Tree Mortality, Biome Shifts, and Living Sustainably to Halt Human-Caused Climate Change

Patrick Gonzalez

A dead tree in Africa was the first sign of climate change that I saw in the field. I was in Sénégal in a sparsely inhabited part of the Sahel, a savanna that stretches across Africa south of the Sahara, 31 years ago. I stood at the foot of a tree called *yir* in Wolof; *Prosopis africana* is the scientific name. Normally, *yir* has a moist green crown of leaves but this tree was gray and lifeless. Yet, it had no axe marks, insect tracks, or signs of disease. It was one in a stand of dead trees. In that region, people depend on trees for wood and poles and to protect their fields from wind erosion.

That part of the Sahel has experienced one of the most severe rainfall declines in the global weather station record—a decrease of 27% below pre-industrial levels. I eventually hiked 1,900 km in the Sahel, counted and measured thousands of trees, interviewed hundreds of local people, and analyzed hundreds of aerial photos. The data showed that one of every five trees had died from 1954 to 1989 and one of every three tree species had disappeared locally from ca. 1945 to 1993. Statistical analyses of 215 environmental and socio-economic variables showed that two factors most explained the tree mortality: temperature and rainfall, more than tree cutting or other activity by local people (Gonzalez 2001).

▲ Kàdd (*Acacia albida*) and séng (*Acacia raddiana*) trees, Sénégal, West Africa, in a region where anthropogenic climate change has caused 20% tree mortality (Gonzalez 2001; Gonzalez et al. 2012). PATRICK GONZALEZ

Previous scientific research had attributed increased heat and decreased rainfall in the Sahel to anthropogenic climate change (IPCC 2001). So, my research provided the first scientific documentation of climate change-induced tree mortality in the Sahel. Human-caused climate change had killed those trees. Greenhouse gas emissions from industrial countries halfway around the world killed those trees in Africa.

I worked to help farmers in Sénégal protect small native trees in their fields and raise them in a traditional practice of natural regeneration. My research also gave evidence to international development agencies to change their policies from plantation of exotic species to natural regeneration of native trees.

The research proceeded through two key scientific procedures—detection and attribution. Detection is examining if a change is statistically significantly different from natural variation. Attribution is analyzing the relative weights of anthropogenic climate change and other factors in causing detected changes (IPCC 2014a). The Intergovernmental Panel on Climate Change (IPCC) has comprehensively assessed scientific research for detection and attribution of impacts and found that anthropogenic climate change has caused drought-induced tree mortality in West Africa, North Africa, and the western United States (US) (IPCC 2022a).

As described above, my research in Sénégal found that human-caused climate change had caused mortality of 20% of trees from 1954 to 1989 (Gonzalez 2001). Research that I conducted with colleagues at additional sites in Sénégal found that human-caused climate change caused mortality of 17–18% of trees from 1954 to 2002 (Gonzalez et al. 2012). At a site in Morocco, research found that climate change, more than livestock grazing, caused most of the 45% tree mortality from 1970 to 2007 (le Polain de Waroux and Lambin 2012).

In the US, human-caused climate change doubled tree mortality across the West from 1955 to 2007 (van Mantgem et al. 2009) and increased tree mortality in California forests 25% from 2012 to 2021 (Robbins et

Dead lodgepole pines (*Pinus contorta*), Rocky Mountain National Park, Colorado, in a region where anthropogenic climate change doubled tree mortality, 1955–2007 (van Mantgem et al. 2009). PATRICK GONZALEZ

al. 2022; Wang et al. 2022). Attribution research on the causes of the tree mortality showed that climate change has caused half the severity of a drought across the southwestern US since 2000 that has been the most severe since the 1500s (Williams et al. 2020, 2022), doubled the average annual area burned by wildfire over natural levels across the western US from 1984 to 2015 (Abatzoglou and Williams 2016), tripled the average area burned by wildfire in summer across northern and central California from 1996 to 2021 (Turco et al. 2023), and led to the most extensive bark beetle outbreak in North America in a century (Raffa et al. 2008; Bentz et al. 2010).

Temperature and precipitation differentiate vegetation into biomes—major vegetation zones characterized by a distinctive plant form. For example, in California, increasing temperature with elevation from the Central Valley up to the crest of the Sierra Nevada differentiates vegetation into six biomes: temperate grassland, temperate shrubland, temperate broadleaf woodland (oaks), temperate conifer forest (pines of warmer conditions), subalpine conifer forest (pines of cooler conditions and firs), and alpine grassland. Tree mortality among currently dominant species and recruitment of trees of species more common in adjacent areas can shift geographic ranges of biomes.

Field research has detected biome shifts at numerous sites in tropical, temperate, and boreal ecosystems and attributed them to anthropogenic climate change more than other factors (Gonzalez et al. 2010; IPCC 2014a).

In West Africa, increasing rainfall from northern latitudes to the Equator differentiates vegetation into five biomes: the Sahara Desert; the Sahel, a savanna with singly spaced trees with bi-pinnately compound leaves; the Sudan, a dry woodland in which trees gather into groves and have pinnately compound leaves and dry fruits; Guinea, a closed-canopy tropical deciduous forest with trees that bear moist fruits; and the Congo, a moist evergreen tropical rainforest. My field research across six countries in West Africa revealed that climate change shifted the Sahel, Sudan,

Tuolumne Meadows, Yosemite National Park, California, a site where anthropogenic climate change has caused a biome shift of subalpine forest into high-elevation meadows (Millar et al. 2004). PATRICK GONZALEZ

and Guinea biomes up to 30 km southward from ca. 1945 to 2000, as arid conditions expanded from the north and moister conditions retracted south towards the Equator (Gonzalez 2001; Gonzalez et al. 2012).

Other biome shifts caused by climate change include a shift of subalpine forest into high-elevation meadows in Yosemite National Park, California, from 1880 to 2002 (Millar et al. 2004; Lubetkin et al. 2017); a shift of boreal forest poleward onto formerly treeless tundra in Noatak National Preserve, Alaska, from 1800 to 1980 (Suarez et al. 1999); a shift of temperate broadleaf forest upslope into alpine heathland in the Parc Natural del Montseny, Catalonia, Spain, from 1945 to 2001 (Peñuelas and Boada 2003); and a shift of temperate broadleaf forest upslope into subalpine shrubland in Fjordland National Park, New Zealand, from 1930 to 1990 (Wardle and Coleman 1992).

If we do not cut carbon pollution from cars, power plants, and deforestation, continued climate change could cause more extensive tree death. In the Amazon, climate change of 4°C above pre-industrial levels could cause the conversion of up to half the area of tropical rainforest to non-forest (Salazar and Nobre 2010; Flores et al. 2024). In the southwestern US, climate change of 4°C above pre-industrial levels could cause the death of up to half the trees in conifer forests (McDowell et al. 2016; Buotte et al. 2019; Goulden and Bales 2019).

Coast redwood trees (*Sequoia sempervirens*) are the tallest living beings on Earth, reaching up to a height of 116 m, in Redwood National Park, California (Sillett et al. 2021). Redwoods depend upon coastal fog for moisture during the heat of summer. Climate change of 3°C above pre-industrial levels could reduce suitable climate to half the current range, potentially increasing redwood mortality in an area that includes Muir Woods National Monument (Fernández et al. 2015).

Bristlecone pine trees (*Pinus longaeva*) are the oldest living beings on Earth, growing to over 4,000 years old in the Inyo National Forest, California (Pritchett 2021). Climate change increases the risk of mortality of bristlecone pine trees from bark beetle infestations, to which the trees have been more resistant under cooler conditions (Bentz et al. 2022).

Continued climate change increases risks of biome shifts, with one-eighth of global land area at high risk under climate change of 2°–4°C above pre-industrial levels (Gonzalez et al. 2010). Habitat fragmentation from agricultural expansion, urbanization, and roads generates barriers to dispersal and increases the area at high risk to half of global land (Eigenbrod et al. 2015).

In this column for *Parks Stewardship Forum*, I've been presenting the science of human-caused climate change and ecosystems and offering specific solutions that each of us can implement to reduce climate change. Grateful for this opportunity, I'm wrapping up the column with this last edition because I will soon complete my two-year assignment as Executive Director of the Institute for Parks, People, and Biodiversity. Continuing at the University of California, Berkeley, I will be very pleased to go forward with the work through which I can produce the most impact—scientific research and assisting resource managers and policymakers with solutions to halt climate change, protecting people and nature.

Key aspects of climate change science and ecosystems covered in *Climate Change Solutions* include impacts in national parks (Gonzalez 2023a), ecosystem carbon (Gonzalez 2023b), wildfire (Gonzalez 2023c), snow and ice (Gonzalez 2024a), species extinctions (Gonzalez 2024b), and vegetation (this edition).

Forward-thinking actions to cut carbon pollution that I practice personally and have encouraged you to take include living car-free (Gonzalez 2023a), eating plant-rich and meat-free (Gonzalez 2023b), traveling by public transit when visiting national parks (Gonzalez 2023c), installing or purchasing renewable energy (Gonzalez 2024a), and implementing energy conservation and energy efficiency measures such as using natural light and ventilation from windows (Gonzalez 2024b). Success in halting climate change requires action at all levels—individuals, corporations, governments.

The scale of the effort is too large for anyone to sit by and wish that someone else does something.

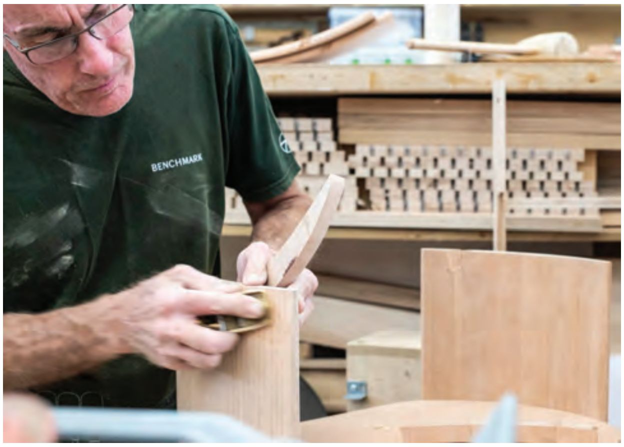
I now encourage you to join me in perhaps the most challenging action yet—minimizing material consumption. The extraction of raw inputs, manufacture, transport, use, and discarding in landfills of material products generates pollution at each stage. Avoiding the purchase of excessive material products can eliminate a long chain of negative environmental impacts.

People in high-income countries like the US can possess a surplus of material things: automobiles, appliances, electronic devices, sports equipment, games, clothes, shoes, papers, boxes, bags of miscellaneous items.… Before you go and buy more, look in your closet or garage and ask yourself, "Do I need all this stuff?"

Scientific research uses a procedure called life cycle analysis to quantify the climate change pollution generated by a product throughout the entire material chain, from extraction of raw inputs to discarding in a landfill. Life cycle analyses of 866 products indicated that they generated average carbon emissions equivalent to 600% of the product mass (Meinrenken et al. 2020). An estimated 45% of emissions occurred upstream of production, 23% during, and 32% downstream. US households accounted for 17% of global material use in 2007, generating one-fourth of global greenhouse gas emissions (Ivanova et al. 2016).

People don't even use all the stuff they buy. As one indicator, self-storage units in the US currently occupy floor space totaling 195 km^2 (75 square miles) (Modern Storage Media 2024). This is more than twice the land area of Manhattan, New York.

People also throw away a lot of stuff. Each person in the US generates an average of 650 kg (1,400 pounds) of municipal solid waste each year, adding up to 2% of US greenhouse gas emissions in 2022 (US EPA 2024). Discarding material products in landfills generates substantial carbon pollution because the low-oxygen decomposition of buried material generates methane, a greenhouse gas 30 times more damaging than carbon dioxide (IPCC 2021).


A carpenter works on furniture in the workshop of Benchmark, a company in England that will take back furniture, refurbish, and re-sell or donate it to help create a circular economy. BENCHMARK WOODWORKING LTD.

A fundamental factor explaining the substantial pollution of material products is inherent energy loss governed by laws of physics. The First Law of Thermodynamics is a principle that energy is neither created nor destroyed, only converted between different forms. The Second Law of Thermodynamics is a principle that a closed system will change toward a condition of increased entropy—disorder and randomness. A key implication of these laws is that no process can convert 100% of one form of energy completely into a useful form. Material processes will always waste energy in forms that are unrecoverable.

For example, the objective of a coal-fired electric power plant is to convert the chemical energy of the covalent bonds of hydrocarbons in coal to heat energy in the boiler to heat energy in steam to kinetic energy in the turbine fan to electromagnetic energy in the generator coil. Along the way, the conversion processes lose energy as light and sound of the boiler fire, vibration of turbine parts, heat of power plant components, and, most of all, waste heat pumped into the environment. Due to the laws of thermodynamics, two-thirds of fossil fuel energy is ejected as waste heat (US EIA 2024). Material production generates more waste at each subsequent step of transformation.

A disposable plastic water bottle demonstrates the extensive resource extraction and carbon pollution that a small item can generate. It starts deep underground in an oil reservoir, such as the oil deposit 2,000 m deep under ocean waters in the East Java Sea off the coast of Indonesia. An oil company pumps the oil and ships it onshore. There, an oil refinery uses fractional distillation to produce gasoline and other compounds, including polyethylene terephthalate (PET). The company trucks the raw PET to an Indonesia factory that produces PET pellets. The factory trucks the pellets to a ship terminal. From there, a ship burns fuel oil 14,000 km across the Pacific Ocean to a port in the US.

A truck or train then takes the PET to a factory that melts the pellets, blow-molds bottles, and trucks the empty bottles to a beverage company somewhere else in the US. The electricity for the factory originates at a power plant that burns coal in a boiler at 700 to 1,000°C, drawing the coal from a distant mine, either from stripping the surface of the land or extracting it from 600 m underground. Recall that two-thirds of the coal energy is lost as waste heat.

The beverage company either fills the bottles with municipal tap water or with local spring water, applies plastic labels (produced through yet another chain of material extraction and manufacture), and trucks the bottles to a wholesale distributor. The distributor trucks the bottles to a local store. A person gets in their car, burns gasoline to go to the store, buys the bottle of water, drinks it, and … throws it in the trash. In one minute, the consumer throws away a product embodying 500 million years of formation of a non-renewable resource and the human labor and technology of a global system of manufacturing and transportation. For-profit corporations and the consumer squander what is actually precious.

Life cycle analysis shows that the production of local mineral water in PET plastic bottles generates 11 to 33 g of carbon emissions per 500 mL bottle (Garfí et al. 2016, Benavides et al. 2018) or 80% of that if using recycled PET pellets (Benavides et al. 2018).

In the US, the sustainable alternative is simple: turn the faucet, fill a glass, and drink; or press the lever on a water fountain and drink. Life cycle analysis shows that municipal tap water generates 2% of the carbon emissions of plastic bottled water (Garfí et al. 2016).

A plastic water bottle is a relatively simple product, yet uses resources and numerous processes that generate substantial carbon pollution. A gasoline-engine automobile is a much more massive and complex product, using steel, aluminum, copper, glass, rubber, and plastic extracted and processed around the world. In addition, the car burns fossil fuels with each use. A medium gasoline-engine car can generate 13,000–14,000 kg of carbon during a 230,000 km lifetime (Buberger et al. 2022; IEA 2024). While electric vehicles use less fossil fuel, they still use substantial amounts of steel and additional amounts of cobalt, lithium, and other energy and resource-intense components. Running on 60% fossil-fuel generated electricity, an electric vehicle can generate 5,000–8,000 kg carbon during a 230,000 km lifetime (Buberger et al. 2022; IEA 2024).

I encourage you to live more sustainably by reducing excessive material consumption, streamlining life, living as free as possible from material accumulation. By minimizing the material that we consume, we reduce waste, fossil fuel burning, and climate change.

Some common-sense practices that many of you and I practice include minimizing purchases to only what is necessary; using durability, repairability, and longevity as criteria; recycling; drinking tap water; and living car-free.

Three specific advanced actions that I practice are: maintaining a paper-free office, by working with electronic documents; keeping a home with no trash can, with organic matter going to municipal composting, paper, glass, and plastic going to municipal recycling, and minimizing anything else; and following a personal goal of no net accumulation of material, in which, for each item I accumulate, I donate or recycle something of equivalent mass.

Minimalism.

Economists have developed these ideas of material use into two types of sustainable systems: a steady-state economy and a circular economy. A steady-state economy is a system in which total resource use remains at an equilibrium with the environment and increases in efficiency power increases in economic benefits for people (Daly 1974). A circular economy is a system that involves reusing, repairing, and recycling existing materials and products as long as possible, reducing waste to a minimum, and, when a product reaches the end of its life, returning the materials to the system for productive use (Stahel and Reday 1977). These contrast with the current economic system of extraction and single use of non-renewable natural resources, trying to grow endlessly.

Forward-looking policies are advancing the vision of a steady-state and circular economy. In the US, the Biden-Harris administration has implemented policies that give individuals the right to repair products and prompts companies to improve the durability of items (USA 2021). The European Union (EU) adopted its *Circular Economy Action Plan* to chart a future of higher efficiency and less waste (EU 2020). The University of California, Berkeley, aims at a goal of zero waste to landfills (UC 2019). The US National Park Service Zero Landfill Initiative seeks to eliminate landfill waste from national parks (Taff et al. 2024).

These policies recognize the environmental benefits of minimizing waste and the employment and economic potential in maintaining, recovering, restoring, refurbishing, refinishing, and upgrading material products. Through these efforts, the US and most EU countries have decoupled economic prosperity from greenhouse gas emissions, increasing economic value without increasing emissions, since 2005 (Freire-González et al. 2024).

In addition to the environmental benefits, reducing material accumulation can also improve emotional well-being. Research has consistently found a significant association of materialism and unhappiness (Dittmar et al. 2014; Shrum et al. 2022).

The challenge of halting climate change remains substantial. IPCC scientific analyses indicate that the world needs to limit the global temperature increase to 1.5–2°C above pre-industrial levels to avert the most drastic consequences of climate change (IPCC 2023). At 2023 rates of carbon emissions, the world could exceed the 1.5°C goal by 2030 ± 5 years (Friedlingstein et al. 2023; IPCC 2023; Lamboll et al. 2023). Meeting the 1.5°C goal requires us to cut carbon pollution 43% from 2022 levels by 2030 and to net zero by 2050 (UNEP 2023; UNFCCC 2023). Every gram of carbon pushes us closer to the limit.

IPCC has assessed published scientific research on carbon solutions and concluded that we can limit the global temperature increase to 1.5–2°C with concerted global action, using existing technologies and practices (IPCC 2022b; IPCC 2023). Many carbon reduction actions, including energy conservation, solar energy, wind energy, and expanded public transit, cost less than current systems (IPCC 2022b; IPCC 2023).

International and US policies have established key enabling conditions to halt climate change. The world joined together in 1992 in a global treaty, the United Nations Framework Convention on Climate Change (UNFCCC). In 2005, all 194 independent nations in the world adopted the UNFCCC Paris Agreement, a science-based protocol to reduce greenhouse gas emissions to net zero by 2050 to limit the global temperature increase to 1.5–2°C above pre-industrial levels.

Before the Paris Agreement, the world was on a path to 3.7–4.8°C above pre-industrial levels (IPCC 2014b). Full implementation of Paris Agreement nationally determined contributions could limit warming to 2.5°C above pre-industrial (UNEP 2023).

US national policies are advancing actions to halt climate change. With the American Recovery and Reinvestment Act of 2009, the Obama-Biden administration substantially ramped up investment in solar, wind, and other renewable energy capacity across the country. With the Inflation Reduction Act of 2022, the Biden-Harris administration established numerous programs to increase energy efficiency, install renewable energy, promote domestic renewable energy production, cut wasteful and damaging leaking of methane, and upgrade public transit and electric transportation. The law provides the highest single US

Redwood trees (Sequoia sempervirens), the tallest living beings on Earth, Redwood National Park, California PATRICK GONZALEZ

government investment ever to cut greenhouse gas emissions and reduce climate change.

Full implementation of the Inflation Reduction Act could cut US greenhouse gas emissions 33–40% below 2005 levels by 2030 (Bistline et al. 2023). The Inflation Reduction Act could cut emissions from US electricity generation 47–83% below 2005 levels by 2030 (Bistline et al. 2024).

Recent results show that energy conservation, energy efficiency, renewable energy, public transit, and other actions have been effective. The US cut greenhouse gas emissions 17% from 2005 to 2022 (US EPA 2024). The EU cut greenhouse gas emissions 30% from 1990 to 2021 (EU EEA 2023). The US doubled renewable energy use and cut two-thirds of coal use from 2004 to 2023 (US EIA 2024). The world increased the installed capacity of solar, wind, and other renewable energy 500% from 2000 to 2023, equivalent to avoiding the construction of 8,000 coal-fired plants (IRENA 2024).

In summary, scientific analyses confirm that we can halt climate change, policies to cut carbon pollution have been established, and recent results demonstrate that actions are reducing carbon pollution. So, science, policy, and results all show that the goal of halting climate change is possible.

An essential part of the solution is you and me. We can take meaningful action by minimizing our material consumption. Because of the cumulative carbon pollution of the past, we can't live like previous generations. Aim to live simply. One person can make a difference. All of us together can make a great difference, to protect people, trees, and all of nature.

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