the ecology of *Spartina*, or mangroves, that one loses track of the fact that the wetland is still behaving in many other ways like a typical wetland. There are hypoxic soils. Water levels change. Nutrients affect plant distributions. Organisms compete for critical resources. Disturbance causes abrupt changes in composition. And so on.

8.1.3 Salinity is a critical gradient for subdividing estuaries

It is frequently convenient to divide coastal wetlands into four categories depending on the salinity: fresh, intermediate, brackish, and saline. Although these

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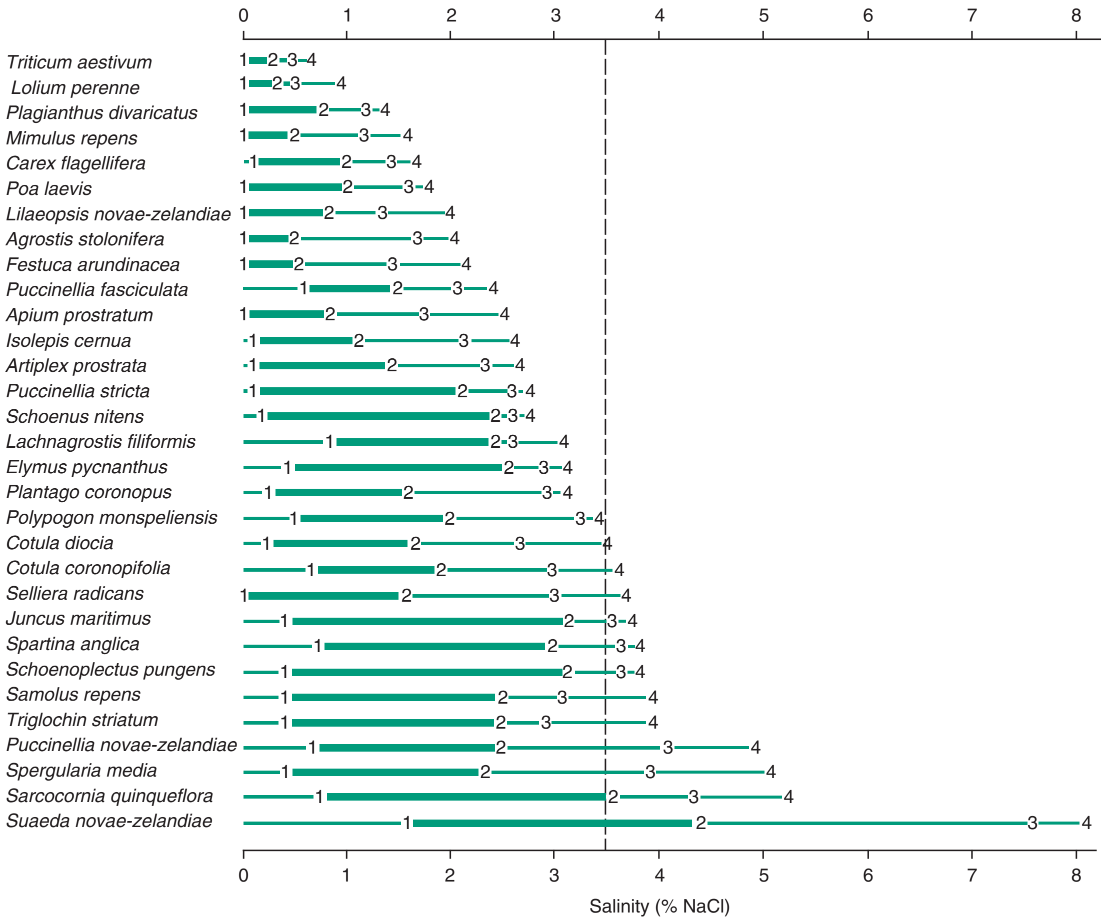

FIGURE 8.7 Coastal marsh plants can be ranked according to their tolerance for salinity (vertical dashed line indicates ocean salinity). (From Partridge and Wilson 1987.)

are designated based on salinity levels, they can often be readily identified by the plant species present (Table 8.1). The fauna changes in response to the salinity and in response to the kinds of plants present.

8.1.4 Salinity is often a short-lived pulse

Although it is convenient to talk about a site from the perspective of a mean salinity (e.g. brackish or intermediate, Table 8.1), in most estuaries, higher salinity arrives in pulses when storms drive salt water inland. When Hurricane Katrina hit the Louisiana coast in 2005, the water in Lake Pontchartrain, which normally oscillates around 2 ppt (1.5 to 2.5), leaped to nearly 4 ppt for a little over a day (Figure 8.8). This was salt water pushed inland. Note, too, that in the wake of the storm, salinity dropped to oscillate at under 2 ppt (1.5 to 2), presumably as a consequence of fresh water arriving in rainfall. Hence, one hurricane can first increase salinity, and then decrease it. The disturbance caused by the hurricane may therefore be followed by a period of more rapid establishment and growth.

Salt water pulses affect estuaries over a wide range of time scales. Figure 8.8 showed a pulse from one

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Table 8.1 **Common plant species (ranked 1 = most abundant to 5 = least abundant), total number of plant species, and area of coastal marsh types in Louisiana**

	Marsh type (salinity, ppt)			
	Saline >15	Brackish 6–15	Intermediate 2–6	Fresh <2
Spartina alterniflora	1	4		
Distichlis spicata	2	2		
Juncus roemerianus	3	5		
Spartina patens	4	1	1	5
Batis maritima	5			
Scirpus olneyi (Schoenoplectus americanus)		3		
Phragmites communis (P. australis)			2	
Sagittaria lancifolia			3	2
Bacopa monnieri			4	
Eleocharis sp.			5	3
Panicum hemitomon				1
Alternanthera philoxeroides				4
Total no. species	17	40	54	93
Area (ha)	323 344	479 957	263 855	494 526

Source: After Chabreck (1972).

hurricane. In the Baltic Sea, which has extremely low salinity levels of ca. 1 ppt (depending, of course, upon location), rivers are the source of fresh water, while saline water enters from the North Sea through the Danish Straits (Helsinki Commission 2003). The wetlands on the coast of the Baltic therefore include many fresh and intermediate species that are not normally encountered in estuaries (Figure 8.9). Occasional low pressure systems allow salt water to flow much more rapidly into the Baltic – 1913, 1921, 1951, 1976, 1993, and 1994 – each had major salinity pulses. These pulses tend to counterbalance the accumulation of freshwater inputs from rivers and raise salinity levels. Pulses also carry oxygen-rich water into the Baltic, which is an important issue for fisheries of the region.

In summary, the major effects of salinity on coastal wetlands are (1) the reduction in plant growth rates and (2) the reduction in the pool of species. The fact that there are fewer species often amplifies the importance of single species such as *Spartina alterniflora* in coastal marshes or *Rhizophora mangle* in coastal swamps. The salinity is determined by the balance between freshwater inputs from rivers and saltwater inputs from the ocean, which can fluctuate at many scales depending upon tides, currents, and storms.

8.1.5 Animals are similarly affected by salinity and salinity pulses

Animals repond in similar ways to the plants. Let us use macroinvertebrates as an example. The number of species of aquatic invertebrates, particularly those in the Insecta, normally increases with increased flood duration, since it allows groups with longer larval stages to reproduce successfully. If the water is saline, however, it lowers the number of species,

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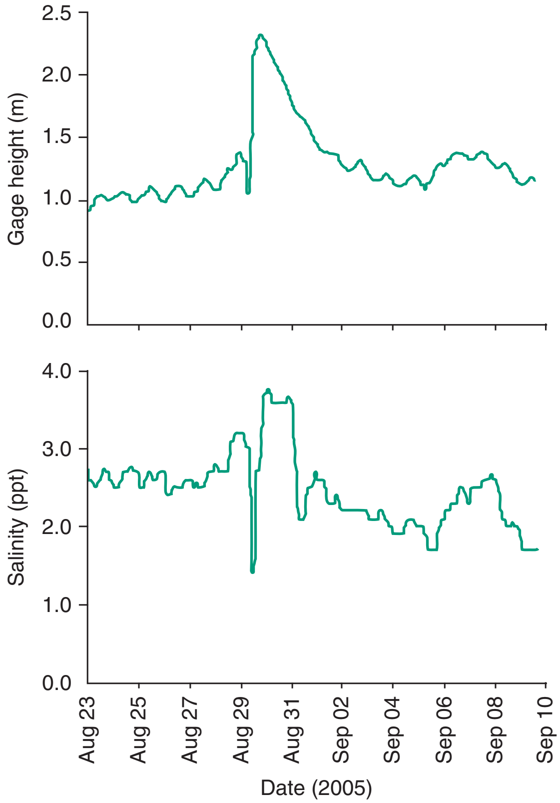

FIGURE 8.8 When Hurricane Katrina hit the Louisiana coast (August 30, 2005), it produced a pronounced pulse in water levels and salinity, here illustrated by a monitoring station at Pass Manchac (measured by U.S. Geological Survey 301748090200900). (After Keddy *et al.* 2007.)

just as with plants, often leading to dominance by a few salt-tolerant genera. Hence, the volume and duration of freshwater input is critical.

The Camargue in southern France is one of Europe's largest deltas, and is bracketed by two branches of the Rhone River. The Rhone carries fresh water from the north southward to the Mediterranean coast, into an area with hot dry summers and moisture deficits. Many of the species that occur here, from reeds to flamingoes, are tolerant of brackish conditions. Thus the delta in general, and the Camargue in particular, are very susceptible to changes in salinity, which can change with freshwater flows from upstream that vary with precipitation, or due to local human impacts of canals and drainage for rice cultivation.

The Camargue is well-known for its populations of waterbirds, including flamingoes (Figure 8.10). Many waterbirds feed on macroinvertebrates. Hence, the factors controlling the composition and abundance of aquatic macroinvertebrates are of broad interest. Many of the wetlands fill with water during the winter, and then dry out during the summer, being flooded for from 5 to 9 months. One study examined a set of 30 such temporary wetlands (Waterkeyn *et al.* 2008). Most macroinvertebrates were identified to genus, except the Diptera, which were identified to family level.

A total of 19 zooplankton taxa and 49 macroinvertebrate taxa were identified. We will look only at the macroinvetebrates. The mean number of macroinvertebrate taxa in a wetland was 14. The number of taxa declined with increasing salinity (Figure 8.11). The rarer species were restricted to the fresher ponds. Some dragonflies appeared to be able to tolerate salinities up to 22–25 mS/cm, but overall they too declined with increasing salinity. A few Coleoptera (such as *Berosus* sp.) and some Hemiptera (such as *Sigara* sp.) were also tolerant of salinity. The snail *Potamopyrgus antipodarum*, originally native to New Zealand, is spreading worldwide (Alonso and Castro-Diez 2008) – note its presence, too, in the more saline conditions.

During the heavy autumn rains, fish can enter the wetlands. Fish have a negative effect on the invertebrates. One of the most common fish is *Gambusia affinis* (the mosquitofish) which has been introduced worldwide for mosquito control; it should be no surprise that a fish feeding on invertebrate larvae can cause changes in macroinvertebrate composition, but it is a reminder that controlling mosquitoes with predator fish may have unexpected effects on other non-insects, some of which may be predators themselves.

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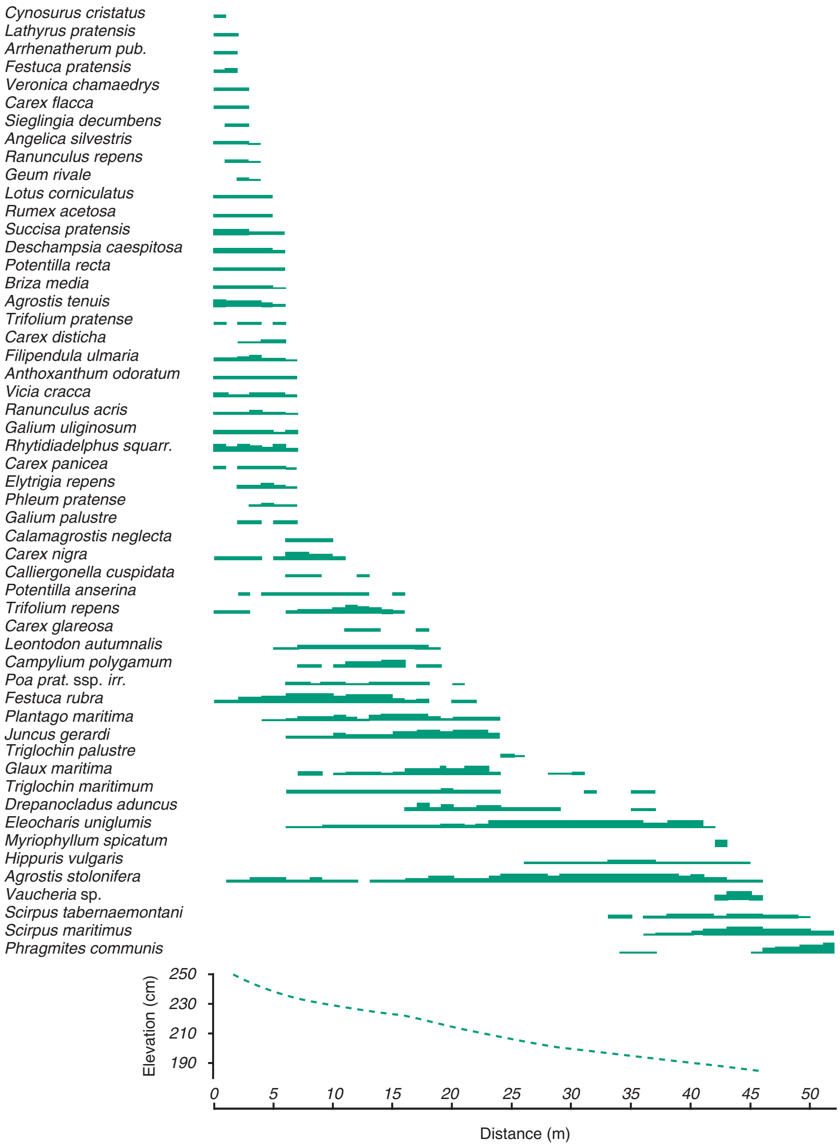

FIGURE 8.9 Zonation of wetland plants on a section of the Baltic coast. Note that the deeper water has *Phragmites communis*, and that *Spartina* is not present, illustrating the relatively fresh conditions in the Baltic Sea. (From Tyler 1971.)

8.2 Roads

Roads and networks of roads now cover large portions of Earth and generally have a profound and negative effect upon wild species and habitats (Forman and Alexander 1998; Trombulak and Frissell 2000; Forman *et al.* 2002). In this section we will not only consider the obvious effects of roadkill, but also a wide array of indirect effects such as altered drainage and fire regimes.

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FIGURE 8.10 The flamingoes of the Camargue wetland on the Mediterranean coast depend upon invertebrates for food. (Courtesy A. Waterkeyn.) (See also color plate.)

8.2.1 Roads are everywhere and still expanding

Roads are now so all pervasive that conservation planners now map "road-less areas" as small fragments of landscape worthy of conservation – simply because of the absence of road effects.

Some statistics (Brown 2001). The area of the United States devoted to roads and parking lots covers an estimated 16 million hectares (61 000 square miles). For every five cars added to the U.S. fleet, an area the size of a football field is covered with asphalt. The United States is losing 650 000 hectares of wild land per year to development. Land that is paved is land lost for wildlife. Moreover, land that is paved drains rapidly into sewers and rivers, increasing local flood peaks.

8.2.2 The direct effect: roads kill animals

One of the obvious effects of roads is clear and direct: the toll taken in animal deaths. Anyone who has paid attention to dead animals on roads will notice the carnage, not only large animals like armadillos and porcupines, but many smaller animals including toads, frogs, salamanders, snakes, and turtles. The mortality rate is so high that the absence of such carcasses on a stretch of road may be a reliable indication that the local populations have been exterminated. To give you a sense of the scale, on one warm spring night I returned from the theater to find my lane carpeted in migrating frogs. We stopped, and individually removed them so we could get home – 101 frogs on that small stretch

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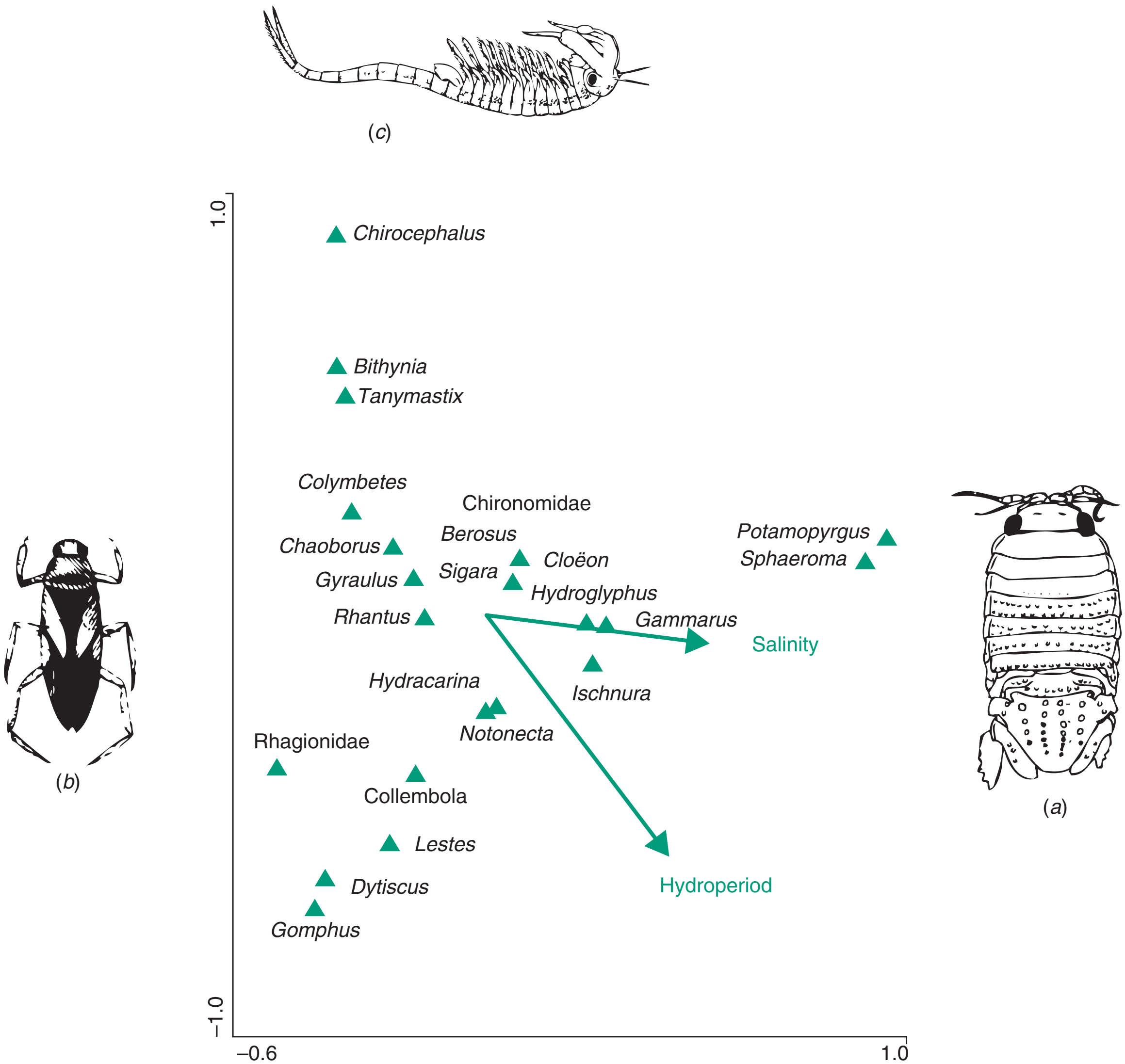

FIGURE 8.11 Rainfall and flooding change the salinity of ponds in the Camargue and produce different populations of invertebrates. The most saline ponds have *Sphaeroma* (*a*) and an introduced snail (*Potamopyrgus antipodarum*), whereas dragonflies and backswimmers (*b*, *Notonecta*) occur at intermediate salinities, and fairy shrimp (*c*, *Chirocephalus*) typify fresh water ponds. (After Waterkeyn *et al.* 2008.)

of road. Imagine if we had simply driven through them, as too many people do.

Here are just four examples that illustrate the rates of death on roads. Snake mortality levels 0.188 per km were found in one set of 15 North American studies (Jochimsen 2006). A study in India found 73 reptiles (representing 24 species, mainly snakes) and 311 amphibians (mainly ranids, rhacophorids, and caecilians); the reptile mortality level was 0.43 per km (Vijayakumar *et al.* 2001). An Australian survey found mortality rates of 0.3 per km per week. There were 529 carcasses of 53 vertebrate species including mammals (bandicoot, brushtail possum), birds (noisy miner, Australian magpie),

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and lizards (eastern bluetongue lizard, bearded dragon) – smaller animals like frogs were thought to be underrepresented in this sample because of issues with visibility and rapid decay. Wider roads provide greater obstacles, and multiple lanes of traffic may be impassible to slow-moving species – Aresco (2004) found that 95% of 343 turtles were killed as they first entered the highway adjacent to the shoulder, and the remaining 5% were killed in the first two traffic lanes, with mortality rates estimated at 1294 per km per year.

8.2.3 Indirect effects may be more important than roadkill

On top of the effects of direct mortality are indirect effects (Trombulak and Frissell 2000; Forman *et al.* 2002). Probably the most important is their interference with natural drainage patterns. They are a source of sediment, particularly during construction, but often for many years thereafter. Salt that is put on northern roads seeps into adjoining wetlands. Roads provide access for hunting and poaching and perhaps off-road vehicles. They provide a route for invasive species. Roads often attract other development such as housing estates or logging. Hence, the extent of the road network near a wetland, is a strong negative predictor of the number of species likely to be found (Figure 8.12).

Roads at a distance from a wetland can still have many effects, but they may be more subtle and require careful analysis for detection. Houlahan *et al.* (2006) studied 74 small wetlands and tried to measure the effects of different land uses upon them. Wetland area and presence of streams had a pronounced positive effect while roads and houses had pronounced negative effects (Figure 8.13). The effects extended as far as 250–400 m from roads. The presence of forests also has a strong positive effect.

Large areas of paved land do not allow water to infiltrate the soil, leading to rapid surges of water immediately after rain, and then longer periods that are comparatively dry. Runoff from paved areas can cumulatively lead to lower water tables that result in losses of small streams and springs.

To put the effects of paving in context, consider how much has been written on coastal wetland loss in Louisiana. Yet in North America as a whole, the loss of land to urban development is proceeding at a rate 100 times faster than the loss of the Louisiana coast.

8.3 Logs and coarse woody debris

There are numerous historical accounts of logs and fallen trees (coarse woody debris) clogging rivers. At one time, river banks may have been littered with this kind of debris, with effects upon everything from rates of soil erosion to fish feeding. So few of us have seen a natural river with natural logjams that it is easy to forget the effects they once had.

One early description of debris in rivers comes from the Freeman and Custis expedition that traveled 990 km (615 miles) up the Red River in 1806 (Flores 1984; MacRoberts *et al.* 1997). This expedition was a lesser-known twin to the famous Lewis and Clark expedition up the Missouri. Freeman and Custis reported that the Red River was entirely blocked by a series of gigantic logjams that began just north of modern-day Natchitoches and continued for approximately 160 km to the vicinity of present-day Shreveport (Figure 8.14). Freeman describes each in turn (since he is compiling a detailed report, and since each must be bypassed “with great exertion”) but let us combine the accounts for an overall picture of this feature.

> It consists of the trunks of large trees, lying in all directions, and damming up the river for its whole width, from the bottom, to about three feet higher than the surface of the water. (Flores 1984, p. 127).

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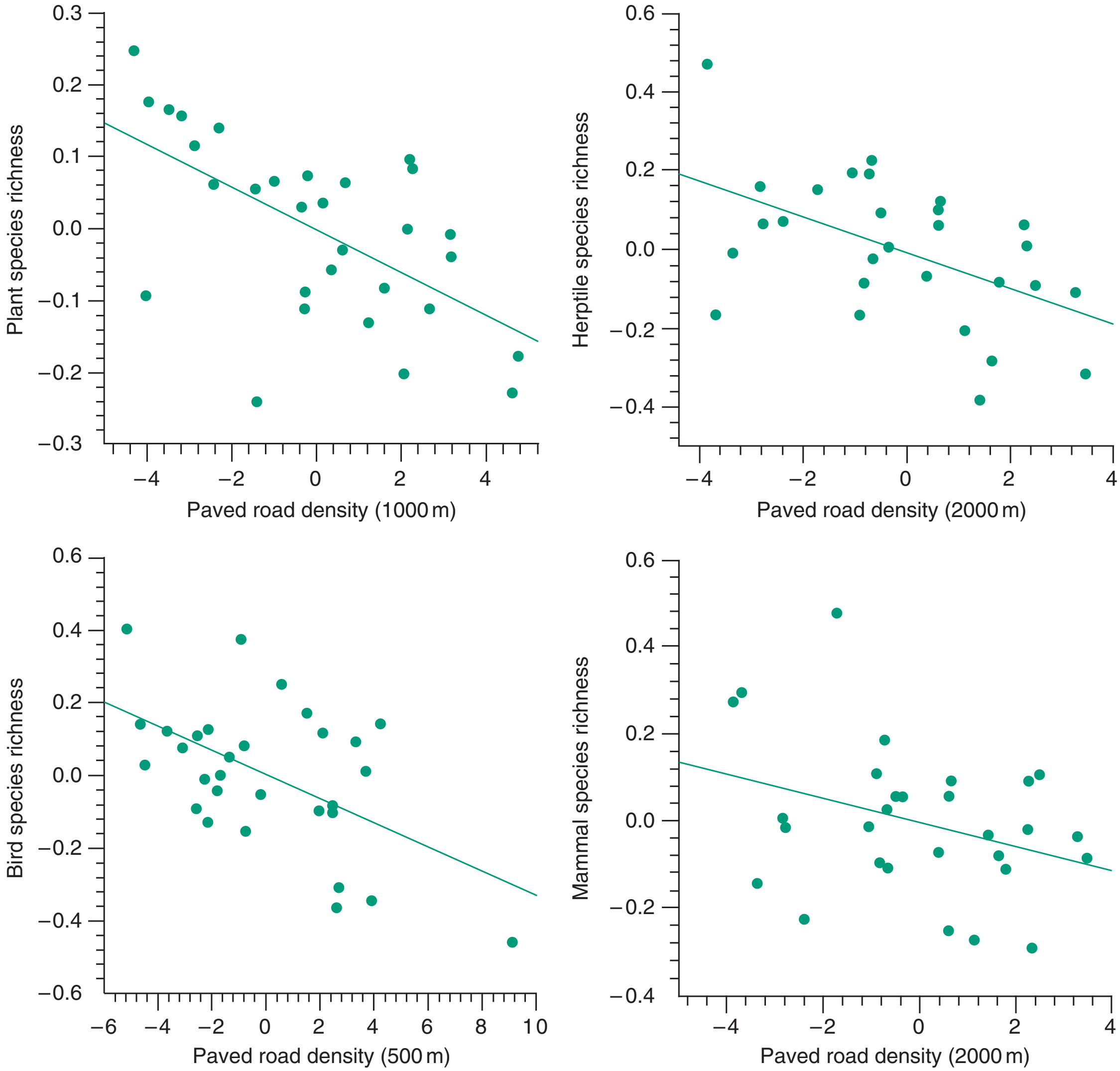

FIGURE 8.12 Roads have a negative effect on the number of species of plants, herptiles, birds, and mammals in wetlands. Residuals of the species richness–area regression are plotted against residuals of the paved road density–area regression. (From Findlay and Houlahan 1997.)

The logjams were so solid that “bushes and weeds” and even trees covered the surface, while “the men could walk over it in any direction.” It took Freeman and Custis “fourteen days of incessant fatigue, toil and danger, doubt and uncertainty” to pass through the Great Raft. The logs blocked commercial boat passage, and it eventually took some 50 years and federal funds to clear it, a task finished finally in the 1870s.

A similar mass of trees blocked the Atchafalaya River in the early 1800s, extending for some 65 km (Reuss 1998). Some witnesses claim that humans and even horses could pass over the river on this debris. Once a cut upstream was made by Shreve in 1831, the source of logs declined and the raft stopped growing. Despite repeated attempts to burn or otherwise clear the raft after 1831, it re-formed. Finally, with the

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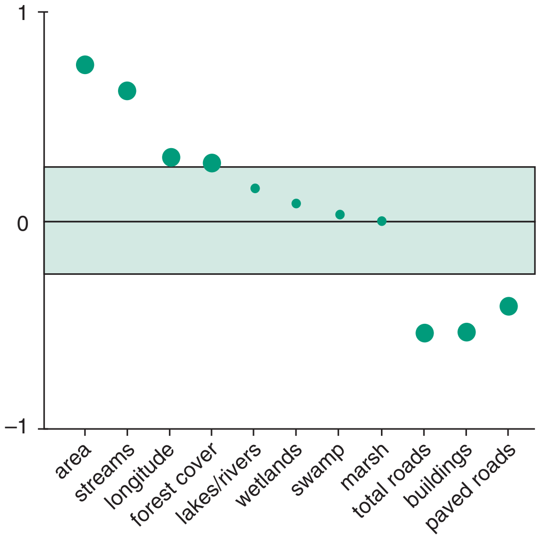

FIGURE 8.13 The effects of different environmental factors upon the number of plant species in a wetland. The vertical axis is the standardized regression coefficient, the gray zone represents non-significance. The horizontal axis lists environmental factors that were measured. Wetland area and presence of streams had a pronounced positive effect (upper left) while the total length of two-lane roads, the number of buildings, and total length of paved roads had a pronounced negative effect. Longitude and forest cover had weak positive effects ($n = 58$). (After Houlahan *et al.* 2006.)

services of a snagboat, the last of the raft was removed in 1860.

These are but two examples. A more quantitative picture emerges from Bayou Teche in 1847, where, over a distance of 32 km, 1455 logs were taken from the bed of the bayou, and 961 stumps and snags removed. Nearby, 1887 snags and logs were removed from Bayou Lafourche (Reuss 1998, p. 34).

It would be interesting to study early explorers' descriptions for a better account of woody debris distribution. Consider a few examples. Iberville's trip from the Mississippi River to Lake Maurepas in 1699 was delayed because the watercourse was clogged with roots and logs (McWilliams 1981, p. 6). He also describes rivers "carrying along many trees" (p. 54). Weddle (1991) reports that Iberville found distributaries choked with drift logs (p. 61) and "choked by sandbars and uprooted trees" (p. 148).

Coarse woody debris is known to be very important to a wide array of forest species (Harmon *et al.* 1986), providing everything from germination sites for tree seedlings to hiding places for amphibians. In contrast, the importance of coarse woody debris for providing wildlife habitat in rivers and wetlands is too often underestimated. It not only provides shelter, but modifies sediment deposition patterns, creating pools that are used by many aquatic species (Bilby and Ward 1991; Francis and Schindler 2006). For fish, coarse woody debris provides at least three positive effects: it provides shelter that decreases predation risk, it provides visual isolation that reduces contact between fish, and it provides refuge from the current that minimizes energy expenditures (Crook and Robertson 1999). Logs on shorelines can provide shelter and basking sites for many kinds of turtles (Figure 8.15). As the human population increases on shorelines, the amount of coarse woody debris declines (Francis and Schindler 2006).

Large piles of dead wood may once have provided a matrix that armored coastal barrier islands, oyster reefs, and wetlands. Human activities have reduced the supply of driftwood. Many of the proposals for coastal restoration that are intended to armor shorelines may simply be an expensive and non-renewable replacement for a natural product that once played a similar role.

8.4 Stream type

We have already seen many examples of how a surrounding landscape affects a wetland. The proximity of roads has negative effects, while the proximity of forests has a positive effect. We have even seen that the presence of a stream has a measurable positive effect on the number of plants

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FIGURE 8.14 Enormous amounts of woody debris were once a natural feature of water courses and shorelines. The Great Raft dammed the Red River and flooded the surrounding area. (Photo by R. B. Talfor, courtesy Noel Memorial Library Archives, Louisiana State University, Shreveport.)

in a wetland. The type of watercourse is therefore likely to be an important factor. Using slope and geomorphology as the main variables, the Rosgen system (Figure 8.16, top) sorts rivers in nine types from Aa + (very steep) though to G (gentle). There are obvious changes in the type of channel configuration along this gradient, with braided streams and meanders on the right. Other factors such as entrenchment, sinuosity, and width to depth ratio also change with slope. Combining eight of these slope categories (A to G) with six classes of bed material (1 (rock) to (6) silt and clay), produces a matrix of 48 possible types of stream. Only a small subset of these, mainly in groups C, DA, and E have large associated wetlands (Figure 8.16, bottom). Thus, simple factors that you can see on maps, like type of substrate and slope, will tell you a good deal about the types of wetlands likely to be found in a landscape. The slope of the river bank is obviously one of the most important factors that will determine whether the wetland is a narrow strip of riparian vegetation or a broad wetland. The type of watercourse also has a great deal of impact on burial, which we explored earlier (Chapter 7).

Although we can think of the Rosgen system as a template that produces different wetland vegetation types, there is also a feedback loop where the vegetation itself controls the river. In classes C, DA, and E, the vegetation can have a strong impact on width to depth ratios.

Wetland ecologists are often expected to be knowledgeable about riparian habitats, particularly where the adjoining wetlands control rates of bank erosion and wildlife habitat. The Rosgen system provides a way to view wetlands from the landscape scale, and from the point of view of freshwater organisms like fish.

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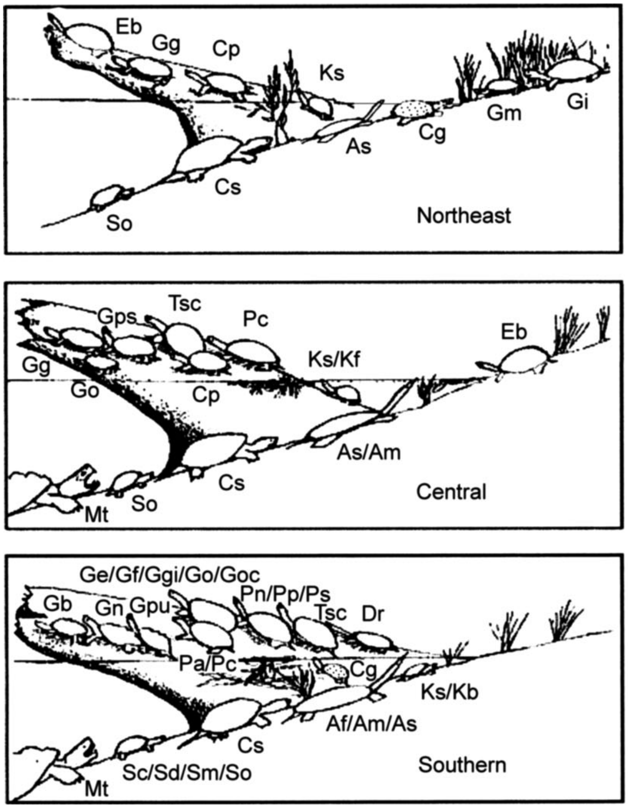

Af	*Apalone ferox*	Florida softshell turtle
Am	*A. mutica*	Smooth softshell turtle
As	*A. spinifera*	Spiny softshell turtle
Cg	*Clemmys guttata*	Spotted turtle
Cp	*Chrysemys picta*	Painted turtle
Cs	*Chelydra serpentina*	Common snapping turtle
Dr	*Deirochelys reticularia*	Chicken turtle
Eb	*Emydoidea blandingii*	Blanding's turtle
Gb	*Graptemys barbouri*	Barbour's map turtle
Ge	*G. ernsti*	Escambia map turtle
Gf	*G. flavimaculata*	Yellow-blotched map turtle
Gg	*G. geographica*	Northern map turtle
Ggi	*G. gibbonsi*	Pascagoula map turtle
Gi	*Glyptemys insculpta*	Wood turtle
Gm	*G. muhlenburgii*	Bog turtle
Gn	*Graptemys nigrinoda*	Black-knobbed map turtle
Go	*G. ouachitensis*	Ouachitia map turtle
Goc	*G. oculifera*	Ringed map turtle
Gps	*G. pseudogeographica*	False map turtle
Gpu	*G. pulchra*	Alabama map turtle
Kb	*Kinosternon baurii*	Striped mud turtle
Kf	*K. flavescens*	Yellow mud turtle
Ks	*K. subrubrum*	Eastern mud turtle
Mt	*Macrochelys temminckii*	Alligator snapping turtle
Pa	*Pseudemys alabamensis*	Alabama red-bellied cooter
Pc	*P. concinna*	River cooter
Pn	*P. nelsoni*	Florida red-bellied cooter
Pp	*P. peninsularis*	Peninsula cooter
Ps	*P. suwanniensis*	Suwannee cooter
Sc	*Sternotherus carinatus*	Razor-backed musk turtle
Sd	*S. depressus*	Flattened musk turtle
Sm	*S. minor*	Loggerhead musk turtle
So	*S. odoratus*	Stinkpot
Tsc	*Trachemys scripta*	Pond slider

FIGURE 8.15 Coarse woody debris provides important basking sites for turtles (species shown for North American regions), as well as habitat for many other animal species. (Adapted from Bury 1979.)

8.5 Human population density is becoming a key factor

Human population density continues to increase – there are twice as many people in the world as when I was born. The human population continues to grow. The rate of growth will depend upon factors like the number of children in a family, access to birth control, religious belief, age of reproduction, and quality of medical care. There are many scenarios (Figure 8.17) but all probable ones show continued growth. According to many calculations, we have already passed the sustainable level for humans, measured as the annual rate of return of natural resources. That is, we humans are now consuming more each year than the Earth produces. We maintain levels above this by eating into the world's ecological capital – old forests, fish stocks, soil, and fossil fuels to give four examples. This is only a temporary solution – it is like living on savings. Once the savings are gone, there is nothing. There are groups promoting zero population growth, and even population reduction. Densely populated countries like China already impose a policy of one child per family, but without other nations following this example, it is hard to envisage a future without severe problems. Since humans manipulate landscapes – whether it is grazing cattle on floodplains, cutting mangroves for fuel, or building enormous dams and levees, the fate of wetlands is closely tied to human populations.

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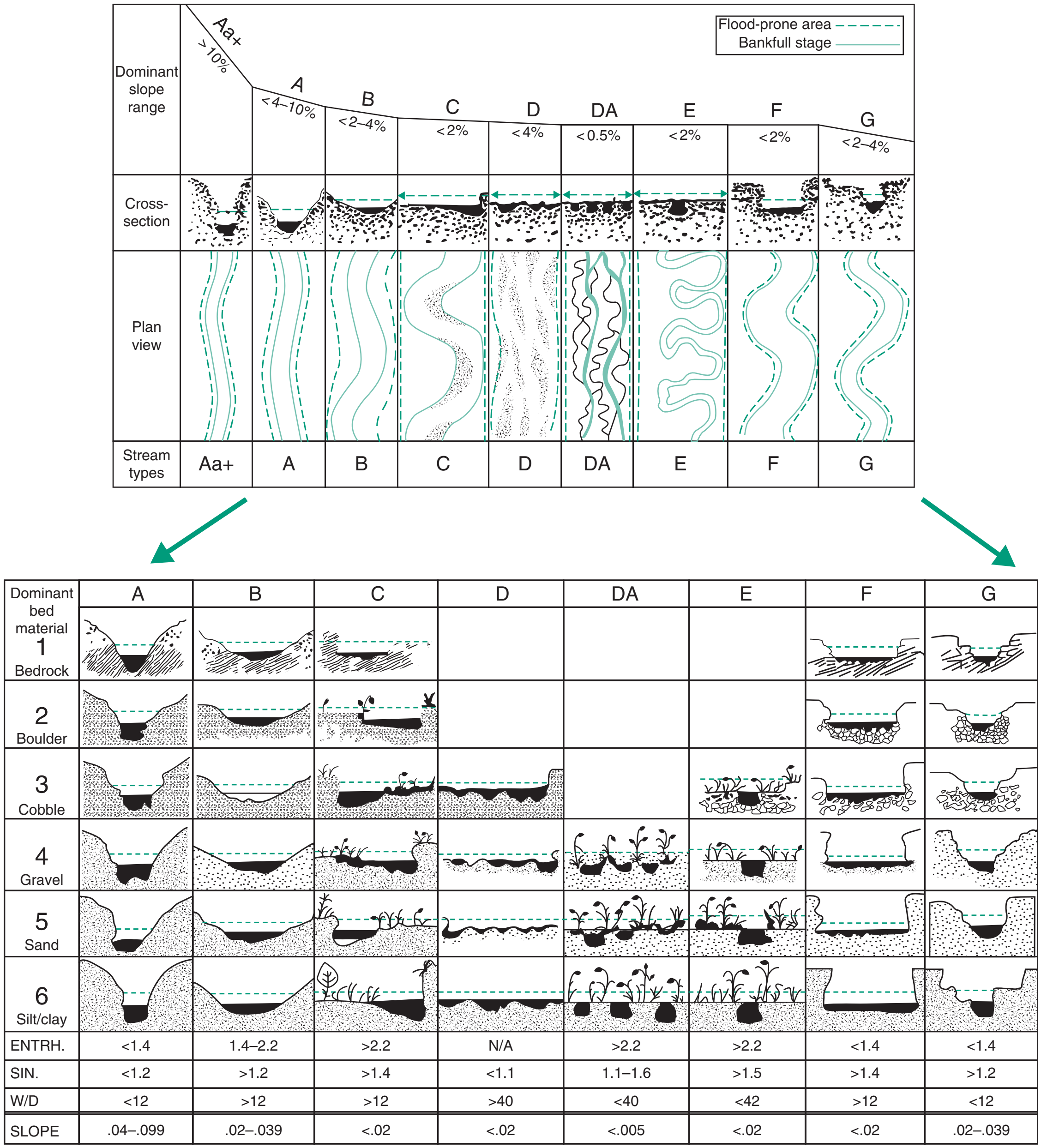

FIGURE 8.16 Wetlands often occur in association with rivers and streams. Nine types can be recognized based upon geomorphology and relief (Aa+ to G). (From Rosgen 1994.)

As humans increasingly dominate landscapes, their activities become an overriding effect. This is not to say that the six main factors (hydrology, fertility, disturbance, competition, herbivory, and burial) are unimportant, but that each of these is itself driven by human activity. Wetland managers may be trying to manipulate one or more of these factors, but human population density is the real driver.

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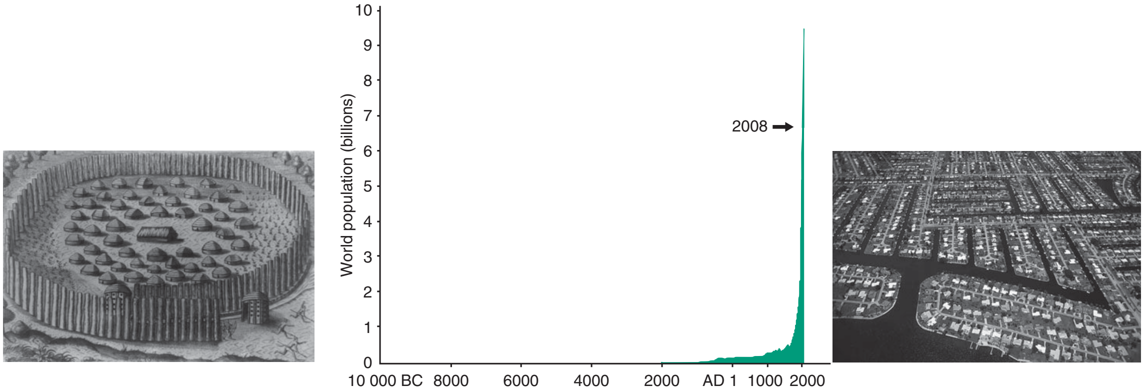

FIGURE 8.17 The size of the human population is an important causal factor that drives many other environmental factors including levee construction, drainage for agriculture, and road construction. Actual population shown as of December 31, 2008 and projected estimates shown to 2050. (Based on data from the U.S. Census Bureau.)

As an example of this, let us turn to one of the world's most densely populated regions, the delta of the mighty Ganges River in Bangladesh. The Ganges River, one of India's best-known rivers, has built a delta with sediment carried downstream from glaciers in the Himalayas. It intersects with a second river, the Brahmaputra, which drains the Tibetan plateau.

Most of Bangladesh is one large delta. It is home to more than 150 million people – about 25 times the population of Louisiana. Yet the land area is almost identical to Louisiana, making it one of the most densely populated countries in the world. A human population of this size is bound to have negative effects on the landscape under the best of conditions. Since most of the area is delta, about one-third of the country floods each year during the rainy season.

The original delta was fringed with enormous mangrove swamps. The original state of the delta was likely similar to the Sundarbans, which are said to be the largest remaining piece of estuarine mangrove forest in the world (Figure 8.18). This area is probably best known for its population of Bengal tigers. Part of the Sundarbans occurs in the Indian state of West Bengal, where it is called Sundarbans National Park (ca. 1300 km^2) while in Bangladesh there are three separate wildlife sanctuaries totaling *ca.* 139 700 ha. The birds include storks, ibis, herons, ducks, and eagles. There are also freshwater crocodiles and dolphins. So important is this area for wildlife conservation that it is also designated as a UNESCO World Heritage Site and a Ramsar site.

Much of the natural coastal vegetation has been altered by logging and agriculture. The delta was once a vast magrove swamp of some 20 000 km^2, complete with animals like Bengal tigers. First settled around 1770, this former mangrove swamp now has a population in excess of 4 million people. The forests were logged, and the land converted to farmland for crops like rice. Saltwater intrusion is causing reduced agricultural production and affecting drinking water supplies. As the land has increased in salinity, rice farmers have converted to shrimp production. The combination of an increasing population with a shrinking land mass seems to be a recipe for distaster.

The current situation along the coast was described in an interview reported in the *Guardian Weekly* (McDougall 2008), with Gita Pandhar, a 25-year-old woman:

When I was young, this was all rice-fields and herds of cows. It was beautiful, a wonderful place to grow up, in isolation away from the mainland. The farmland my grandfather first

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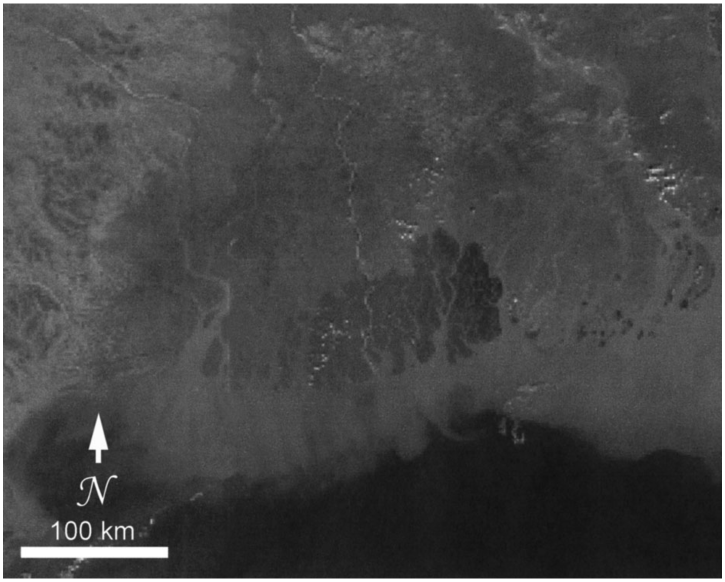

FIGURE 8.18 The Sundarbans, the world's largest mangrove swamp, occur largely in one of the most densely populated areas in the world, Bangladesh. Note the abrupt boundary where the wetland is not protected from exploitation, and note the sediment plumes coming out of the Ganges River. (From Earth Observing System, NASA.) (See also color plate.)

tended is now poisoned with salt. All the arable land has been replaced by swamp. We used to burn dung as fuel, but there is nowhere to graze and now we have to cut the last of the wood here to cook with.

The flood problems in this delta are often reported in connection with global warming, but many factors have to be considered. Deforestation of the Himalayas may have increased flooding and the load of silt. Dams upsteam in India have changed the hydrology of the rivers. Levees, when built, interfere with sedimentation, and trap water during heavy rains. Human population density is very high, and lack of planning allows people to live in highly flood-prone areas. Melting glaciers do appear to have increased runoff, at least temporarily, though once the ice has melted, river flows may then decrease. Overall, flood records show that the height of the average spring flood is decreasing, while simultaneously the occasional flood peaks are increasing (that is, decreased mean with increased variance). Of course, all of these issues may be secondary to the most basic fact that deltas are unstable landscapes. River courses in deltas naturally shift during flood pulses and hurricanes, eroding some areas while building new areas.

Typically, structural solutions are being implemented. Hundreds of kilometers of embankment are being strengthened, accompanied by drainage sluices to allow better drainage from the impounded areas (Agrawala *et al.* 2003). Drainage is being improved, with new bridges and culverts on rural roads. Mangroves are being replanted. New proposed expenditures are in the billions of dollars for projects ranging from hurricane shelters to river "erosion control." Here is how the OECD study summarized the situation:

The huge sediment loads brought by these Himalayan rivers, coupled with a negligible flow gradient add to drainage congestion problems and exacerbate the extent of flooding. The low coastal topography contributes to coastal inundation and saline intrusion inland. Bangladesh also lies in a very active cyclone corridor that transects the Bay of Bengal. The societal exposure to such risks is further enhanced by its very high population and population density, with close to 800 persons per square kilometer in vulnerable areas such as the coastal zones. (p. 49)

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In 2007, Cyclone Sidr hit Bangladesh and killed over 3000 people. To what do we attribute this? Natural deltaic processes? Overpopulation? Lack of land use planning? Deforestation in the mountains? Dams upstream? Global warming? Rising sea levels? Increasingly, the task of managing wetlands will be difficult to separate from managing human societies.

CONCLUSION

Both the type of wetland, and the composition of the species, are a consequence of many environmental factors acting simultaneously (Section 1.7). Some of these factors are likely more important than others. In Chapters 1 to 8, we have looked systematically at these causal factors, starting with those that are generally most important. Of course, there are factors beyond those discussed here (Section 1.7.2). We might profitably add sections on mutualism, or calcium, or warfare, or heavy metals, or exotic species, or off-road vehicles, as six examples. Each of these may be important in certain locations. We have to stop somewhere. We could also observe that human population growth is an overriding factor that controls many of the factors we have discussed here. Having now covered the essential factors that are generally important around the world, you have the background to explore any specific wetland you encounter. Often your work may involve deciding which factors are currently most important in influencing a wetland, and which are having positive or negative effects. Starting with hydrology, fertility, and disturbance will usually be helpful. You now have a shopping list.

We could say that the general purpose of wetland ecology is to determine which causal factors determine which consequences. We are now going to change focus and begin to explore just what kinds of biological consequences arise from these causal factors. That is, we are going to move from factors that cause events to factors that are consequences of events. Another way of describing this is a change from independent variables to dependent variables. The consequences, or the dependent variables, include diversity, productivity, and ecosystem services.

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