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Obstacles to Clear Thinking about Natural Disasters: Five Lessons for Policy

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Popular and policy misperceptions of disasters arise from three key concerns: social choices "Jeopardizing Assets that are Remote" (JAR) in time and space; failures to distinguish between the likelihood of disastrous events and the magnitude of loss experience; and the location of critical activities in the riskiest geographic areas. Rules of thumb utilized by disaster planners and private actors too often ignore costly externalities. Lessons to be drawn from past experience with floods, earthquakes, wildfires, and insect infestations involve, among other elements: distinctions between occurrences and losses; problematic assumptions regarding the applicability of conventional probability distributions, thus ignoring "fat tails" and underestimating worst-calamity likelihoods; and the necessity of distinguishing between "noxious" and "amenity" risks.

1. Introduction

Hurricane Katrina drew increased attention to natural disasters and natural disaster planning in the United States. Katrina was particularly extreme. Yet, on average, losses from natural disasters in the United States and worldwide have been increasing exponentially since 1960 (Cutter and Emrich, 2005; Munich Re, 2005). This rise has continued despite growing scientific understanding, policy attention, and investment in protection.

Natural disasters impose major losses, often abetted by humans. We take actions, such as building in a floodplain, that compound losses when a disaster occurs. Advance measures to curb devastation often go untaken. Why are we so poor

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at dealing with disasters? This chapter identifies three obstacles that hinder the adoption of prevention and preparation policies that could bring down disaster costs in the future. First, we often undertake actions that increase the risk of a disaster or magnify disaster losses at a faraway location or at some point in the future. We call these "JARring actions," actions that Jeopardize Assets that are Remote, whether in time, distance, or likelihood of occurrence (Kousky and Zeckhauser, 2006). We often fail to recognize JARring actions, and when we do, traditional approaches only poorly control these negative externalities. Second, many natural disasters are characterized by "fat tails," meaning that the probability distribution for losses has a thick right-hand tail. That is, very extreme events can and will occur. People regularly fail to recognize this, and so underestimate future consequences from disasters. Third, businesses and residents often choose to locate in areas known to be risky, putting themselves at risk, often at subsequent public expense.

As definitions vary, we will take the approach of David Alexander (1997:290–91) and define a natural disaster as "a rapid, sustained, or profound impact of the geophysical world upon human lives and socio-economic means of support." The second section of this chapter examines four particular natural disasters—floods, earthquakes, wildfires, and pine beetle infestations—through the lens of JARring actions, the distributions of losses, and locational choices. These four examples provide the context for the third section, which presents five lessons for natural disaster planning in the United States. Section 4 concludes.

2. Natural Disasters

Floods, earthquakes, wildfires, and pine beetle infestations vary on many dimensions, such as the amount of warning society has before an incident, the geographic areas at risk, and the extent of our knowledge regarding their underlying causes. Despite the differences among these cases, however, people make similar mistakes in thinking about these disasters, often leading to substantially suboptimal policies.[1]

2.1. Floods

Floods account for one-third of disasters worldwide and half of disaster-related fatalities (Berz, 2000). In the United States during the 20th century, floods were the natural disaster responsible for the highest number of lives lost and the most property damage (Perry, 2000). Floods often affect small areas, but severe floods on the Missouri and Mississippi Rivers can affect a major portion of the country (see, for example, John Barry's excellent book on the flood of 1927 [1997]). For example, the 1993 flood in the upper Mississippi-Missouri basin, one of the worst in the nation's history, flooded twenty million acres in nine states. Fifteen million acres of farmland were inundated, with the river depositing sand, mud, and silt over the land. At least 10,000 homes were destroyed, tens of thousands of people evacuated, and seventy-five towns put completely under water (Larson, 1996). Many levees failed during the event—forty of the 229 federal levees and 1,043 of 1,347 nonfederal ones (NOAA, 2003).

The most deadly flood in US history occurred in 1889, when 2,200 people in Johnstown, Pennsylvania, lost their lives.[2] Since then, the installation of warning systems and other protective measures have substantially reduced the number of lives lost to floods, but not the damage. This disparity in patterns, between decreases in lives lost and increases in property lost, is a worldwide phenomenon. An examination of worldwide flood data since 1950 reveals that economic losses from floods have increased significantly over time (Berz, 2000). The increase in losses can be attributed to multiple factors, including increased development and population density in risky locations, and environmental changes. Tentative findings suggest that climate change will intensify the water cycle and contribute to increased flooding in the future (Milly, Wetherald, et al., 2002).

Construction of levees for flood control in the United States was well underway by the 1800s,[3] but federal involvement in structural projects expanded significantly with the Flood Control Act of 1936. The Army Corps of Engineers has spent over $23 billion on flood control projects (GAO, 1995), most of them structural approaches to controlling floods like channel alteration and levee and floodwall construction. While such structures often prevent flood damage, they impose costs elsewhere. Levees, for example, constrict floodwaters, producing increased flood heights (GAO, *op. cit.*; Faber, 1996; Pinter, 2005).

While the extent of flooding is largely dependent on natural conditions, such as the duration of precipitation and previous ground-saturation levels, human actions in addition to flood control projects affect flood frequency and height. Development in a watershed expands the impervious surface area, increasing the amount of water that runs off the land into streams. Wetlands act as a natural sponge, absorbing floodwaters and slowly releasing them; when they are developed, this natural storage is lost (EPA, 1995). A handful of communities in the US have found it preferable to preserve wetlands for their flood-mitigating capacity. This was done along the Charles River in Massachusetts, the Napa River in Napa, California, and the Truckee River in Reno, Nevada. Protecting wetlands can be less expensive than a structural approach (National Research Council, 2005), and it also provides increased areas for recreation and an aesthetically preferable solution.

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[1] These cases were chosen in part because the authors already had some expertise in them.

[2] Worldwide, the Johnstown flood is nowhere near the most deadly. The deadliest flood on record in the world occurred on the Hwang-Ho River in China in 1931; 3.7 million people died. The second deadliest flood on record occurred on the same river in 1887, when 2 million people lost their lives (Knauer, 2006).

[3] Barry (1997) discusses the political reasons for a de facto "levees only" policy on the Mississippi and analyzes earlier practices on the river.

2.2. Earthquakes

Very minor earthquakes occur often across the world. Larger quakes, which can cause significant loss of both property and life, are much rarer. Ninety percent of the world's earthquakes occur along the Ring of Fire, an area that arcs up the west coast of the United States to Alaska, then crosses over to Asia and moves down the coast to Indonesia (where a major earthquake occurred in the spring of 2006). The Ring of Fire is composed of volcanic arcs and oceanic trenches created by plate tectonics. Along the coast of California, for example, the Pacific plate is slipping beneath the North American plate.

Areas outside the Ring of Fire also face some risk. In the winter of 1811–1812, three earthquakes erupted along the New Madrid Fault in Missouri, with the highest magnitude quake estimated as equivalent to 8.1 on the Richter scale. The earthquakes were so powerful, it is said, they caused church bells to ring as far away as Boston, and the Mississippi River to temporarily reverse course. Fatalities were relatively low, since the area closest to the epicenter was sparsely populated. Today, fifteen million people live in the region; such an event would likely kill hundreds of thousands (Knauer, 2006).

The earthquake that lives in national memory as the most devastating is the San Andreas Fault earthquake that shook San Francisco in 1906. This earthquake, estimated at 7.9 in magnitude, was the deadliest US quake. Fires ignited by the earthquake destroyed most of the city, burning freely for days, as underground water mains had been damaged by the earthquake. Indeed, the larger a given disaster is, the greater the likelihood of other negative outcomes, that is, the correlation between risks increases as the magnitude of disaster increases.[4] While the death-toll was initially put between five hundred and one thousand, scholars now believe the number was significantly higher.[5] City leaders had promulgated the low figure to avoid dampening growth in the area. This imposed silence prevented important mitigating actions from being taken for some time (Steinberg, 2000).

The United States Geological Survey (USGS) and other scientists predict there is a sixty-two percent chance that an earthquake of magnitude 6.7 or greater will hit the San Francisco Bay region before 2032 (Michael, Ross, et al., 2003). This area is densely populated, with a likely gain of 1.4 million residents from 2000 to 2025, with most of them moving to the northern and eastern counties – all areas of significant seismic hazard (*op. cit.*). In the 1980s, the National Security Council examined the expected impact of a major earthquake in California. The scenario for a 7.5 magnitude quake on the Hayward Fault, for example, projects casualties of 1,500 to 4,500 and dramatic damage to infrastructure (Steinbrugge, Lagorio, et al., 1986). A more recent study found that damages from a large earthquake in San Francisco, Los Angeles, or Tokyo would be much larger than previously estimated, with higher fatalities in the California cities (Stanford University News Service, 1996).

Homeowners and firms can use two approaches to reduce losses from earthquakes. The first is to take mitigating actions to increase the likelihood that a building withstands an earthquake, and the second is to purchase insurance (Kunreuther, Doherty, et al., 1992). In many communities at risk for earthquakes, a large proportion of buildings are not built to current levels of seismic resistance (Steinberg, 2000); building codes can be enacted to move the building stock in that direction. Codes mandating mitigating actions that are usually cost-effective can save taxpayers money when the next earthquake occurs, as damage and government relief costs will be reduced. (The government has shown its inability to withhold disaster relief, whatever actions or lack of actions the victims may have taken beforehand.)

2.3. Wildfires

Wildfire policy in the United States reflects a complex mixture of historical experience, mechanical abilities and limits, and political pressures ranging from environmental to industrial timber concerns. Private companies and various government agencies employ multiple strategies to work with wildfire in some circumstances and resist it in others. Policies employed in Yellowstone National Park and its surrounding ecosystem provide a telling case study.

The 1988 wildfires in the Greater Yellowstone Ecosystem (GYE), which includes Yellowstone National Park, several national forests, and surrounding lands, warrant close study for three reasons: (1) these wildfires were the largest in the United States in recent decades (1.2 million acres burned); (2) they received extensive coverage in the news media; and (3) Yellowstone remains central in the formation of wildfire management policy. An extremely large landscape of 2.2 million acres, with resources of considerable biological, historical, and cultural value, Yellowstone stands in the vanguard of experimentation in wildfire management and its associated effects (Barker, 2005). Backtracking through the stages of wildfire management there demonstrates the gross miscalculations by experts as to wildfire's possible scale, speed, and intensity.

Wildfire was largely accepted in Yellowstone and other federally controlled lands by the 1970s as a natural phenomenon and a powerful shaper of landscapes. Policymakers and land managers began to allow lightning-ignited wildfires to burn in wilderness areas and parks, as long as they did not directly threaten public safety or valuable facilities such as Old Faithful geyser or the Mammoth Hot Springs Hotel.

This "natural" wildfire policy came on the heels of the military's quite contrary wildfire suppression activities (Arno and Allison-Bunnell, 2002). The supposition for suppression was simple: the appropriate manpower and machines could

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[4] This is a point made by Robert Hartwig at a conference on risk and disaster following Hurricane Katrina, held in Washington, DC in December 2005, and sponsored by the University of Pennsylvania and its Fels Institute of Government, among others. Daniels, Kettl, and Kunreuther (2006) was published after the event.

[5] The 1906 earthquake does not approach the deadliest twentieth-century earthquake. That distinction goes to a 1976 quake in Tangsan, China that killed 255,000 (Knauer, 2006).

control wildfire. This policy was supported by a massive influx of equipment and men to fight fires in the post-World War II era (surplus bombers and smokejumpers snuffing out wildfires with missionary zeal) (Barker, 2005). Despite the "let-it-burn" era that followed, the suppression policy was a primary force shaping the age and structure of the forests we see today.

Observing the regrowth and evolution of burned-down forests since the post-World War II era has led researchers to ponder the long-term effects wildfire might exert on landscapes. Naturalist and ecologist Aldo Starker Leopold, while teaching at Berkeley in the 1940s, noted a buildup of scrubby undergrowth on managed lands due to wildfire exclusion. At the fifth Biennial Wilderness Conference of 1957, Starker Leopold noted that wildfire was the "one striking exception" that remained absent as an instrument in the preservation of park lands (Barker, 2005). After the issuance of the 1963 Leopold Report, fire was included as a land management strategy in most federal lands in the western US (Arno and Allison-Bunnell, 2002). The Leopold Report's recommendation to include fire as a management tool on federal lands came after nearly a century of wildfire exclusion as national policy.

Yellowstone ecologist Don Despain and others began working on wildfire histories in the 1970s, surmising that some wildfires over the past four centuries burned as many as 50,000 acres (Romme and Despain, 1989). Although Despain's Yellowstone-specific data collection was thorough, it focused on a 300,000-acre area, thereby ignoring data that could have suggested the potential for much larger wildfires. Rather than trying to predict the probability of a wildfire of one million or more acres, researchers automatically assigned that outcome a zero probability. The managers and wildfire experts involved in national wildfire policy research believed a wildfire would burn out as normal rain came, and as it reached areas already burnt over (Barker, 2005).

Meanwhile, Romme and Despain presented their appropriately timed research at the August 14, 1988 meeting of the Ecological Society of America, updating their conservative estimates to include the 200,000 acres burning before their eyes at Yellowstone that year (Barker, 2005). However, even this enlarged estimate gave no indication of the fire that ultimately burned across Yellowstone by the end of the 1988 fire season. Even with ecologists ardently surveying fire history in the area and a natural-fire policy in place, the mere conception of a wildfire on the order of a million acres was never even conjectured.

Eventually, only seven major fires claimed ninety-five percent of the 1.2 million acres burned in Yellowstone in 1988. Five of those fires began outside the boundaries of Yellowstone and three were human-induced. One hundred and twenty million dollars was expended on the firefighting effort, including the use of 25,000 firefighters over the summer months until September snows dampened the last fires.[6] Overall, the strictly direct financial costs of the Yellowstone fires, estimated at $140 million including timber outside the park, significantly underestimate the total impact of burning large tracts of a nationally significant landscape (Barker, 2005). Inestimable damage, such as lost tourism spending, air pollution impacts as far away as the East Coast, and ecological loss, remain uncalculated. Remarkably, only two fire-related fatalities occurred in the firefighting effort; sixty-seven government and private structures burned, and 30,000 acres of timber suitable for harvest were destroyed outside of the park. But the prime loss was that thirty-six percent of Yellowstone's acreage burned.

These costs are relatively minor compared to the immense fire suppression funds approved yearly by Congress ($1.6 billion in 2000) to allay the constant wildfire fears. These funds, and the fire suppression activities they support, could potentially extend the costs of wildfires in the decades ahead. Yellowstone's 1988 wildfire season blasted way beyond previous predictions, surprising even the scientists most attuned to that landscape's wildfire history.

Why did the wildfire ecologists miss the possibility of a million-acre fire? Why was the Yellowstone mega-wildfire event not considered a possibility? Several factors contributed to a gross underestimation of the extreme event's probability. First, within the GYE, no single wildfire had burned more than 25,000 acres in nearly a century (Barker, 2005). Since the 1971 natural wildfire policy was instituted, the largest wildfire in the park had burned only 7,400 acres (Wallace, Singer, et al., 2004; National Interagency Fire Center, 2005). Second, the years from 1950–1970 were particularly uneventful for droughts and wildfires (Romme and Turner, 2004). Even in an expanded time frame, the Little Ice Age (about 1550 to 1850) may have contributed to wetter, cooler climes, and thereby reduced wildfire activity over the period prior to the 20th century (Millspaugh, Whitlock, et al., 2004). Third, an accumulation of undergrowth, decadent older trees, and dead material from years of suppressive wildfire management surely increased the probability of multiple intense, if not large, wildfires. Moreover, the extremely dry conditions that summer of 1988 were beyond the variability expected by all the personnel and experts in the area.

Each of these factors helped shape experts' extremely conservative probability estimates concerning on the possibility of wildfire events. Given the extreme size and intensity of the Yellowstone wildfires of 1988, one would expect that the experts would have drastically adjusted their estimates regarding the severity of wildfires, and that appropriate policy adjustments would have ensued. In fact, wildfire policy became more confounded. Since 1988, most land managers have harked back to a wildfire suppression policy, but others—even given several dangerous wildfires in subsequent years—have continued to fight for prescribed burns and natural wildfires (Barker, 2005). The previously held assumptions about wildfire are reflected on Yellowstone's own website, which notes that ninety-four percent of wildfires there never burn more than 100 acres and eighty-three percent of naturally ignited wildfires never exceed 1.2 acres. These statistics ignore wildfire's extreme variability.

Although wildfire has been accepted as an integral part of landscape management, different policies persist within and across landscapes (Arno and Allison-Bunnell, 2002). The mosaic of prescribed burns, thinning, cutting, and natural

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[6] These figures and other background may be found at Yellowstone's website, via http://www.nps.gov/yell.

wildfires produces a variety of wildfire management strategies from which few overriding principles can be extracted. However, it is clear that contemporary prediction of "normal" conditions (e.g., expected precipitation, winds, and wildfire size) vastly underestimates the possible scale of wildfires, whether natural or human-induced. Ignoring the fat tails of massive losses in Yellowstone represents a particularly poignant example of this underestimation.

2.4. Pine Beetles

Much like wildfires, earthquakes, and floods, the epidemic infestations of mountain pine beetles (MPB [*Dendroctonus ponderosae*]) are caused by a synergistic combination of human-induced effects and natural processes. The habitat of the MPB, an insect endemic in western North America, ranges from British Colombia (BC) to northern Mexico, and from the Pacific Ocean to the Black Hills of South Dakota (Wulder, White, et al., 2006). Increasingly epidemic levels of infestation have catapulted the insect onto the international agenda; huge areas of economically, recreationally, and visually valuable forests in Canada and the United States are at risk, or already infested. The infestation can destroy forests on a regional scale, and simultaneously, greatly increase wildfire hazards through the accumulation of dry wood and plant matter.

Beetle infestations in Canada at the "red-attack" stage (when a tree's foliage color changes and decline toward death begins) increased from around 400,000 acres in 1999 to over twenty-one million acres by the end of 2005 (British Columbia Ministry of Forests and Range, 2006). The acreage lost thus dwarfs that of the 1.2 million acre great Yellowstone fire. In the United States, infestations quadrupled in four years to over two million acres by 2003 (Wulder, White, et al., 2006). The BC infestation is considered the province's worst natural disaster ever, exceeding the beetle infestations of the 1930s by a factor of twenty (Associated Press/ABC News, 2006).[7] Over the next ten years, MPB infestation is expected to destroy eighty percent of the lodgepole pine forest in BC. Why was an infestation of this scale not foreseen?

Perhaps the major condition contributing to the accelerating infestations has been rising temperatures over the past two decades (Logan and Powell, 2005). Milder winters allow a brood to flourish, and warmer summers permit MPB to produce successful populations at higher altitudes. The result is large swaths of beetle-induced tree mortality.

The factor that links all of the elevational and the latitudinal ranges of the infestation is the vast and largely mono-specific stands of lodgepole pine forest (*Pinus contorta* [var. latifolia]). Although beetle infestations and the pines' competing adaptations have been ongoing for millions of years, humans have introduced complicating influences sufficient to overcome the formidable defenses that

have evolved in pines. MPB primarily infests weakened, mature trees. Historically, mature stands were distributed in isolated patches due to frequent disturbances such as wildfires, blowdowns, and previous infestations; today's mature stands are greatly expanded due to the suppression of wildfire and other disturbances (Taylor and Carroll, 2004; Wulder, White, et al., 2006). An expanse of mature lodgepole pines has created a sumptuous buffet for the opportunistic beetle populations. As the MPB infestation spreads, an accumulation of dead trees, paired with warmer temperatures, could further enhance the probability of large wildfires.[8]

As in the wildfire example, the lesson has not been entirely heeded. The US Forest Service's website dedicated to beetle research describes MPB outbreaks in the Rocky Mountains as out of the beetle's "natural range of adaptive variability" (see also Mattson, 1996). While the website's literature recognizes that human management has altered the MPB habitat, it fails to consider whether the MPB outbreaks in the Rocky Mountains should alter our estimates of variability. Since insect and pathogen outbreaks can affect forty-five times the acreage that wildfires do, and exact five times the economic damage, they merit active consideration (Dale, Joyce, et al., 2001). Our persistent and comfortable characterization of wildfire and MPB outbreaks as they relate to normal distributions and nonexistent natural conditions has constrained our predictions. Whether or not the causal factors are created by people, expanding these distributions to fatter-tailed versions, and perhaps those with shifted means (see Lesson 2 below), may help us prepare for future disasters.

3. Five Lessons for Natural Disaster Planning

We often use heuristics and rules of thumb to guide our natural disaster planning and our decisions regarding development in risky locations. For example, we base policies on the hundred-year flood level (i.e., a flood with a one percent annual chance of occurring), or assume that since a large disaster has not occurred in a particular area, one is not going to occur. Rules of thumb such as these lead to suboptimal decisions. Where the stakes are large and the decisions infrequent, it is important to give each one careful analytic consideration.

The four examples above, while dissimilar in some ways, each point to five lessons that can help improve our *ex ante* decision making *vis-à-vis* natural disasters:

- It is useful to distinguish losses from occurrences.
- The magnitudes of losses from natural disasters have fat tails.

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[7] Also see the US Forest Service website on the topic: http://www.usu.edu/beetle/index.htm.

[8] As mentioned earlier, as the magnitude of a disaster increases, the correlation between disasters may increase as well. This is seen here with wildfire and pine beetles. Once there has been a large pine beetle infestation, the chance of a large wildfire increases.

- Planning for the x-year event (a hundred-year event, say, or a thousand-year event) is a mistake.
- Decisions made long before, far away from, or with little apparent connection to a disaster can influence damage.
- We need to recognize the different risk levels associated with different locations.

Lesson 1: It Is Useful to Distinguish Losses from Occurrences

There are two components to losses from a natural disaster. The first is whether or not a natural disaster occurs. The second is the size of the loss if a disaster does occur. All loss distributions involve both components, occurrence and magnitude. Familiar situations where uncertainty plays a role often have only one of the two elements. For peoples' heights, assuredly an uncertain quantity, there is no uncertainty as to whether the event will occur. Each of us has a human height. For basketball free throws, there is no uncertainty as to the magnitude. Each shot counts as one.

With natural disasters, by contrast, both occurrence and magnitude are uncertain. It is helpful to distinguish between them, whether the goal is prediction or mitigation. Society can work to mitigate either dimension of loss—reducing the likelihood of a disaster, or reducing a disaster's likely effect. For example, we can remove debris from a forest to make a wildfire less likely, or we can create firebreaks to reduce the scale of conflagrations. We can locate people out of the floodplain, where the occurrence of a flood is smaller, or we can build levees or raise houses on stilts to reduce the likely damage when a flood does occur.

The distinction between occurrence and magnitude is critical for designing optimal insurance policies. A severe natural disaster could bankrupt an insurance company, suggesting a role for reinsurance, which is insurance for the insurers. The possible uncertainty, regarding both the probability of a disaster occurring and the magnitude of the loss, creates two dimensions for an information asymmetry between the insurer and the reinsurer. The optimal reinsurance policy varies with whether one party has better information on the probability of a loss or the magnitude of that loss (see Cutler and Zeckhauser, 1999).

Lesson 2: Magnitudes of Losses from Natural Disasters Have Fat Tails

The probability distributions of many occurrences that we are familiar with in everyday life follow a normal (bell-shaped) distribution. For example, the distribution of human heights is bell-shaped, as is the number of successful free-throw shots a player makes in basketball. Normal distributions are the mental model many people carry in their heads and engage with when they think about uncertainty in a variety of different settings. They are fundamentally misleading, however, when it comes to low-probability catastrophes, such as natural disasters.

The distribution of losses from natural disasters have much thicker tails than the normal distributions to which we usually expect the world to conform (Helbing, Ammoser, et al., 2005). That is, the magnitude of the damage from a natural disaster, whether acres lost to wildfire, people killed in a terrorist attack, or property damaged from flooding, is highly variable relative to the mean. An extreme event is much more likely than a normal distribution would predict with the same mean and variance.

Power-law distributions, a class with fat tails, have been found to characterize many natural disasters, such as earthquakes, landslides, and wildfires (Guzzetti, Malamud, et al., 2002; Malamud, Millington, et al., 2005). These distributions also fit other activities, such as the distribution of police officers who receive allegations of excessive force, the numbers of homeless, and the magnitude of pollution emissions from vehicles (Gladwell, 2006). Our misuse of normal distributions goes beyond natural disasters.

Data from USGS on the largest and deadliest earthquakes between 1990 and 2005 illustrate earthquakes' fat-tailed distribution of deaths.[9] The highest number of deaths, around 283,100, was from a 9.0-magnitude earthquake off the west coast of northern Sumatra. The second deadliest earthquake, a 7.6-magnitude quake in Pakistan, took just over 80,300 lives. Thus, the deadliest earthquake took 3.5 times as many lives as the second deadliest earthquake. (See Table 5.1.) This is characteristic of a distribution with fat tails; the events in the far-right of the distribution can be really large. Data on the number of acres burned in wildfires also follow this pattern.[10] From 1900 to 2005 the most deadly wildfire in the United States caused about five times as many deaths as the second deadliest, and the deadliest avalanche worldwide caused about 3.3 times as many deaths as the second deadliest (Knauer, 2006). Thick tails imply a chance of staggering losses relative to the worst event seen to date.

Can we use fat-tailed distributions to predict the likely magnitude of the largest disaster we will experience in the next fifty-one years, given data from the previous fifty-one years? (We use an odd number of years to get an unambiguous median.) A simulation offers some insight. Consider a distribution of losses that is known to be both stable over time and lognormal. A lognormal distribution has its logarithm normally distributed, which implies that an outcome twice the mean is as likely as one-half the mean. With the high level of variability in the distributions of natural disasters, there is rarely symmetry in the distribution of the magnitude of the losses. Symmetry in the logarithm of the magnitude of a loss is more plausible.

Moreover, to simplify, there is precisely one loss each period. The variance of the distribution is unknown. However, we do know the ratio of the largest loss to the median loss over the last fifty-one periods. What does that tell us

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[9] See http://earthquake.usgs.gov/regional/world/byyear.php.

[10] See http://www.nifc.gov/stats/historicalstats.html.

Table 5.1. Distributions of Disaster Losses

	Annual US Flood Damage, 1926–2003 ($Millions [Year])	Deadliest Annual Earthquakes, 1990–2006 (Casualties)	US Fires >100,000 Acres, 1997–2005 (Acres)
Highest	16,365 (1993)	No. Sumatra (9.1, 2004) 283,106	Oregon (2002) 499,570
2nd Highest	8,935 (1997)	Pakistan (7.6, 2005) 80,361	Arizona (2002) 468,638
Median	306	5,530	170,046
Mean	1378	30,291	206,742
Highest to Median (Ratio)	53.6	51.2	2.9

Sources: Pielke, Jr., Downton, and Miller 2002 (floods [years are Oct.-Sept. water-years; amounts in current dollars]); USGS Earthquakes Hazard Program, http://neic.usgs.gov/neis/eq_depot/byyear.html (earthquakes); National Interagency Fire Center, http://www.nifc.gov/stats/lrg_fires.html (fires [excludes Alaska]). *Note: With Alaska fire-data included, its massive 2004 fires (Taylor Complex, 1.3 million acres; Eagle Complex, 0.6 million acres) rank highest; then, median is 192,450 acres, mean is 272,545 acres, and ratio highest-to-median is 7.7.*

about the ratio of the largest loss in the next fifty-one years to the largest loss to date? We simulated this problem by running a large number of scenarios with lognormal distributions of losses having varying levels of variability.

We posited a mean of one, and analyzed standard-deviation values from one to two in increments of one-tenth. For each level of standard deviation, we ran fifty samples of 102 periods. For each sample, we computed the largest loss in the first fifty-one periods over the median loss. We then computed the largest loss in the next fifty-one periods and computed how it compared to the largest loss in the first fifty-one periods. We then computed averages for each level of standard deviation. Figure 5.1 shows the results.

How likely is it that we will get a loss in the future much larger than what we have observed to date? A very large maximum loss relative to the median to date, the pattern we see with the specific catastrophes under study, has favorable and unfavorable implications. On the favorable side, it is likely that a high ratio implies that the maximum loss was a high outlier, unlikely to be exceeded,

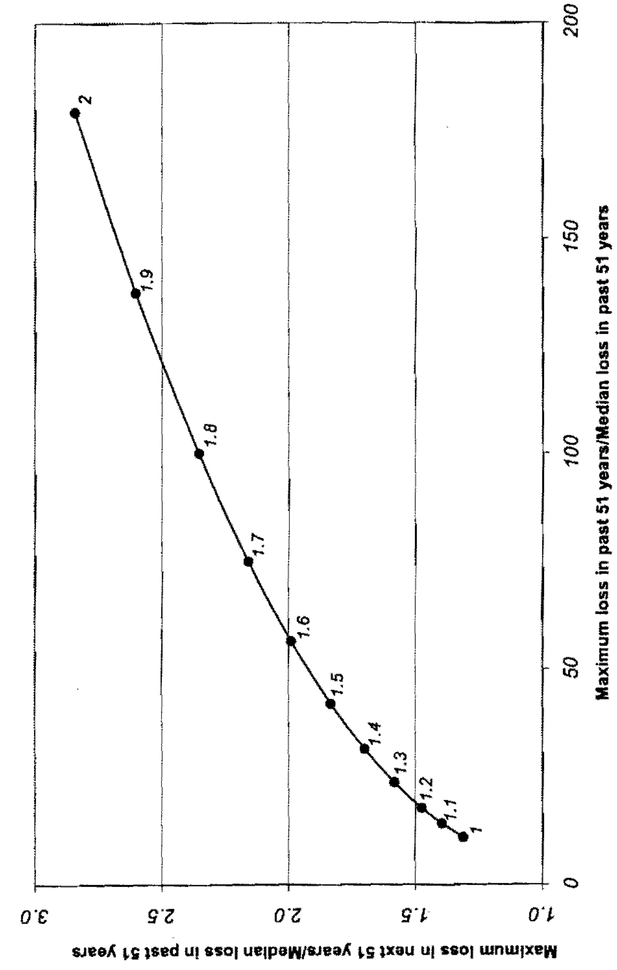

Figure 5.1. Maximum Loss Relative to Past or Median Experience Given the Standard Deviation of Losses (Losses are Lognormal with Mean 1)

Note: Each point represents the average of 50 scenarios for a particular value of sigma. The numbers at points along the curve give the associated value of sigma.

given a specific level of standard deviation. On the unfavorable side, if the standard deviation of losses is not known—and it certainly will not be for natural disasters—a high ratio suggests that the standard deviation is large. That has an unfavorable implication for the greatest future loss relative to the greatest loss to date, as shown in the figure.[11]

It is important to think about the distribution of losses in a manner that can accommodate fat tails. One useful approach is to think of the losses from disasters in terms of multiples. Call the median loss from a given natural disaster M and the mean K. Then we can ask questions such as: what multiple of K is required to have a fifty percent chance of observing a given outcome? And, we can inquire of experts, for what K do they believe the outcome would be as likely as not to be between the ratio M/K and the product KM? For a potentially shifting distribution, expert assessment may be a critical tool for anticipating future disasters.

However, people generally estimate distributions too tightly (Alpert and Raiffa, 1982). A well-known experiment asks people to estimate the quartiles of a distribution, and then the first and ninety-ninth percentiles for known quantities, such as the area of Finland in square miles. If a "surprise" is when the true value is below a respondent's first percentile or above their ninety-ninth, people would be surprised two percent of the time if they accurately assessed their own level of ignorance. In fact, they are surprised *roughly thirty-five percent of the time*, even after they are warned that people make assessments that are substantially too tight.[12] We suspect that if we asked people to guess future events, where the distribution of outcomes has fat tails, this effect would be even more pronounced.

Yet, history demonstrates that extreme events are possible. For example, 640,000 years ago a supervolcano exploded in what is now Yellowstone National Park, depositing ash across the western United States. This volcano put two thousand cubic kilometers of debris in the air. In contrast, Mt. St. Helens ejected one cubic kilometer. Geologists have warned that such an explosion is possible in the future and it would cover half the United States in three feet of ash and rock were it to occur (Knauer, 2006). It would be erroneous to think that since an explosion of such magnitude has not happened in our lifetime, or even human memory, it is not possible. In this case, there is little that we could do to plan for such an event, and we probably should not if it were expected to happen even once in 100,000 years.[13] But many serious natural disasters considered in this essay occur perhaps once in 100 years or less, which makes forethought and forward planning worthwhile.

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[11] Future work will treat this problem in a Bayesian decision framework, with a prior distribution on the standard deviation that gets updated by observing the ratio of the maximum to the median loss.

[12] Zeckhauser has conducted this experiment in his classroom for thirty-five years, and has found roughly thirty-five percent surprises on average.

[13] Future science, of course, may be able to predict such events sufficiently far in advance to allow mitigation measures to be taken.

Even at shorter timescales, individuals are poor at learning from experience. If a number of years go by without losses, particularly if people do not see the risk factors, such as how dry the forest is, they may forget that losses can be large. The inability of Yellowstone ecologists to recognize the possibility of a large-scale fire, as discussed above, is an example of erroneously believing that fat tails do not exist. Yet disasters will occur, and we know from empirical findings that most losses will be incurred in the rare situation where losses are extreme. For example, on September 11, 2001, we lost more Americans to terrorism than had been killed that way to date. However, it should not be surprising if some terrorist event in the future produced many times that number of deaths. That is the implication of a fat-tailed distribution.

When a disaster has not occurred for some time, however, people tend to think it is less and less likely. This failure to remember low-probability events, or surprises, extends to other types of disasters as well. Nassim Taleb, in his *New York Times* bestseller *Fooled by Randomness* (2005), discusses how traders often lack an appreciation for the possibility of the extreme event. He writes, "I associate rare events with any misunderstanding of the risks derived from a narrow interpretation of past time series" (Taleb, 2005:94). When we make comments such as, "there hasn't been a terrible flood for years, it must be safe to live here," we are engaging in this misunderstanding. In part this is an example of what Tversky and Kahneman call belief in the law of small numbers (Tversky and Kahneman, 1982). Individuals often view a small sample as representative of the population, in effect, thinking the law of large numbers holds for small numbers as well. This can prevent one from seeing the possibility of an extreme event in the right-hand tail of the distribution.

The explanation for fat tails implicit in this section is that the underlying distributions of losses from natural disasters just have that property. There is a second, quite distinct explanation: the underlying process is changing over time. That is, both its mean and variance are shifting. If that is true, even if the shifts are as likely to be down as well as up, that will substantially fatten the right tail of the distribution. Having people move into flood-prone areas, or undertaking activities that promote global warming, shifts the underlying distributions of losses, and does so in unfavorable directions. A full discussion of shifting distributions and their effects on natural disasters is left to future work.

Lesson 3: Planning for the X-Year Event Is a Mistake

Governments, individuals, and businesses often use rules of thumb when planning for natural disasters. For example, the National Flood Insurance Program requires regulation of activity in the hundred-year floodplain in order for a community to receive insurance. Such rules of thumb may reduce transaction costs, but they ignore both the costs and benefits of disaster protection. This can lead to suboptimal investments in protection, whether it is providing too much protection to an area with a relatively small amount of life and property at risk, or not providing enough protection to areas where damage could be severe.[14]

Instead, protection levels should be chosen by weighing the costs of the protection against the benefits such protection will provide. Confronted with the same threat, the soybean fields of the Midwest do not need the same level of flood protection as the cities along the Mississippi River. The Netherlands has put this principle into practice. Its flood protection was designed after estimating the costs of providing flood protection and the benefits such protection would provide. Less densely developed areas, which would suffer lower losses from flooding, receive less protection (Vrijling, 2001). Furthermore, when increased development puts more assets at risk, the level of protection should increase. In effect, given the larger asset base, protection should be provided against less frequent events.

Another problem in planning for the hundred-year (or thousand-year) event is that what constitutes a hundred-year event could be in flux. For example, as economic development takes place in a watershed, the impervious surface area increases and wetlands are filled. Water washes off the land faster and the heights and frequencies of floods increase. Thus, what was a hundred-year flood before development could be a much more frequent occurrence after development. In this way, the occurrence of a catastrophic event can sometimes offer information on the change in the distribution of such events (Zeckhauser, 1995).

As another example, the 2005 hurricane season made many people wonder whether we were entering a new era of more frequent and more intense hurricanes. Warming ocean temperatures may be increasing the frequency or intensity of hurricanes in the North Atlantic (Webster, Holland, et al., 2005; Emanuel, 2006). Warmer winters are changing the pattern of pine beetle outbreaks, as discussed above, possibly increasing infestations. The distribution of losses from hazards could shift as a result of where humans choose to locate. As more people move to coastal areas or the wildland-urban interface (the latter being an area at high risk for wildfires), damage will be higher and more frequent. Disasters could also lead to the opposite shift if an extreme event triggers major investments in protection, making future disasters less likely.

Finally, the occurrence of a disaster could offer no information at all.[15] Determining how much and in what direction we should update our prior estimates of the probability of a disaster in response to new experience and new scientific understanding is a challenging task.

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[14] The interdependence between development and protection levels could create multiple Nash equilibria when private actors invest in a risky location and the government provides protection, due to an ill-behaved benefits function (Kousky, Luttmer, et al., 2006).

[15] Interestingly, the 2006 hurricane season passed without a single hurricane making landfall in the United States (NOAA, 2006b), despite earlier official warnings of high storm-risk (NOAA, 2006a).

Lesson 4: Decisions Made Long Before, Far Away from, or With Little Apparent Connection to a Disaster Can Magnify Risks—If So, They Are JARring Actions

Following a natural disaster there is often extensive analysis of what could have been done differently once the disaster was looming, for example, once the hurricane was on the radar screen. There is often a review of what should have been done after the disaster struck to have reduced its impact. There is generally little discussion of the numerous actions taken before, far away from, or with little apparent connection to a disaster than can increase risk levels or damage given a disaster. (As mentioned, we call these "JARring" actions, those which Jeopardize Assets that are Remote [Kousky and Zeckhauser, 2006]).[16] Instead, people tend to look for local causes to explain events. This is one reason society often misses JARring activities that affect the frequency of disasters or increase the magnitude of damages when they do occur.

JARring actions impose a particular type of negative externality—one in which the cost is imposed on people who are spatially or temporally distant. For example, when private landowners build in a previously undeveloped floodplain, they increase the impervious surface area, leading to higher rates of runoff and an increased risk of flooding. Therefore, when a watershed is developed, the probability of flooding increases even though a flood may not occur for many years. This creates a temporal distance between those undertaking the development and those suffering the impact. In addition, those flooded may not be located close to the developments that increased their flooding risks, creating spatial distance. Finally, dozens of players may be responsible for the development, which would make it hard for the tort liability system to function even if causal links could be inferred.

As another example, the coastal wetlands of Louisiana, which buffer storm surges, are being lost at an alarming rate, as shown in Figure 5.2 (NOAA, 2005). The Louisiana Department of Natural Resources estimates that between 1990 and 2000, 24 square miles of wetland were lost a year—about one football field every 38 minutes.[17] One of the causes is a lack of sediment, which nourishes coastal wetlands. Much of the sediment that previously reached the wetlands was from the Missouri River—the Big Muddy—but now that sediment is trapped by six dams constructed on the river between 1944 and 1963 (Meade, 1995). This consequence of the dams was both unintended and largely unforeseen and, thus, represents the most difficult type of JARring action to curb.

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[16] Oftentimes we fail to recognize JARring actions. Stanley Cavell wrote, "We do not see our hand in what happens, so we call certain events melancholy accidents when they are the inevitabilities of our projects" (quoted in Steinberg, 2006:vii). Ted Steinberg argues that the justification of natural hazards as "acts of God" or "freak nature" prevents us, as a society, from recognizing our own role in such disasters and thus from taking actions that could reduce our vulnerability.

[17] See http://dnr.louisiana.gov/crm/coastalfacts.asp.

Figure 5.2. Louisiana Coast, 1932–2002

Source: Map composited by Alan Berger and Case Brown. Original map sources from Louisiana State University Center for GeoInformatics, National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Office of Coast Survey, Office of Ocean Resources Conservation and Assessment (ORCA), U.S. Geological Survey.

JARring actions contribute to many disasters besides flooding. For example, fire-suppression policies created larger expanses of mature pine for mountain pine beetles to attack. The fire policies were enacted long ago, but their impact is felt today as forests are destroyed by the beetle. Climate change, caused by distant actions, contributes to beetle outbreaks as the insect can now survive through the winter and in higher elevations.

These examples demonstrate some of the difficulties in regulating JARring actions. It is often impossible to calculate the exact change in risk levels from a given action. And after a disaster such as a major flood or pine beetle outbreak, it is difficult to assign responsibility for damage to any particular previous action, such as a particular development or particular policy, given the absence of counterfactuals like "no development" or "no policy." A further problem arises if the actions are undertaken in a different jurisdiction than where the costs are imposed; local governments have a limited ability to control the JARring actions that hurt their constituents. New Orleans cannot regulate land use in Missouri, for example. The ultimate JARring action may be the emission of greenhouse gases that contribute to climate change. Burning fossil fuels imposes a negative externality on future generations (wherever they are located). This temporal distance demonstrates a final difficulty, as the future cannot contract with the present to reduce emissions. While JARring actions will always be difficult to control, we must take steps beyond merely examining local causes and consequences and experimen with new regulatory approaches to minimize these negative impositions at a distance.

Lesson 5: Differences in Locations' Risk Levels Must Be Recognized

We routinely build in areas that are at risk from natural disasters—on shorelines, faults, the bases of volcanoes, steep slopes, and the banks of rivers. In fact much of the increase in damage from natural disasters over the past five decade has occurred because more people have located in harm's way (Cutter and Emrich 2005). Tokyo and San Francisco are two major cities built atop faults; a stron earthquake in either could cause massive loss of property and life. Population along the coast have been increasing around the world. The UN Atlas of th Oceans estimates that forty-four percent of the world's population lives within 15 kilometers of the coast. In the United States since 1970, two thousand homes pe day have been built near the coasts.[18]

Though concrete data are not available, it is believed that throughout th western US, population in the wildland-urban interface (WUI) has been growin with increased wealth and infrastructure. Kennedy (2006) estimates that thirty-nine percent of houses nationwide now reside in the WUI; in California, roughl seven percent of land is in the WUI (a low percentage due to the large amount o desert, mountain, and paved land in the state), but five million houses occup merely that space, and in 2003 alone the area suffered $2 billion in fire losses. In separate assessment, FEMA estimates that three to four million people live i California's WUI and over six million in wildlands. Furthermore, five thousan homes were destroyed by fire in either wildlands or the WUI between 1980 an 1995, three times as many as in the preceding fifteen years.[19] Figure 5.3 shows th population growth rates in states with high risks of wildfire.

Why do people move to areas that are known to be risky? Some people ma not know the risks they face; others may underestimate certain risks. One reaso for this is the availability heuristic—people tend to inflate the risk of dangers o events they can easily recall and discount those they cannot (Tversky and Kahneman, 1973). If it has been several years since the last major flood, hurricane, o other disaster, people may underestimate the likelihood of an event in the futur and overestimate their safety.

Many times, however, the risks are known, but people locate in areas vulnerable to natural disasters to secure other benefits. We label these "amenity risks, risks undertaken because of other benefits that are correlated with the ris

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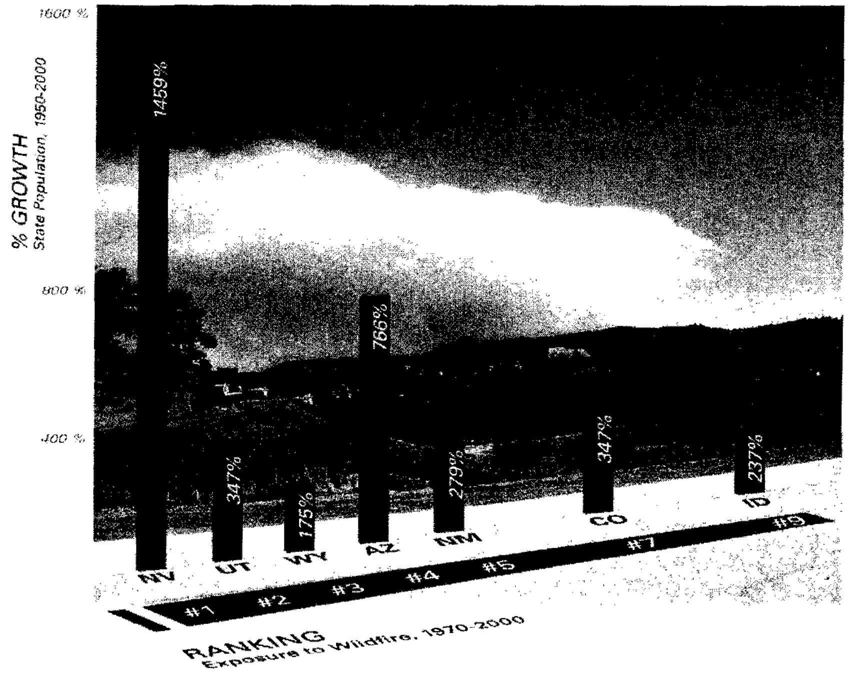
[18] The United Nations Atlas of the Oceans is available online at: http://ww oceansatlas.com.

[19] See http://www.training.fema.gov/EMIWeb/downloads/is111_Unit%207.pdf.

Figure 5.3. State Population Growth by Wildlife Exposure Ranking



Source: Composited by Alan Berger and Case Brown, from U.S. Census, U.S. Forest Service data, photograph by Alan Berger. This figure (its original version with the photograph of Colorado's Hayman Fire burning in the background and the skewed bar graph) also appeared in Roger Kennedy's *Wildfire and Americans: How to Save Lives, Property and Your Tax Dollars*, Hill and Wang, 2006.

(Kousky, Luttmer, et al., 2006). We build on beaches that are threatened by hurricanes because the view of the water and the ability to walk out the door and have sand beneath our feet are worth it to us. We live in San Francisco despite the earthquake risks because of the hilly topography, beautiful bay, and temperate climate the city offers. We build homes at risk of wildfires because we like being surrounded by trees.

Amenity risks should be contrasted with noxious risks, those associated with a location that brings no other benefits apart from a reduction in property values. High crime rates are an example, as is living next to a Superfund site. Such sites are not usually located in especially scenic or otherwise desirable locations and they bring a health risk. Often floodplains in the Midwest are also a noxious risk. As Midwest floodplains do not have the scenic value of coastal areas, they more often are inhabited by poorer households (Steinberg, 2000). Federal disaster aid or subsidized insurance will have different distributional impacts depending on whether the risk is a noxious or amenity risk.

An observed correlation between minority households and pollution—that is, a noxious risk—has been at the center of the environmental justice movement. However, whether minority communities face an injustice is a bit more complicated than the mere correlation would suggest. For example, Spencer Banzhaf and Randall Walsh examine the possibility that a Tiebout-type sorting argument could explain the observed correlation: if, as seems plausible, demand for environmental quality increases with income, lower-income households will locate in areas of lower environmental quality when housing prices are also lower (Banzhaf and Walsh, 2004). Thus, the correlation could be explained by different marginal rates of substitution between income and environmental quality, or noxious risks more generally. That is, lower-income households might trade off a higher risk for lower housing costs.

This raises the question of whether the government has a responsibility to distribute risk, income, or welfare more evenly. If the government cleans up a previously toxic area, housing prices in the community may rise. If many of the residents were poor renters, this leveling of risk levels could force them from their homes as rents rise. Of course, some level of environmental quality, for example safe drinking water, is legitimately considered a human right, regardless of income level. Clearly, this is a deeper philosophical problem and this chapter only raises it as an issue requiring further thought.

4. Conclusion

Society makes mistakes that preclude its enactment of policies that could reduce the rise in disaster-related losses. We fail to distinguish efforts to reduce occurrences from those aimed at lowering the magnitude of losses. We mischaracterize the distributions of disasters, and so are underprepared for extreme events. We focus unduly on the local, the near-term, the likely, and the recently newsworthy at the expense of recognizing the myriad actions, remote from the time and place of a given disaster, that contribute to its likelihood or the magnitude of the losses it imposes. We use rules-of-thumb to guide our decisions instead of properly considering benefits and costs. Finally, we routinely dismiss the risks of locating in certain areas, especially when they come with an amenity we desire, and we fall victim to behavioral biases that lead to us to miscalculate the risks we do consider.

Natural disasters focus the mind, but usually only after they have occurred. While natural disasters will always be with us, sensible planning can significantly reduce their consequences and, sometimes, their frequency and scale. Appropriate incentives can deter JARring actions, such as filling wetlands, and discourage activities, such as building in fire-prone areas, that raise costs when a disaster occurs.

In that way both the scale—how many thousands of trees the pine beetles eat—and the cost of a disaster can be reduced. Equally important, models of natural disasters that recognize the extreme outcomes they can produce will guide us to invest more to trim our losses when the inevitable happens. We will never be able to predict all the consequences of our actions, or overcome all the errors in judgment to which we are susceptible. Despite this, the lessons developed here should lead to policies that reduce both the likelihood and losses from natural disasters.

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