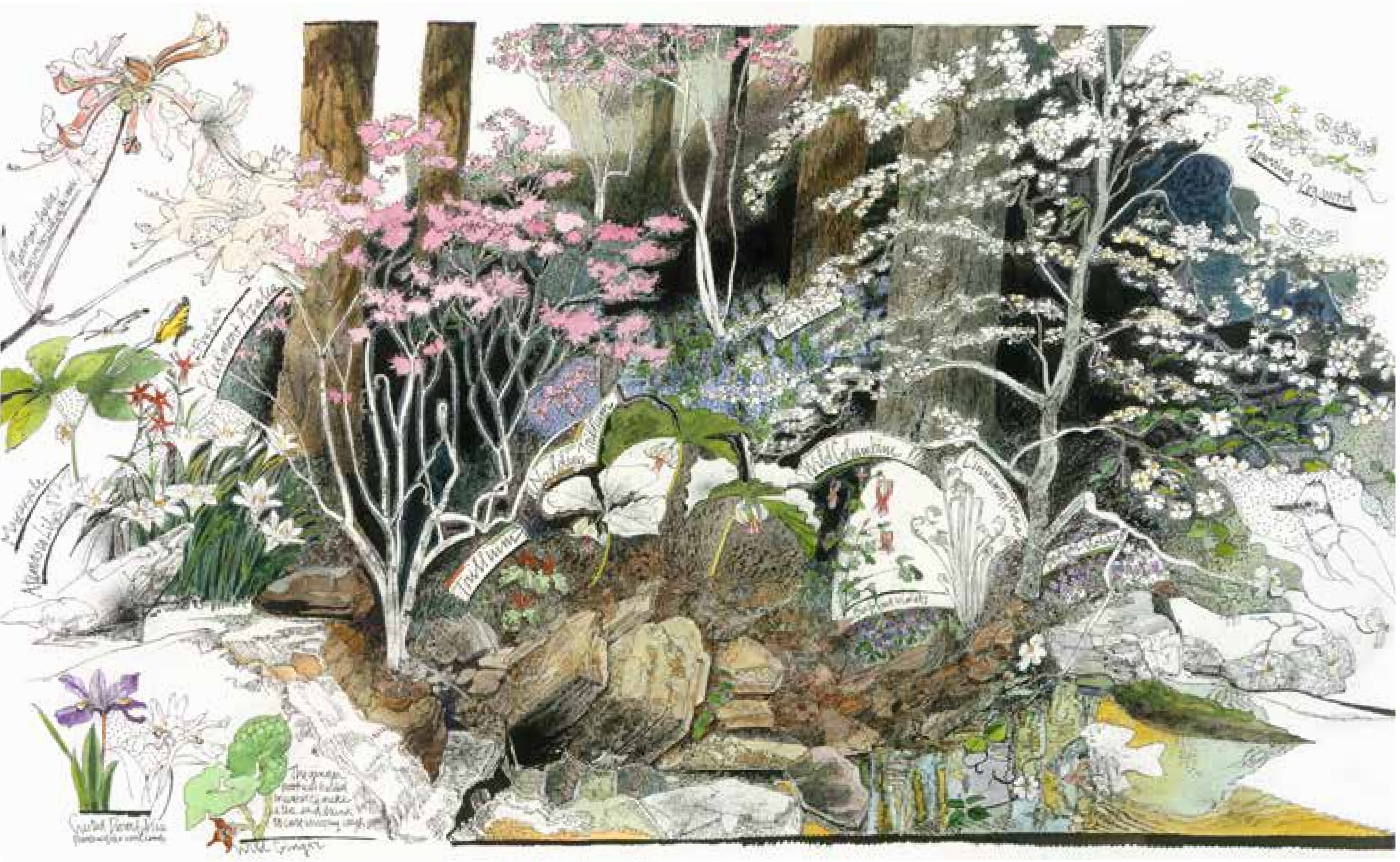


Forests are built on complexity and life takes advantage, from ephemeral wildflowers such as trillium, to flowering head-high azaleas, to towering oaks and pines.

clean water, flood control, and habitat; we turn away from stagnant ponds laced with weedy overgrowth from pollutants, from fatty sheens over dry hardpack. We lament the coastal nutrient pollution that creates dead zones on our waterfronts, driving away fish and sliming our swimming holes. Wetlands are our partners in avoiding those losses. Wetlands, by virtue of their nature—one foot in the water, the other on land—perform functions that we cannot get elsewhere, the critical nexus of life that cleanses some of our sins of pollution. You have to bend over and look closely; the wonders of wetlands occur on the tiniest of scales, but with global implications—and we continue to reap those benefits, as long as we can keep them intact.

FORESTS: REACHING THE LIMITS OF LIFE

> For me, trees have always been the most penetrating preachers. . . . Nothing is holier, nothing is more exemplary than a beautiful, strong tree. When a tree is cut down and reveals its naked death-wound to the sun, one can read its whole history in the luminous, inscribed disk of its trunk: in the rings of its years, its scars, all the struggle, all the suffering, all the sickness, all the happiness and prosperity stand truly written, the narrow years and the luxurious years, the attacks withstood, the storms endured. And every young farmboy knows that the hardest and noblest wood has the narrowest rings, that high on the mountains and in continuing danger the most indestructible, the strongest, the ideal trees grow.
>
> —Hermann Hesse, *Trees: Reflections and Poems*

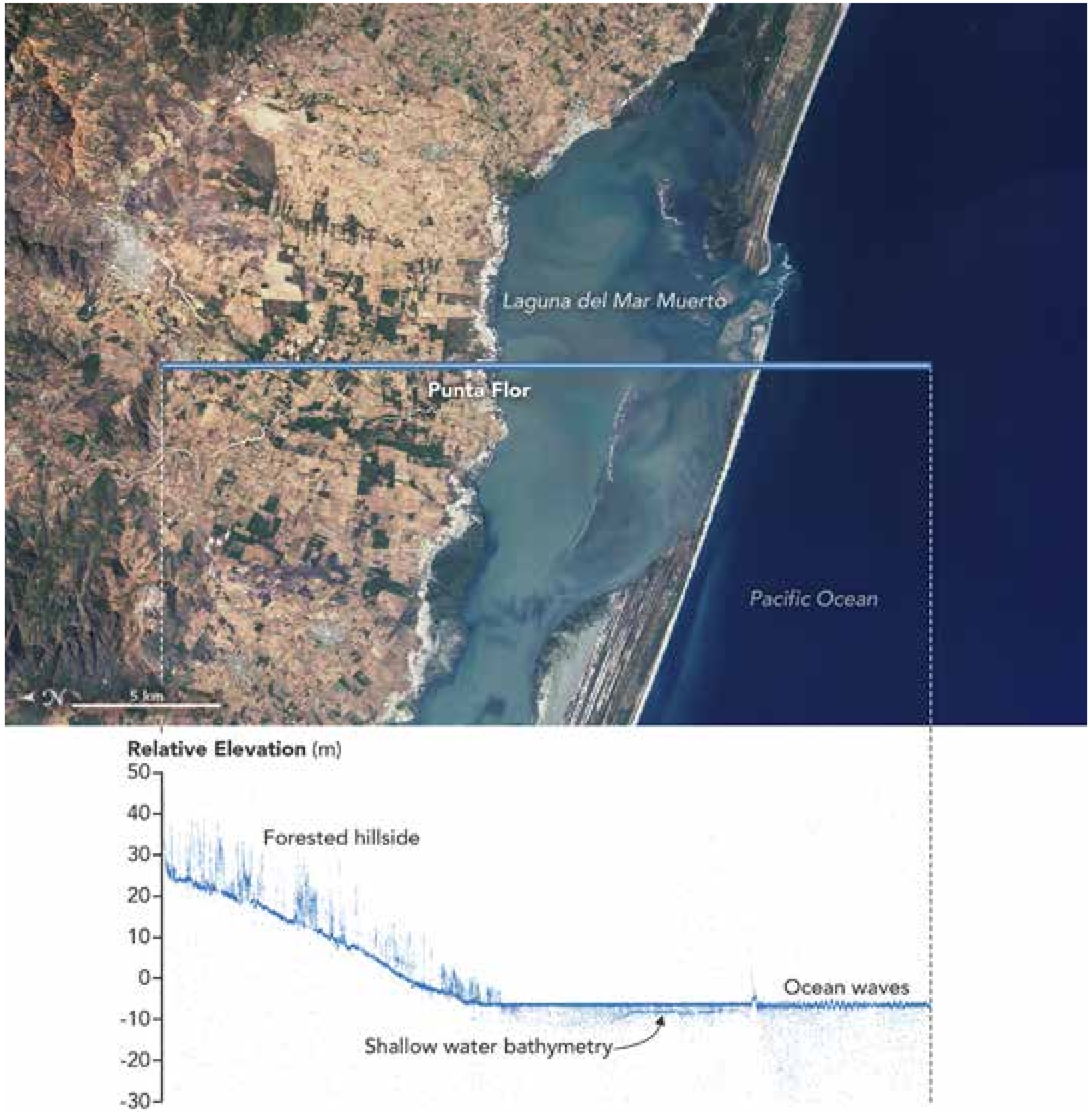
Forested landscapes capture the imagination. From the dark, Big Bad Wolf–infested hills of Bavaria to the dry, cowboy-infested woodlands of Montana, forests have their own character, feel, and temperament. Humans have a special relationship with forests and trees, perhaps spiritually harkening back to our arboreal past and practically a result of the utility of wood, the animals that thrive in trees, and forests' role in the water cycle. They are messy ecosystems: layers and layers of structure, jumbled, leaning, and stretching both up into the sky and down into the soil. The reason they are so biodiverse, so valuable as habitat, is in large part due to this complexity and height. Trees are not necessarily long lived, not in the big scheme of things; some trees can grow and reproduce in as little as a decade. Others last thousands of years, but that is still relatively short in the context of the world. Plants grow on plants (termed "epiphytes") and have a lot of choices in forests—high in the canopy for maximum light, low on the ground for cool shade. Animals are similar; small mammals may spend their entire lives in the canopy, without once touching the dirt. Others burrow among the roots, finding protection in the woody hollows that twist through the upper soil layers. The magic of forests thus comes from complexity, from variability. Growing in nooks and crannies are plants with medicinal value, food value, spiritual value. But the defining attributes of forests, whether in Siberia or Brazil, are their height and structural complexity, the jumble.

FOREST BIOGEOGRAPHY

Forests occupy a particular spot in climatic space. Temperatures have to be warm enough for trees to grow away from the ground (the sun heats the ground surface more than the air, so staying close to the ground means staying warmer in cold landscapes). As mentioned previously, you can more or less approximate global tree line quite well by the 50°F (10°C) summer isotherm, meaning the line around the world where average summer temperatures are at least 50°F. The landscape must also be wet enough for trees to survive. Many trees have deep taproots and are fairly resilient to low-water conditions, but there is a minimum, which is highly species dependent, and early life is the hardest for a seed. But if they get started, trees can be quite tolerant of variable climates.

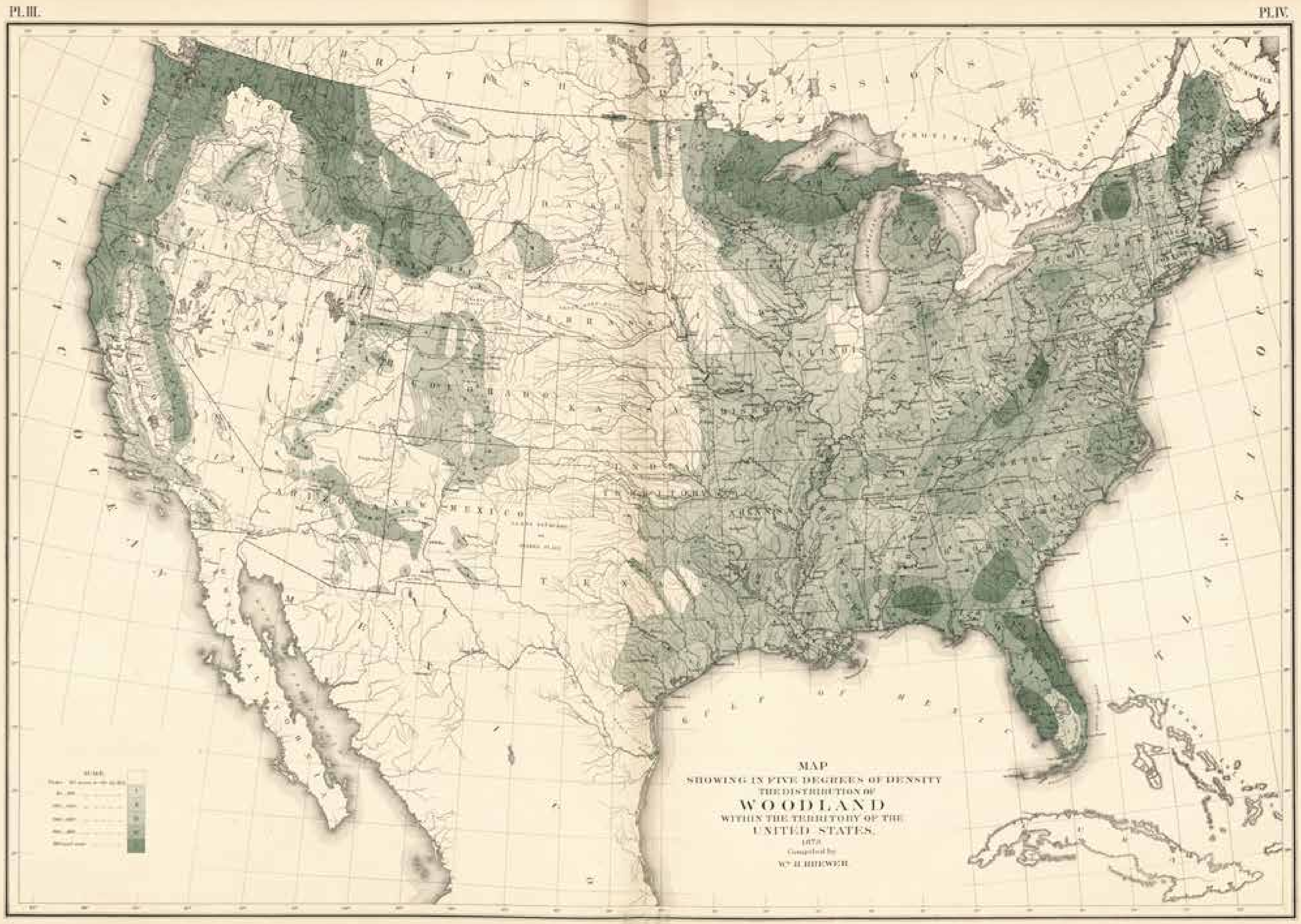
Once established, trees dominate. They shade out grasses and other more height-challenged competitors—that is one of the main reasons to grow tall. It is rare to find a nice lawn underneath a thick canopy. But grass isn't entirely helpless, and early on, grasses are typically much stronger competitors for water than tree seedlings. One-on-one, seed versus seed, grasses will carpet the ground and exclude any trees from infiltrating the soil. If the environment is wet enough, though, that advantage goes away—hence the widespread domination of forests at higher latitudes and the true tropics, where water isn't a limiting factor. But if it is dry or cold (in the summer) enough, trees cannot compete for water and lose out to shrubs or scrub vegetation. Think tundra or desert. However, there is an interesting middle ground, too, in which grasses and trees battle for domination. Here either could dominate, and what you see is the product of what ecologists call exogenous factors, things originating outside the system or just random historical chance.

Coastal forests in Mexico are mapped here in three dimensions from a satellite laser altimeter system. The horizontal line (relative elevation) shows the path of the laser; the lower elevational profile shows the slow descent of the land to the ocean, then the flat level of the sea (plus some waves). The trees are the spikes of higher "elevation" values above the land; sharp changes in forest cover are apparent as the lower profile moves through developed areas en route to the water.

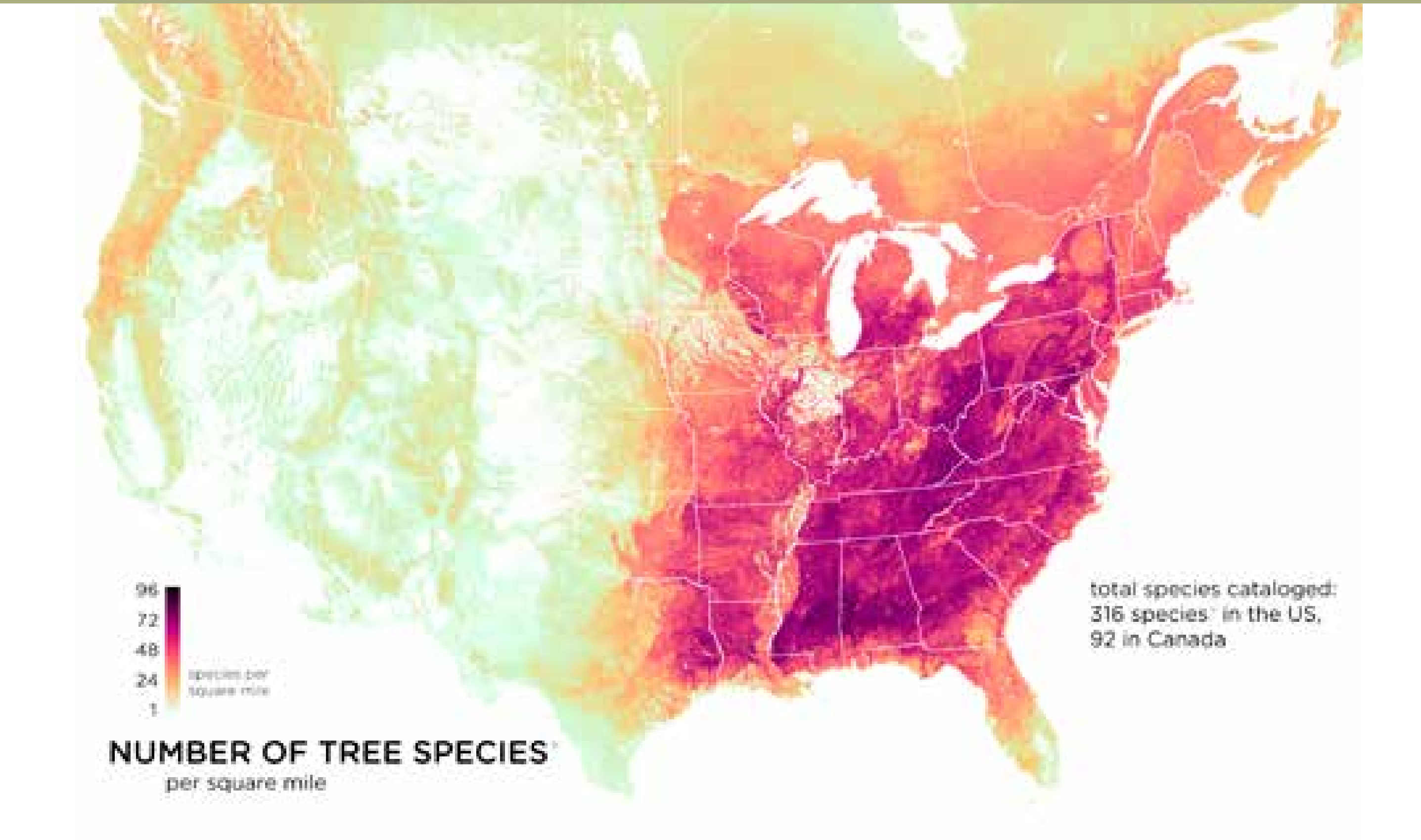


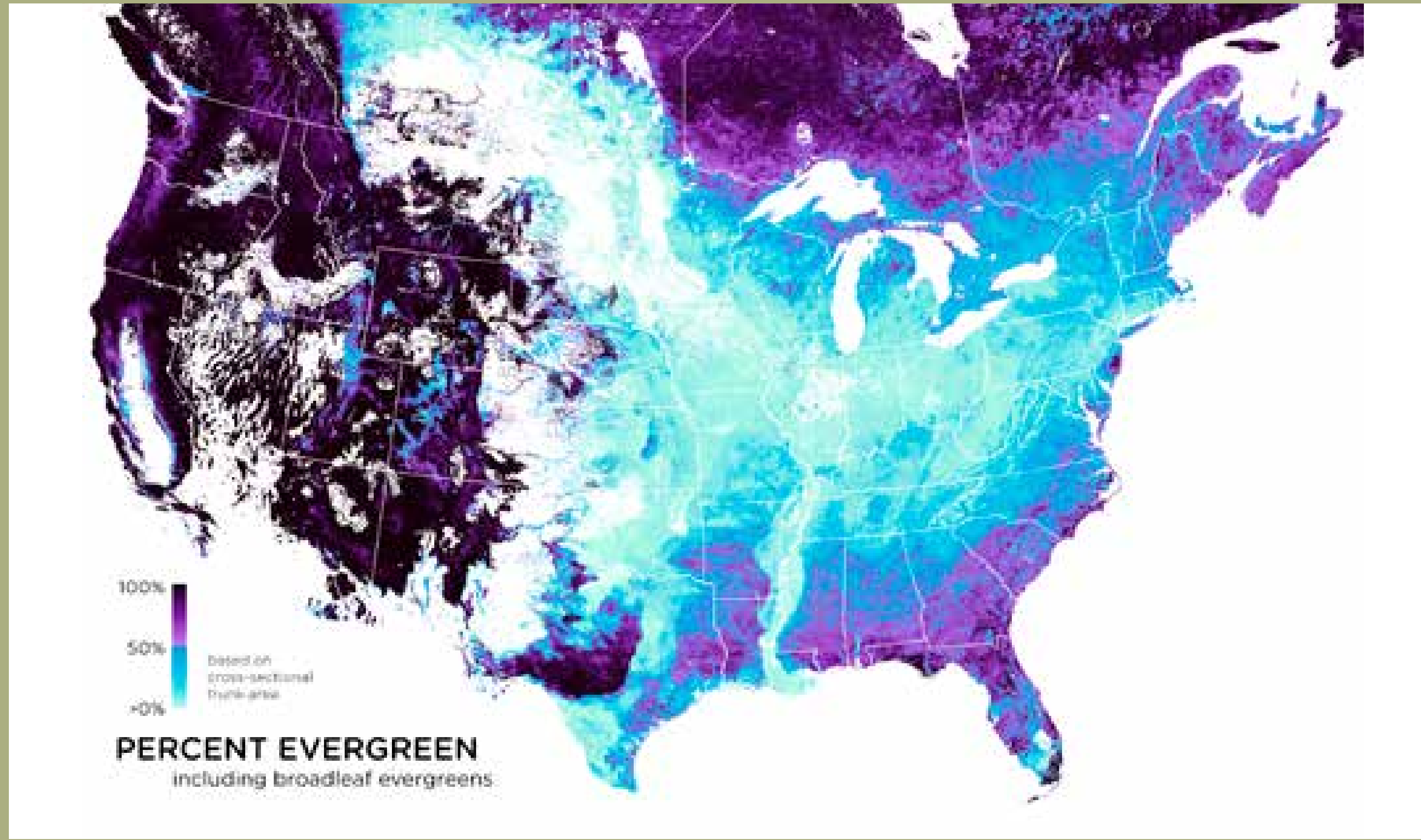
It took more than three thousand years to make some of the trees in these western woods … Through all the wonderful, eventful centuries since Christ's time—and long before that—God has cared for these trees, saved them from drought, disease, avalanches, and a thousand straining, leveling tempests and floods; but he cannot save them from fools.

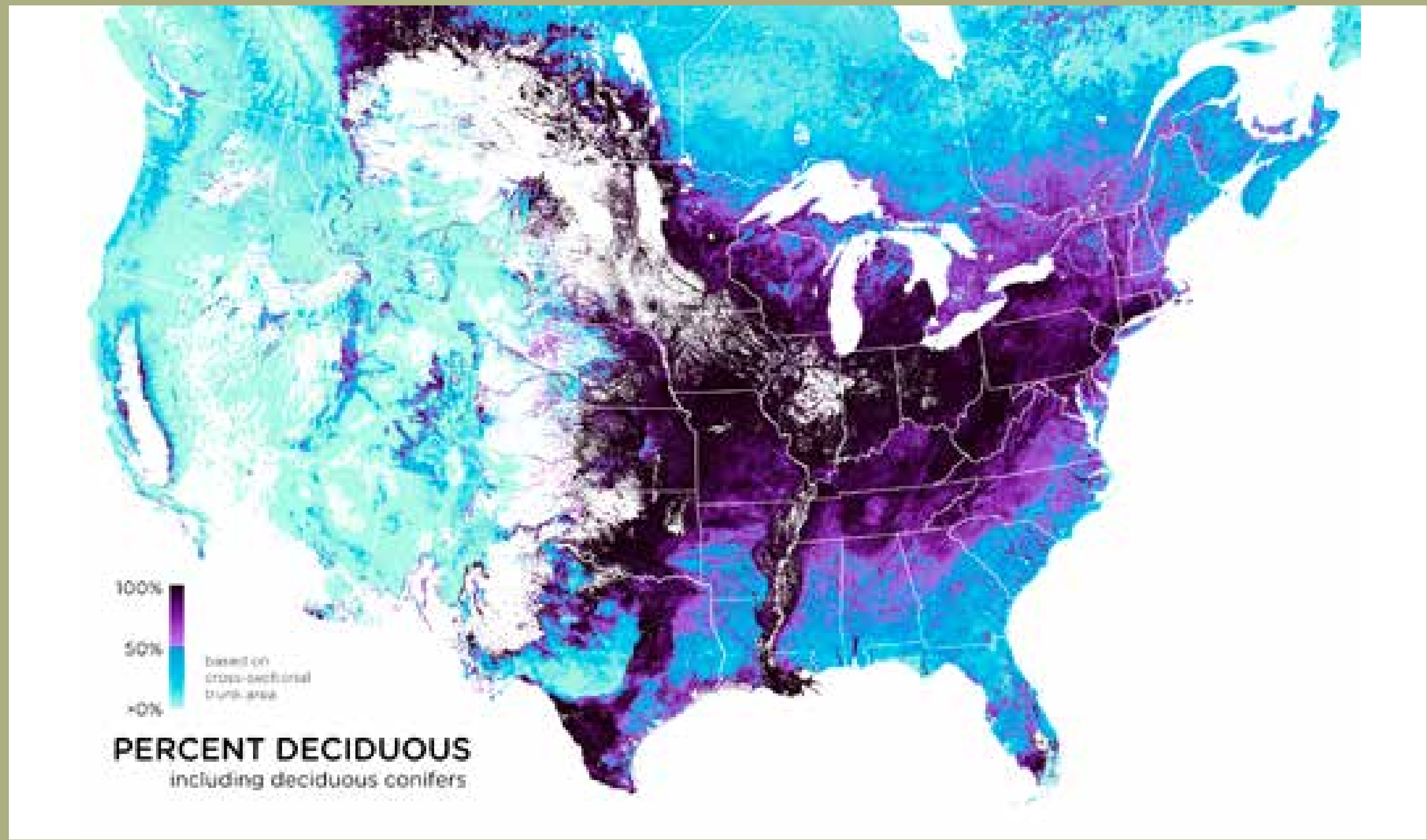
—John Muir,
Our National Parks



Even as early as this 1873 map of forest density (measured as acres of forest per sq. mi., with darker colors indicating denser forests), the deforestation of the northeastern United States for agriculture is apparent, with dense forests limited to upland New York State and Maine.







Forestation Patterns

The forests of North America have a split personality. In the East, there is high diversity and a dominance of broad-leaved, deciduous species. In the West, low-biodiversity conifer forests brave the dry interior and blanket the maritime West Coast. Broad, continental patterns are readily apparent. The floodplain of the Mississippi River, many times as wide as the river itself, guides deciduous trees through the piney fringe along the Gulf Coast—evidence of recent flooding and rich riverine soils, which disfavor conifers. The sudden elevational uptick of the Rocky Mountains means trees can survive in dense forests, unlike the dry, shortgrass steppes just east and below. The folds and "hollers" of the Appalachians (southeast of the Great Lakes) are home to some of the highest tree biodiversity on the continent. Similar but unique; not all forests are created equal, and they are all shifting with climate.

In the case of the African savanna, those factors are wildfires and seed establishment. In that system, wildfires feed on grass, like herds of wildebeests, consuming vast amounts of biomass rapidly. But because grass has a relatively low density, the fires are fast and not particularly destructive. Tree seedlings are killed off, of course, but the grass itself bounces back the next growing season. That means fires can occur every few years with little consequence to the grass, while holding the forest at bay. But if, for whatever reason, there is a gap in the fires for a few decades, you may see a few trees pop above the grass layer. Newly tall, they are less likely to be killed in a low fire and their shade begins to push back the grasses. That reduces the probability of fire a bit (less grass to burn), and more trees can pop up. Eventually, a forest can take over. It's an "alternate stable regime," an entirely different but equally stable ecosystem. Hence, the mosaic of grass and trees that dot the iconic subtropical latitudes of Africa and elsewhere.

There are other considerations—photosynthetic molecular machinery, for example, or wind exposure or soil type, but those are primarily fine-scale factors. The global biogeography of forests can be coarsely described by low-moderate to high water availability and moderate or warmer growing-season temperatures in summer, coupled with the temporal variability of fires. Masters of this pleasantly temperate realm, forests blanket about 30 percent of the planet's land in their thick-covering towers of temporary stability. Perhaps it is no surprise that humans and trees have such a deep bond, seemingly more than just a utilitarian relationship of wood, fiber, and food. Our connection to the woods is a shared link with climate; we like the same things. Their environment is our environment. Their world is our world.

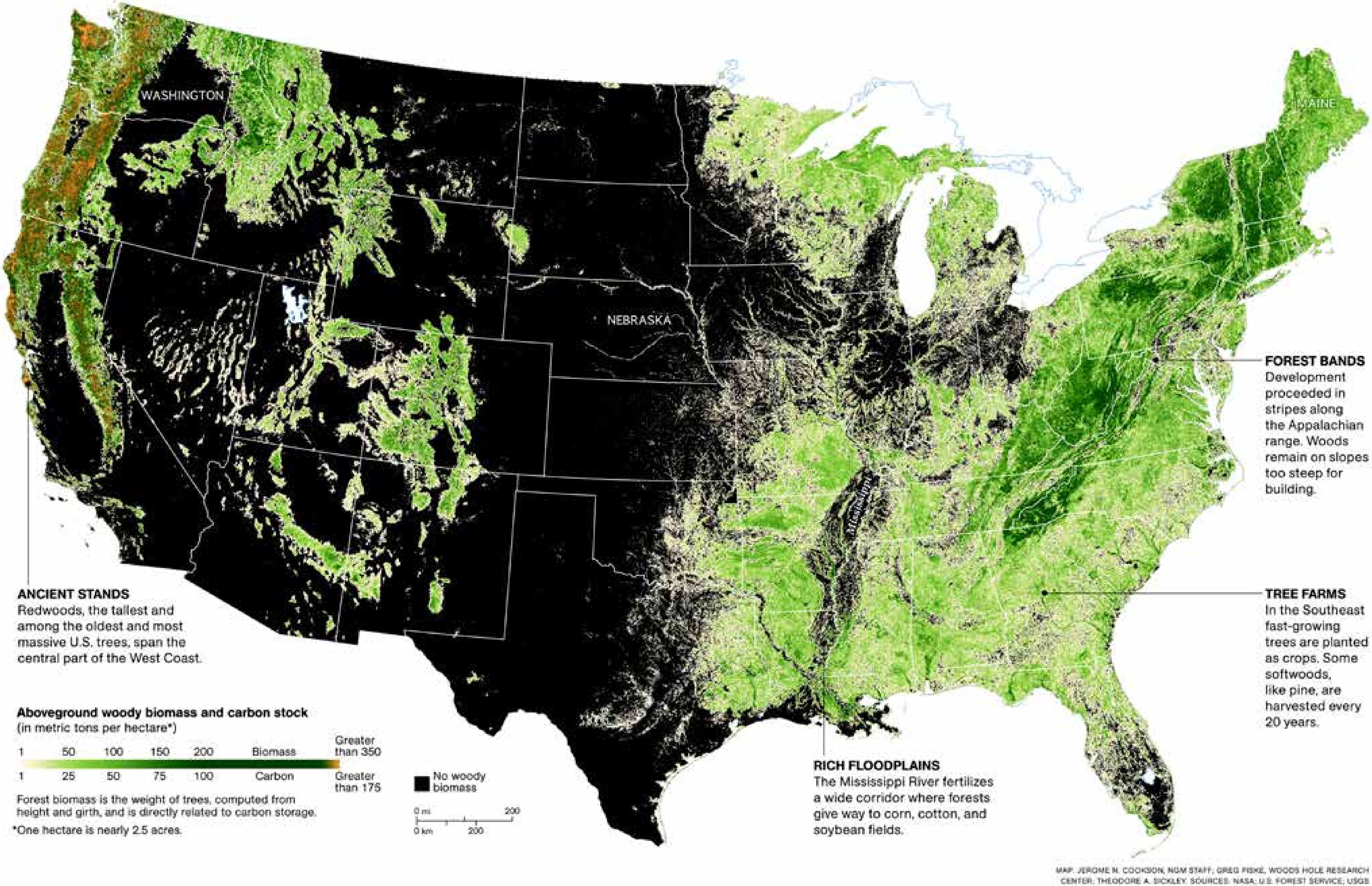
THE DECLINE AND FALL OF THE FOREST EMPIRE

To describe how forests are changing, we need to talk not only about climate but also about human activity and deliberate manipulation. Of all the ecosystems in this book (except the urban system), forests are managed perhaps the most intensively. The origins of forest management depend on the scale of investigation: many argue that there is evidence of intentional promotion of palms in Amazonia in prehistorical times (though the widespread impact is debatable). Tribes in the Pacific Northwest planted crabapple orchards along riversides as gallery forests. And much of western Europe was cleared for agriculture before the fall of the Roman Empire. Fire was an extremely common tool for widespread forest removal and a form of wild agriculture (for example, cultivation of the camas in Washington State). There have been notable achievements in conservation—from the rudimentary Forest Laws of William the Conqueror (not equitable from a human standpoint, but a form of early forest protection) to recent broadscale reserves in Patagonia. Trees are an integral concern of the human enterprise.

Overall, though, the net direction of forest cover change must go either up or down, and it has been downward. Native forest loss has been the story for millennia. Over the last 1000 years, forest area has been reduced by half. The majority of that (about 75 percent) has been in the last 200 years, and in the last 25 years we have lost a little over 3 percent of the total remaining forest area, from 10.1 billion acres (4.1 billion hectares) to just under 10 billion acres (4 billion hectares) remaining. Note that those numbers do not take into account domesticated forests (such as forests maintained for palm production or timber); they only speak to complete loss, such as forest to farmland conversions. The majority of recent forest loss has occurred in the tropics (Brazil, Indonesia, and Myanmar primarily). About 75 percent of this is due to human activity, roughly split between forestry, commodity production, and agricultural clearing. Higher latitudes have actually recorded forest gains over the past few decades; China leads with a net rate of 0.8 percent growth (3.7 million acres or 1.5 million hectares gained) between 2010 and 2015. In the United States, net forest loss stopped relatively early, around 1910, with the establishment of the National Forest System. While individual regions still saw massive destruction of forest ecosystems, and their replacement with industrial, so-called forest agricultural systems, the mass movement of rural populations to urban centers resulted in forest regeneration across wide swaths of formerly cleared land, especially in the Northeast. So while US forests have continued to be industrialized, trees (if not true forests) have gained in area over recent years.

> OVER THE LAST 1000 YEARS, FOREST AREA HAS BEEN REDUCED BY HALF . . . ABOUT 75 PERCENT HAS BEEN IN THE LAST 200 YEARS.

Climate change threatens, however. Being masters of a particular climate space means problems if that climate shifts. From 2011 to 2019, 150 million trees died in California alone due to drought (part of that mortality results from the forests being overly thick due to decades of fire suppression, which led to a higher demand for water that didn't arrive; part of it is increasing temperatures causing more water stress). Insect outbreaks, windstorms, and fires are increasing in frequency and severity; while many forests specialize in fires and fire recovery, no forest can persist with severe fires every decade. Estimates are a 40 percent reduction, or at least simplification, of forests, with a rise in global temperatures of 5.4°F (3°C), which is highly likely in the coming decades. The actual change may lag temperatures a bit—trees are tough creatures—but they are not invincible. And when change happens, it can happen fast.



The legacy of historical harvest, farmland abandonment (resulting in forest recovery in the Northeast), and the new prioritization of forest carbon as an important, ecosystem-based service at the national scale are readily apparent in more recent assessments of forest distributions, such as this one.

Attack of the Mountain Pine Beetles

The mass outbreak of mountain pine beetle in the early 2000s, which can kill multiple species of pines in North America, was unprecedented in scope and extent, spanning from northern British Columbia to the desert mountains of New Mexico. The species is not invasive; it is a native beetle. The beetles kill healthy trees only when the insect's populations get extremely high. A combination of extensive drought, warming winters, hotter summers, and extensive, homogenous forests (caused by humans and wildfires) led to the perfect conditions for an explosion in mountain pine beetle populations. The insect now threatens the jack pines of the boreal (northern) forest, the largest biome on Earth, though the beetles' viability in those systems, and at those densities, is still unknown. As the climate warms, conditions for the beetles will only improve—an example of how climate change can destabilize formerly stable relationships within pristine ecosystems.


PINE BEETLE, ACTUAL SIZE

Death by a Thousand Bites

For centuries the relationship was mutually beneficial: Pine beetles culled older, weaker trees, producing new beetles but also a healthier forest. Climate change, with its warmer, drier conditions, has upset that balance, leaving even healthy trees vulnerable to attack.

FIRST WEEK

Selection and Invasion
The cycle begins in summer, when a lone female beetle bores into a tree's bark and releases a pheromone that attracts hundreds of other beetles.

SECOND WEEK

Burrowing and Egg Laying
Beetles dig galleries under the bark, depositing eggs and blue fungi to feed the next generation. The galleries block nutrient flow in the tree's phloem layer.

THIRD WEEK TO 4 MONTHS

Hatching and Feeding
Larvae hatch and chew side galleries, feeding on the phloem and the fungi.

◂ The tree remains green for months after beetles have fatally mauled it.

5 TO 12 MONTHS

Overwintering and Dispersal
The beetle larvae lie dormant until spring, when they'll turn into pupae, then adults. The new brood feeds on fungal spores before dispersing to another tree.

◂ Needles turn yellow in the dry heat of summer.

13 TO 24 MONTHS

Red Means Dead
The beetles are long gone, and the drying tree turns red. Finally it loses most of its needles and becomes gray.

ILLUMINATING THE MYSTERIES—AND WONDERS—ALL AROUND US EVERY DAY
NATIONAL GEOGRAPHIC VOL. 235 NO. 2

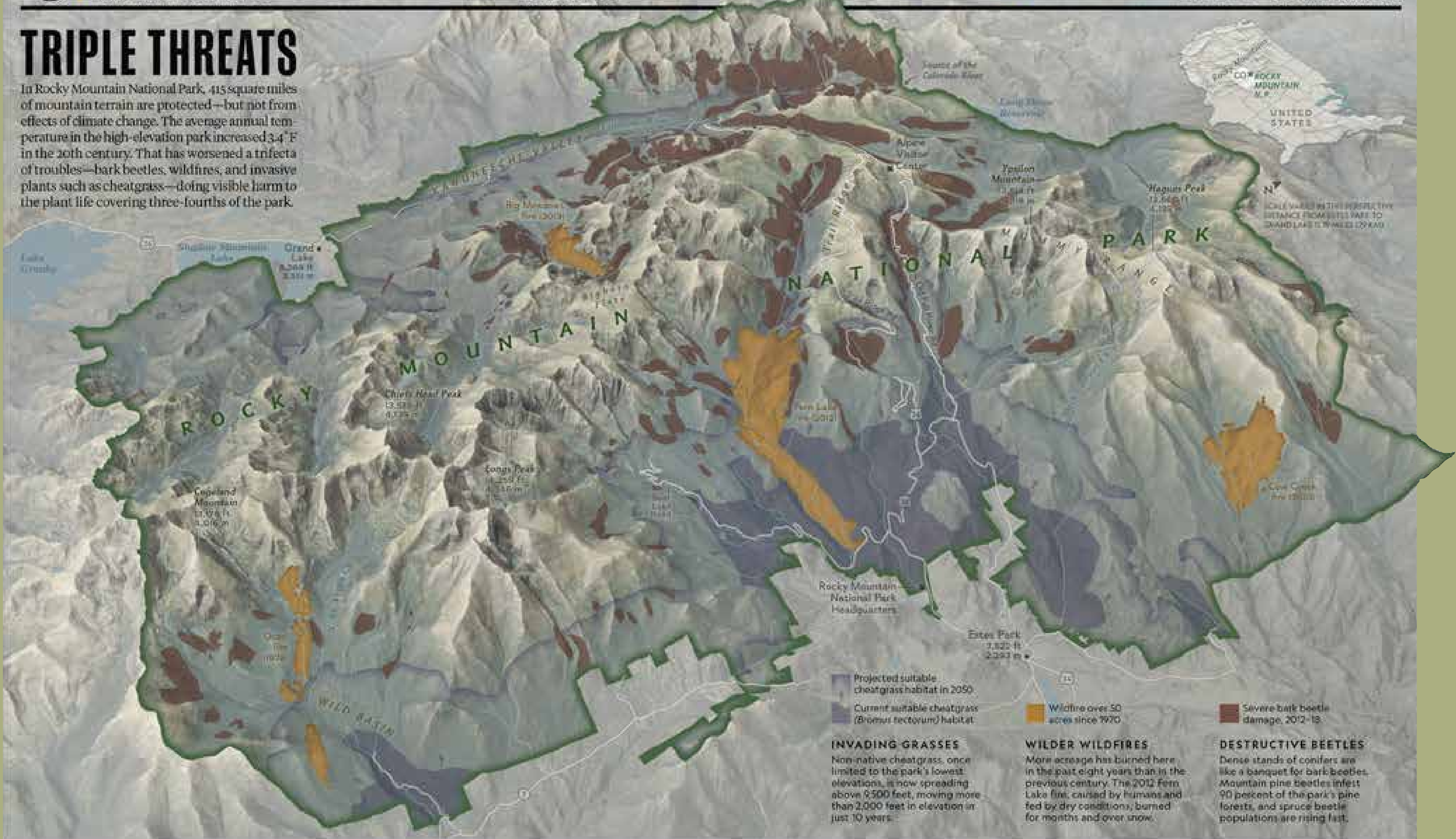
DOMINO EFFECT

Bark beetles, fires, and cheatgrass can play important ecological roles, but climate change exacerbates their effects on one another. For example, cheatgrass thrives when temperatures rise, adding kindling to wildfires that are already more intense due to drier conditions, and fires can spread faster where bark beetles have killed trees.

ATLAS BY **CLARE TRAINOR**

TRIPLE THREATS

In Rocky Mountain National Park, 415 square miles of mountain terrain are protected—but not from effects of climate change. The average annual temperature in the high-elevation park increased 3.4°F in the 20th century. That has worsened a trifecta of troubles—bark beetles, wildfires, and invasive plants such as cheatgrass—doing visible harm to the plant life covering three-fourths of the park.



Projected suitable cheatgrass habitat in 2050

Current suitable cheatgrass (*Bromus tectorum*) habitat

Wildfire over 50 acres since 1970

Severe bark beetle damage, 2012–18

INVADING GRASSES

Non-native cheatgrass, once limited to the park's lowest elevations, is now spreading above 9,500 feet, moving more than 2,000 feet in elevation in just 10 years.

WILDER WILDFIRES

More acreage has burned here in the past eight years than in the previous century. The 2012 Fern Lake fire, caused by humans and fed by dry conditions, burned for months and over snow.

DESTRUCTIVE BEETLES

Dense stands of conifers are like a banquet for bark beetles. Mountain pine beetles infest 90 percent of the park's pine forests, and spruce beetle populations are rising fast.