This is a call to action. If you love forests, if you think for a moment about the obligation we have to those who come after us, then you’ll see, this is a forest issue, it’s a political issue, it’s an economic issue, it’s a national security issue, it’s a jobs issue, but at bottom it is a moral issue.

— Al Gore
Table of Contents

Introduction by John Bennett, The Aspen Center for Environmental Studies ................ 5

Jim Worrall, U.S. Forest Service ................................................................. 7
Sudden Aspen Decline & Climate Change – Why More SAD May Await Us

Diana Six, University of Montana .............................................................. 10
Climate, Forests & Insects: From Montana White Pine to South African Euphorbia

Phillip van Mantgem, U.S. Geological Survey ............................................ 13
Can Our Forests Take the Heat? Increasing Tree Mortality Rates Across the Western U.S.

Tom Swetnam, University of Arizona .......................................................... 16
Wildfire, Climate & People: Perspectives and Warnings from the Past

Werner Kurz, Canadian Forest Service, Natural Resources Canada ....................... 21
Sinks & Sources: The Role of Forests in Carbon Sequestration ... and Why It Matters

Craig Allen, U.S. Geological Survey ............................................................ 25
We’re Not Alone: Forest Die-off Risks Around the Globe

Linda Joyce, U.S. Forest Service ................................................................. 30
The Future of Our National Forests: Enhancing Adaptive Capacity

Tom Cardamone, Aspen Center for Environmental Studies .................................. 34
Sequestering Carbon in a High Elevation Peat Bog

A record of the presentations from the Forests At Risk Symposium in
Aspen, Colorado on February 18, 2011
Our Forests At Risk
by John Bennett, The Aspen Center for Environmental Studies

The top scientists and policy makers who gathered at our 2011 *Forests At Risk* symposium represented a remarkable acknowledgement that climate change is profoundly affecting the region many of us call home – the Rocky Mountain West.

For those of us living in Colorado, the destruction of millions of acres of pine forests by the mountain pine beetle, and hundreds of thousands of acres of aspen, spruce and fir from other parasites and infestations, is not news. What’s new is the emerging scientific consensus that climate change lies behind many of these forest threats and that our environment, quality of life and local economies hang in the balance. Consider the following:

- According to the study led by scientist Phil van Mantgem of the USGS, the death rate of the West’s old growth forests has more than doubled over the last two decades.

- Werner Kurz of the Canadian Forest Service and Intergovernmental Panel on Climate Change calculates that the 41 million acres of beetle-killed forests in British Columbia are adding roughly a billion tons of CO2 to our atmosphere. (And that’s minor compared to what will happen if the permafrost continues to melt and release its vast store of carbon.)

- Dr. Thomas Swetnam of the University of Arizona points out that the annual wildfire season in the West is already 78 days longer than just 20 years ago. Since the 70’s, the Rocky Mountains have witnessed a 60 percent increase in large fires. If warming trends continue, Swetnam and others predict we could lose half the forests of the West during this century.

- According to Diana Six at the University of Montana, the whitebark pine, a keystone species in high elevation zones of the Northern Rockies, is dying across most of its range. This could precipitate the loss or reduction of many plant and animal species, including the endangered grizzly bear.

These are startling trends. If the forests of the West are our canary in the coal mine, the canary is not doing so well.

The 2011 symposium – *FORESTS AT RISK: Climate Change & the Future of the American West* – was an opportunity to engage in thoughtful discussion and focus on serious challenges. It also highlighted the opportunity that arises when people – and their leaders – recognize challenges and are motivated to act.

*We’ve arrived at a critical time and place in history.*

The landscape of the West is undergoing a profound and complex transformation. Four million acres of Colorado pine forests killed by the mountain pine beetle are now decaying, releasing their carbon into the atmosphere. The old-world view that “forests always renew themselves, let nature take its course” is clearly obsolete. Forests require up to a century to recapture all of the carbon released in a beetle epidemic, wildfire or other die-back, and climate scientists are virtually unanimous about the fact that we don’t have that long. Put simply, if the great forests of the West continue turning from carbon sinks into carbon sources, we’re all in deep trouble.

We’re going to win or lose the great carbon battle in the here and now, in our short lifetimes, so what can we do? Two answers come to mind: forest stewardship and clean energy.

At a regional level, we can employ scientifically based forest stewardship over large landscapes that are home to myriad types of flora and fauna. Outside of protected wilderness areas, good stewardship practice could begin...
to make up for past fire suppression policies that helped create unnaturally dense, mono-culture forests that undermined forest health and wildlife habitat.

In forests across the West, we can support the efforts of the U.S. Forest Service to restore critical wildlife habitat through prescribed burns, thinning and other forest health measures. We can also support the efforts of local communities to protect forest health in the wildland/urban interface and forge a balance between ecological and recreation values in these “backyard” community forests where we enjoy both nature and recreation.

Most important, we can develop enlightened energy policies at the local, state and national levels to break our addiction to fossil fuels. We could generate biomass energy from beetle-killed trees, develop uses for biochar in restoring our environment, and expand the use of wind, solar and appropriate hydro power. While reducing atmospheric CO2, these steps would also stimulate our clean energy economy, create millions of new jobs and enable us to compete internationally with countries like China, which are pulling ahead in the clean energy race.

Our choices are clear. As individuals we can act to reduce our impact on the environment. As a society, we can enact policies that promote forest health and develop green energy alternatives that are both environmentally and economically smart.

_Aren't the forests and quality of life of the American West worth the effort?_
Jim Worrall is a plant pathologist with the US Forest Service, who received his PhD in plant pathology from the University of California, Berkeley, and was associate professor at the College of Environmental Science and Forestry in Syracuse, New York before joining the Forest Service. He has conducted forest research in Germany, Alaska, California, New York, New Hampshire and Colorado. Jim is the leading authority on sudden aspen decline, a phenomenon of widespread, severe, rapid, dieback and mortality of aspen forests that is linked directly to climate change.

I’d like to share with you what’s been happening in some of our aspen forests over the last decade, how it’s connected to climate change, and projections for the future of aspen over the rest of this century. First, let’s consider why we should care about aspen. Three reasons: first, aspen is a biodiversity magnet. There are more species that are associated with and in many cases specifically depend on aspen than on any of our major tree species. It also produces a lot of forage and browse for ungulates such as elk and deer. Overall, it’s the most diverse upland forest type that we have in the Rocky Mountains.

Second, it does good things for water. It starts with the rich organic soils that build under aspen forests. They have a high water holding capacity, low potential for erosion, they moderate stream flow and improve aquatic and riparian habitats downstream. Water yield of aspen forests can also be higher than from conifers. Finally, we all know that aspen is a beautiful tree and forest type and visitors know this too, and that is part of the reason for the tourism economy we have in Colorado.

That beauty began to fade in 2004; we started getting calls from foresters in Southwestern Colorado telling us about branch dieback and mortality that they hadn’t seen before occurring over very large areas. It was apparently very recent and ongoing. In some of the lower elevation forest, such as you see here below, (see Figure 1), the patches of aspen were completely dead with no regeneration and no sprouting going on. Over the next few years, this got worse and occurred in more and more areas. By 2006, we knew it was a serious problem and started to study it.

This thing we call sudden aspen decline is characterized by a rapid, synchronous, branch dieback and mortality. It occurs on a landscape scale over a large area, not on the stand level that we’re used to seeing aspen mortality occurring at (see Figure 2). The trees are ultimately killed by secondary insects and pathogens, those that depend on a stressed tree, not by the primary insects and pathogens that usually kill aspen trees in Colorado.
This disease increased rapidly from 2004 to 2008. In 2008, over half a million acres were affected in Colorado. That’s over 17 percent of the aspen forest type that we have. It also occurred in southern Wyoming and similar damages in northern Arizona, southern Utah and in the prairie provinces of Canada. It is important to note that the spread to new areas has stopped now, but some of the affected areas have continued to worsen.

In all the plots we did in southwestern Colorado, we found that regeneration was not increasing with overstory death, as you would hope to see. On the lower axis, the horizontal axis, you see recent crown loss, which is a measure of tree damage and stand damage (see Figure 3). Regeneration does not increase as the amount of damage increases.

Aspen typically regenerates vegetatively by sending up sprouts from the roots. In this case, there was not new reproduction occurring as the overstory died. One of the primary reasons for this lies belowground: the roots were dying in many SAD stands. By comparing damaged stands to healthy stands, we found that there were fewer live roots and more dead roots in damaged stands, so fewer live roots to produce sprouts to replace the dying overstory (see Figure 4).

A complex disease like this has a variety of different categories of causes, but in this case we have strong evidence that the 2002 drought was the primary inciting factor. All of the predisposing factors that we identified here are moisture related. The fact that it’s more severe on low elevations, south and southwest slopes, indicates that a moisture deficit existed. In fact, in Colorado we had this very severe multi-year drought that peaked in 2002. I remember walking in some aspen stands that summer and seeing leaves of the aspen that were scorched black around the edges, as if somebody had taken a blow-torch and just played it around the edges of the leaves. The drought that caused this has been characterized as a “global change type drought,” because it was not only very dry but also very hot. That’s a bad combination for trees.

To get more quantitative evidence, we analyzed a climate moisture index, which indicates degree of moisture deficit. Basically, the geographic variation in the climate moisture index was related to the amount of damage that occurred later. A group of Forest Service scientists in Moscow, Idaho, led by Jerry Rehfeldt, studied this too and they solidified evidence tying SAD to the drought and ultimately to climate change as well. They developed an aspen climate profile, which quantified climatic variables that determine where aspen can and cannot grow on the landscape. They found that 2002 was the most extremely unfavorable conditions for aspen in the entire climate record. More importantly, they found that sites where SAD was occurring are the most climatically sensitive ones. They are at the margin or fringe of aspen’s climate niche, more sensitive and vulnerable to drought. They projected severe loss of suitable climate area in the future, especially at lower elevations.

Based on their model results, we did some analyses, calculations, and maps (see Figure 5). This is a map of the area around Aspen and it encompasses the White River National Forest. The area shown in green is the area that was climatically suitable for aspen in the latter part of the 20th century. Let’s call that recently suitable for aspen. This graph now shows over a much larger area, all of Colorado and Southern Wyoming, the area that was recently suitable. You can see it’s just over 16 million acres.

Using the climate models of the IPCC, they were able to crank forward the aspen climate profile into the coming
century to see how the area that’s suitable for aspen would change. The area shown in blue is the area that’s projected to be suitable for aspen in 2060. They used three climate models to do this, and the depth of the blue indicates whether one, two or three models agree that each pixel is going to be suitable. You can see there is a lot of green showing. That green showing is of course area where suitability is lost between the latter part of the 20th century and the 2060’s.

In red, you see the area where suitability is projected to be lost by 2060. That’s about two thirds of the recently suitable projected to be lost. Now, this is actually an estimate that’s fairly optimistic, because if any of the three models says that a pixel will be suitable, we’re accepting that in this. Finally, as you might expect there is some area that becomes newly suitable. For instance, upslope becomes warmer and more conducive, and that does compensate for a small portion of the loss of suitability. We didn’t calculate the map and numbers for 2090; there is less certainty as you look farther ahead. However, Rehfeldt et al. projected that by 2090, the lower elevation of the suitable aspen climate will rise 2,500 ft.

This is what is projected for aspen by 2060 in this area, so that’s the first half or more of the century. We’re already one decade into that time, so what’s been happening in that time? As you know, sudden aspen decline is what’s been happening. This shows in red the area where SAD was mapped by aerial survey from 2003 to 2009 (see Figure 6). Two things about it: one is it’s a fairly large area over Colorado and Southern Wyoming; it’s about 1.1 million acres. The most important thing to notice in this map is that the sudden aspen decline is occurring primarily in the areas that are projected to be lost to suitability early in the century. These are the areas that are most climatically sensitive. It’s hard to avoid the conclusion that sudden aspen decline is really fulfilling the projections or at least beginning to do so.

The big question here is, is SAD due to climate change? Because of differences between climate versus weather and global versus local, it’s not possible to definitively answer that question. But common sense tells us if it looks like a duck and it quacks like a duck, it’s most likely a duck.

Here we have a drought that instigated SAD that was of the type projected to occur more commonly under climate change, with impacts on trees that are of the sort that are projected to occur commonly under climate change. I think most importantly, it occurred specifically where climate suitability is projected to be lost, early this century. I would say yes, SAD does seem to be a harbinger of climate change. That being the case, we can expect it to occur not at a steady rate, but in spurts, because trees and tree diseases don’t respond to the climate mean, they respond to the climate extremes. They respond to those edges of the variability or the tails of the distribution if you will. We can expect SAD to recur more frequently in the future, to have less aspen in the future, and the values that aspen brings with it - biodiversity, water and so on - will be affected accordingly.

I struggle to end on a positive note, but I would say that aspen is the most widespread tree species we have in North America. It’s very adaptable to many different kinds of sites. Therefore, it seems certain that we will have aspen somewhere on the landscape far into the future.
Today I’m going to talk a little bit about interactions between climate, forest and insects. I thought a good place to start would be to give a short introduction into why we are particularly interested in insects and climate change. I’m going to talk a little bit about some of the factors that have some pretty strong impacts on insect populations, and then I’m going to talk about a couple of systems that I work in currently where we’re already seeing some really dramatic impacts. These include whitebark pine in our western and subalpine ecosystems, and also South African giant euphorbia trees.

I like to call insects, “nature’s first responders.” That’s not because they’re the first ones to show up and provide first aide to our forests when they’re in trouble. Actually, it’s quite the opposite. Insects are incredibly sensitive to even small amounts of environmental change. When you think about forest insects, the environmental triggers that they really respond to most rapidly are temperature and host tree stress. Insects are what we call ectotherms, which means they can’t really regulate their own body temperatures, leaving them very much at the mercy of the environment. For all of their vital rates, such as activity, feeding, reproduction and development, as things cool down all of those rates slow down. Conversely, as you increase temperature, all of those rates increase. It doesn’t take much of a change in temperature to see a big change in those rates.

For a lot of insects, a two-degree change in temperature will cause approximately a doubling of things like reproduction and development, which can really rapidly impact population growth. Something else that’s really important with forest insects is the state of the condition of the tree host. For example, we have a bit of warming and drying across the west, and that’s expected to continue. That puts a lot of stress on trees, which has the effect of really lowering their defenses and making them easy food for insects, which can also greatly contribute to their population growth.

Living in Aspen and Colorado, you know we already have some very rapid responders, and some of these are bark beetles. It has been pretty amazing for us entomologists to see how three bark beetle species have already responded primarily – not completely, but primarily – to the changes in climate. This has been primarily driven by a few degrees increase in temperature, which allowed insects like the spruce beetle to go from a two-year life cycle to a one-year life cycle. If you’re a bark beetle, that’s really important.

In a two-year life cycle you’ve got to get through two winters, which is bad enough. Even worse, you have to be able to feed and get moisture out of a tree that’s been dead for two years. If you look at a tree that’s been...
dead a year, you can see that that’s probably not going to happen too much. It really regulated their populations. When they switch to a one-year life cycle they took off and we got this massive epidemic. The pinyon ips, bark beetle (see Figure 1) was also driven very much by a hot/dry weather, stressing trees and allowing this particular non-aggressive bark beetle, to take off and create an epidemic that has probably has altered those forests forever.

It is normal for mountain pine beetle to have periodic outbreaks. This has been the case for thousands and thousands of years. But it’s very, very different now. This outbreak is much more extensive, much more severe, and some other things are also very different. The beetle has expanded its geographic range much further north because it’s now warm enough to survive there. It has jumped the continental divide and it is now found in Alberta, all the way up into the jack pine forests. The fear now is that it will move across the continent and into our eastern pine forests.

Something else that’s different with mountain pine beetle is that it has also moved up in elevation, and that’s one of the systems I work in. I’d like to introduce what’s happening now with mountain pine beetle in our subalpine whitebark pine forest. If you know about whitebark pine, this is the tree that’s up at the highest elevations. It is the keystone species that keeps that ecosystem together. The beetle didn’t used to do well up in the high elevations because it was too cold. It had a two-year life cycle, which is quite maladaptive. It is now warm enough for that beetle to go through in one generation, so it’s doing very well up there.

We’ve had a couple of outbreaks we know of in whitebark pine in the past, but they were due to very short term pulses of warm dry temperatures, (in the 70’s and with the dustbowl and so forth). What happened there was once it returned to normal cooler weather conditions, the beetle pretty much got shoved off the mountain. The problem now is that we’re not expecting to return to these cooler weather conditions, so we think the beetles currently up there will stay. The extent of the outbreak now is much, much bigger than it was in the past. We think that we’re probably going to lose this tree across most of its range, and it won’t recover. It’s a permanent alteration of this ecosystem.

Something we’re noticing with mountain pine beetle in whitebark pine is that it goes through that tree very fast. If you look at lodgepole pine, it takes about 7-10 years for the beetle to work through. With whitebark pine, it’s three. We can’t even keep our study sites going. You find a site with a few dead trees, the next year it’s 50%, and the next year it’s 90-100%. This right here is just a two-year progression. Part of that, we think, is that the tree really doesn’t have much in the way of defenses because it hasn’t really had to battle a beetle. This is what you would see with ponderosa or lodgepole pine: the tree trying to pitch the beetles out (see Figure 2). When you look at whitebark pine that has been attacked by a beetle, what you see is boring dust (see Figure 3). The beetles are just walking in and there’s no fight.
This is what Yellowstone, the Tetons and the Wind Rivers in the high elevations look like right now, over a million hectares dead already just in the greater Yellowstone ecosystem (see Figure 4). Again, we don’t believe this tree is going to be coming back. It’s probably a permanent shift in our subalpine ecosystem.

I’d like to talk about this other system that I also work in, and that’s looking at the Southern African giant euphorbia tree. Starting in about 2000, people started reporting massive really rapid die-offs of this incredible, large succulent tree. It looks like a saguaro except on major steroids. This thing is about 35-40 feet tall, almost as wide when they’re mature. They are really magnificent, considered a national treasure, and they’re dropping dead (see Figure 5). At first the suspect was an exotic pathogen or an insect that might have gotten in. They did notice that these trees were very, very heavily attacked and often killed by ambrosia beetles, which happen to be relatives of the bark beetles. Then of course, climate change was also suspected.

One of my colleagues in South Africa, Jolanda Roux, a plant pathologist, and I have been looking at these trees for about six years. We’ve cataloged all the diseases and insects. They all appear to be native, and they all appear to be benign. Even the ambrosia beetles, typically only attack trees that are very, very stressed.

We began to look at the potential that a changing climate might be driving this. These are some data from one our sights (we have several). It’s from a place called Last Post, which is a wildlife reserve. It’s very well protected. It’s an interesting place to work that is intermediate in damage. It is not one of our extreme sights. What we found, looking at the weather data that was available for the last 40 years, was that at the beginning of that period, temperatures were overall cooler and precipitation was higher. The intermediate years were highly variable with big swings in temperature and precipitation from year to year. Then the last period (approximately 10 years) was dry and hot. The thing that is most important to consider here is precipitation. Now that we’ve moved into a period where it’s hot, where there’s a lot more demand for moisture, the trees are getting a lot less. From these data we’ve been able to calculate something called potential evapotranspiration, which is the estimated amount of the loss of moisture from the vegetation at these sites (that’s the output). Then we look at the input which is precipitation and determine if there’s a deficit and how much. For each of the sites where we see trees tipping over the edge, we find a particular deficit that appears to be a threshold. Once trees hit that threshold they begin to decline and die within about two years. It’s a constant signal across these sites.

This is my take home message: we see more and more insects developing these large outbreaks. The thing to remember is, when you’re dealing with insects they are responders. If you’re going to think about managing an insect or trying to deal with their impacts, it’s very important you realize that actually they’re responding to something, and that just focusing on insects is probably not going to be very successful. You have to go to the ultimate cause of that response. Unfortunately more and more, the cause is climate change. So if we’re really going to start dealing with some of these insect problems that are emerging, we have to go to the initial underlying cause.
Phillip van Mantgem is a research ecologist with the U.S. Geological Survey Western Ecological Research Center. He received his doctorate in ecology from the University of California Davis. His research interests include Conservation Biology, Fire Ecology, Forest Ecology and Global Change Biology. He’s currently leading the USGS Fire Severity Trends Project, which is testing the idea that climate may affect forest fire severity independent of fire intensity.

What I’d like to talk about today isn’t massive forest dieback, which is mostly what we’ve been hearing about so far [in this symposium]. What I’m interested in is slow, subtle changes that have been occurring over the last couple of decades in Western forests. I don’t have to convince anybody in this room that climate change is here already. No matter what resource you’re looking at, whether it is animal movements, timing of flowering of different plants, or the diebacks that we’re talking about today, we’re seeing the effects of climate change already.

In the western United States, one of the biggest effects we’re seeing is in the hydrologic cycle – what’s happening with our water, the big limiting resource here. Scientists have been finding that the snowpack has been decreasing over time, and we have less snow. More precipitation is falling as rain rather than snow, so it doesn’t stick around as long. Stream flow is peaking earlier and earlier, which is another indication that things are getting dryer over the summer. What does that mean for forests?

One of our recent findings is that background tree mortality rates are increasing in old forests in the western United States. Detecting this trend is fairly easy because we have good data. Attribution, or what’s causing this trend, is more difficult. I’m going to present evidence today that the increasing background mortality rate is due to warming temperatures.

What is forest mortality rate and why are we concerned? Just like a human population, if you know how fast trees are growing, how fast they’re reproducing and how fast they’re dying, you actually know a lot about their population. Again, what I’m talking about today isn’t large-scale die-off, rather it’s the background mortality rate, which is a slow, subtle but important process. It’s important for a couple of reasons. First of all, you can kill a tree a lot faster than you can grow a new one. If you start changing the forest mortality rate, you can change a forest relatively quickly. What I’m going to be showing today is changes in tree mortality rates from about half a percent to about one-and-a-half percent over a couple of decades. That doesn’t seem very big, but it’s a compounded rate. If those changes are maintained year after year after year, it has a big effect.

For example, my wife and I are now shopping for a home loan, and we would be very concerned if interest rates were to rise by 1 percent! Again, it’s a compounded rate.

The idea that demographic rates might be changing over time isn’t new. In tropical systems, researchers have noticed an increase in what’s called recruitment, or birth, of new trees and mortality rates overtime. They’re seeing changes in stand biomass and in species composition. In the tropics, they’re seeing an increase of lianas, which are creeping, vine-like species. So we ask the question: can we see similar changes in western forests? Here’s the data that we used.

We were able to find 76 plots out of all the western United States that had the kind of information we needed to ask this question. We focused on old forests, forests that were more than 200 years old. We don’t expect old forests to have highly dynamic populations, so any changes to these populations are likely caused by external forces. We followed these plots over 20 years, tracking the fates of individual trees to get carefully measured demographic rates. Figure 1 shows our finding in those areas. The red symbols indicate sites where mortality rates were increas-
ing; blue shows areas of decreasing mortality. The size of the dots indicates the magnitude of change we observed. What we’re seeing is that 87 percent of our plots have increasing mortality rates. That’s unusual. In these old forests, you wouldn’t expect rapid, directional change. We expect them to be demographically boring.

Over the short span of only two decades, it may be normal to have some instances of increasing mortality rates, but not 87 percent of the time. It’s like flipping a coin 100 times and getting 87 heads … something is going on. The mortality rate is doubling over an 18-year period, and we observed a trend towards increasing mortality over the entire length of our observations.

If background mortality rates are increasing, what’s causing that trend? It was a surprising result, so we thought that maybe there’s something in our data that’s really driving the overall trend. Maybe there’s some sort of artifact in there. We split out our data by regions, elevations, tree sizes, major species groups and historic fire frequencies, places that you’d expect to see a big impact of fire suppression or not. Essentially, we are seeing the same trend no matter where we look. Increasing tree mortality rates is a solid, robust, trend. And that trend is correlated with climate change.

We used weather station data interpolated with the PRISM model to our particular study sites and found that changes in tree mortality rates correlated really well with changes in either temperature or water deficit (see Figure 2). Climatic water deficit is a good measure of water stress in plants. In the Sierra Nevada, we have some higher resolution data showing that tree mortality rates track changes in water deficit over time. The correlation is really tight. Unfortunately, it’s just a correlation, so we can’t say for certain what’s really driving this trend. If we want to predict what’s going to happen in the future, we really need to understand those mechanisms of tree mortality. We don’t have that level of understanding yet.

So why should you care about increasing mortality rates? One reason is that forests hold a lot of carbon. If you compare forests to other plant communities, an estimated 82 percent of the world’s terrestrial carbon is held up in forests. That amount compares rather favorably to the amount of carbon that is in the atmosphere right now. If all
of our forests suddenly dropped dead and evaporated, the level of atmospheric carbon would essentially double. I don’t think that’s going to happen, but our data suggest that our forests might be slowly leaking carbon.

Increasing background tree mortality rates also suggest that our forests are being subjected to chronic stress. When we get an acute stress like a drought event, they might be more susceptible to massive dieback events. Figure 3 is a photo taken by Craig Allen of a dieback event in the Four Corners region of the western U.S. We think that such dieback events might be more common in the future — not only as climate changes, but as forest populations become more and more susceptible to those stresses.

This type of long-term research is very important to help people make critical decisions about our forests. The work that I’ve been showing you today is boots-on-the-ground research. We can’t get this from remote sensing. We can’t model our way to these results. The only way to do it was to have people out there counting trees and measuring trees year after year after year. We need to be committed to getting these measurements and seeing what the patterns they reveal. There has not always been a great deal of support for monitoring programs. Everybody wants this kind of data, but it is important to acknowledge the need for funding to support for these studies.

If things are actually changing, then we are going to have to rethink how we manage our forests. The National Park Service, for instance takes the idea of “naturalness” very seriously. Whenever possible, they try to restore and maintain naturally functioning ecosystems. When that’s not possible, they work to maintain the closest approximation of that “natural condition,” using 1850 as a target period because it was a time prior to the significant changes to the landscape that occurred with mechanized development. It has been a good model and probably still is in many cases. However, with climate change, we no longer have environmental conditions similar to 1850.

My research suggests we are going to have to re-think how we’re going to manage these areas in this new context. It might mean trying some different management approaches. For example, do we want to use more intense prescribed fires to thin out some of our forests? Should we start engaging in assisted species migration? I don’t think we have the answers for that yet, but we need to start asking these sorts of questions. Once we start asking such questions, we hope that there will be some light at the end of the tunnel.
Dr. Tom Swetnam is a professor of dendrochronology and director of the Laboratory of Tree-Ring Research at the University of Arizona. He studies changes in climate and forest disturbances using tree rings and other data. His work centers on understanding forest and wildfire dynamics in pine-dominant and giant sequoia forests of the western United States. He has also worked in Mexico and South America and is currently studying fire, climate and carbon dynamics in central Siberia. He has authored and co-authored more than 120 papers and serves as the director of the world’s largest laboratory dedicated to all aspects of tree-ring research and education.

I’m going start with a long-term perspective of natural and cultural history in our landscapes here in the western U.S. and particularly in the southwest. I am referring in part, to the rather ominous word, “warnings” in the title of my talk.

Figure 1 is a photograph of the magnificent cliff dwelling called Keet Seel, at Navajo National Monument in Arizona. There are other truly spectacular ancient ruins around the Southwest, such as Pueblo Bonito at Chaco Canyon in New Mexico and Cliff Palace at Mesa Verde, Colorado. Anyone who has been to these sites is struck by the mystery. You see the ancient, monumental architecture, the imposing, great cliffs and wonder: why did people build in these rather ominous, but beautiful places? Who were they? And, especially, why did they leave? It has been a mystery since European-Americans first saw these ruins. It was only during the beginning of the 20th century that scientists began to solve the mysteries, to discover the timing of when people lived here and the reasons they left. These discoveries came about in part because of the work of an astronomer by the name of Andrew Ellicott Douglass, who was the first dendrochronologist (that is, tree-ring scientist).

Douglass came to the Southwest to build the first astronomical observatory in Flagstaff, Arizona in 1894. His interest was solar variability, sunspot cycles, and how the sun might affect the Earth’s climate. At that time there were very few long-term rain gauge records that he could use to compare with the 400-year sunspot record that astronomers had been keeping since Galileo. But he realized that he could use tree rings in pine trees from the Southwest as a proxy for rain gauge records, because he found that in this arid region, wide rings were correlated with wet years and thin rings grew during drought years.

In developing the science of dendrochronology, Douglass devised a method of dating wooden materials. With this method, which is called “cross-dating,” he was able to match ring-width patterns between living and dead trees during the period that they overlapped in time, and in this way bridge back in time and determine the calendar dates of the outermost rings of the roof beams from the great ruins. From this work, he discovered that people built these...
magnificent structures from about the ninth century onward, and then mostly abandoned them in the 12th and 13th centuries, with different timing in different places. (These people were the ancestors of some of the Native Americans who live today in New Mexico and Arizona.)

When cross-dating the roof beams, Douglass noticed that the outermost rings on many of them were very narrow. He inferred that this was likely a drought period and probably had something to do with the abandonment of these sites. This became known as the Great Drought of the late 1200s AD. That interpretation has more or less held up over the decades, but it is not quite so simple a story that only drought was responsible for people leaving these places.

As with most things in human and ecological history, more than one thing usually causes change. It is notable, for example, that people living there had survived previous droughts as bad as the late 1200s drought, but they did not leave during the earlier dry spells. This is in accord with a general theme of Collapse, Jared Diamond’s book about societal disruptions around the world. It is usually not just one thing, but multiple contributing factors and contingent events. For example, various social stresses can occur that increase vulnerability of societies to climate shocks, such as warfare or arrival of a large number of strangers who compete for resources. Other key factors may be over-use of a vital, local resource, or overdependence upon an imported resource that suddenly becomes unavailable, or agricultural problems and so on. Does that sound familiar?

But still, climate has been centrally important in some past collapses. Again, it seems that social systems and ecological systems can become more vulnerable over time to climate change because of things that people do — or do not do. There are a number of new papers on the topic of climate variability and its likely impacts on societies, but I’ll draw attention to two examples that involve tree rings: the fall of the Roman Empire and the collapse of the Ming Dynasty, both of which correlated with drought or cold periods. (See Cook et al. 2010 and Büntgen et al. 2011 in the references.) Again, climate is not discussed as a single causal factor, but as a likely contributing factor.

Closer to home and time, we can look at the Dust Bowl as an example of increased vulnerability caused by humans, followed by an extreme climatic event. This case is indeed close to home for me. My parents, Fred and Grace, grew up in Trinidad, Colorado, right on the edge of the Dust Bowl during 1930s. They told me stories from their childhoods about these great clouds of dust coming in. This story is presented well in Tim Egan’s book, The Worst, Hard Time. Millions of acres of prairie sod were ploughed over for farmland. This was well intentioned. They were converting ancient grasslands to farmlands, and it was boom time. People were told, “The rain will follow the plough.” There were good times in the 1910s and 20s, but they turned over the sod that had held the soil in place for thousands of years through many previous droughts of worse magnitude than that of the 1930s. Then the soil was exposed to the elements, drought came, markets changed, crops failed, and the winds blew away the soil and many of the people.

Increased vulnerability combined with climate extremes and change, is, in part, the situation with our forests today. The causes of increased vulnerability include over grazing, logging without adequate follow-up forestry practices, fire suppression, and introduction of non-native species that are often highly flammable. And now, climate is changing too.

Even, however, if we did not have greenhouse gases driving a large part of the recent warming, we would still be in trouble here in the West. Here is how we know this from our tree-ring studies: Since A.E. Douglass’ time, we have greatly expanded our tree-ring collections all around the world. We have thousands of sites now, and each site is a forest or woodland where we have sampled 10 to 30 trees or more, and measured all of the tree rings. In the western U.S., these are mostly “drought sensitive” tree-ring sites where the tree-ring growth is primarily controlled by seasonal, annual, and decadal variation in rain fall amounts. The extensive data networks and calibrations of these ring-width records with rain gauge records and drought indices from the 20th Century have enabled us to reconstruct very detailed maps of past drought extent and magnitude. From these maps we can see the great droughts of the 1100s and late 1200s when the massive pueblos and cliff dwellings were abandoned, and we can assess the long-term context of more recent droughts.
An example of how accurate these records can be, especially for drought and river flow reconstructions, is this time series of the Colorado River illustrated by Figure 2. The green is the record from tree rings from hundreds of trees and dozens of sites on the west slope of the Colorado Rockies and in the headwaters of the Colorado River. The blue is the river gauge record from Lee’s Ferry. Dendroclimatologists calibrated 20th century tree ring records with the gauged river record from the same time period. More than 80% of the variance in the gauged record is estimated by the tree-ring record. From these tree-ring estimates, then, we can derive this long perspective of the past 1,200 years of Colorado River flows.

Unfortunately, this is really bad news for the West. Former Colorado Governor Richard Lamm said that one of his “worst days in office” was when he went to Boulder to talk to tree-ring scientists. They told him about the 30-year droughts of the 12th and 13th centuries that were of greater magnitude than anything that we’ve witnessed during this time of building up our populations with all of our dependence upon surface water in the West. This is a worrisome story — and a warning — that is largely unheeded by most people living in the western U.S.

This is why we are in trouble, even without the greenhouse-warming problem, which is also quite real. Consider the difficulties we will have if human-induced climate change exacerbates drought magnitudes and duration in the Southwest even beyond what had occurred naturally before we started pumping large amounts of greenhouse gases into the atmosphere. Unfortunately, most computer models of future climate changes in the Southwest as a consequence of increasing greenhouse gas concentrations in the atmosphere point to increasing drought conditions.

Getting back to the topic of forests, I will now focus primarily on wildfires, because others here today are discussing beetle outbreaks. Drought and fire are obviously correlated; but we’ve been learning a lot more about important aspects fire, climate and forest ecosystems in the last 20 or 30 years. In particular, from tree rings, we can obtain a long historical picture of the interactions of climate, people and fire in forest ecosystems. I’ve been very fortunate to have studied giant sequoia over the last 20 years when we have been unraveling these connections.

Sequoias are truly magnificent trees (see Figure 3). Some trees are more than 3,200 years old. They live in a habitat we call a “frequent fire regime” type, or a “surface fire” type. That is, before forest managers begin to put fires out, surface fires burned here about once or twice per decade. We can get a very detailed record of fires by studying tree rings in these trees. For example, you can in Figure 3 see scars as blackened lines within the rings (lower right).
This particular cross section is located in the parking lot in front of the General Sherman Tree, the world’s largest tree, at Sequoia National Park in California. This cross section goes back to about 259 BC, and it has more than 130 different fire dates recorded on it as fire scars and growth changes. Sequoias are well-adapted to fire. I’m skimming over a lot of work on this, but we see that drought and hot periods are very well correlated with the large fire years and highest fire frequencies.

One of the most striking things we find in tree-ring and fire scar studies across the western U.S. is the lack of widespread fire through most of the 20th century. The longest intervals between fires occurred after we began to put surface fires out. Figure 4 is another example from the Southwest: a time series of numbers of sites showing fire scars over the whole region. The history is one of many big fire years and some small fire years.

The 20th century is very different, though, with its greatly reduced fire frequency. This was originally due to heavy livestock grazing by pioneers who brought in huge sheep and cattle herds, which grazed the fine grassy fuels. These grasses carried the frequent surface fires, but after heavy grazing began, the widespread fires tended to cease. Then Smokey Bear (that is, government agencies) began putting fires out very effectively, especially after World War II with the use of surplus aircraft. So, over most of the past century, we have effectively eliminated surface fires from many of these pine forests. Now uncontrollable fires are returning during the hot and dry years, and they are burning with very high severity and through the forest canopies over increasingly large areas.

This historical pattern was typical of the lower elevation, dryer kind of pine-dominant forest, such as ponderosa pine, but also of many of our mixed-conifer types. A lot of this kind of landscape exists in Colorado and elsewhere in western U.S. The consequence of disrupting these frequent fire regimes is changed landscapes, particularly increased woody fuels on forest floors. Figure 5 is an aerial photograph of the Santa Fe Watershed as late as 1935 on the left, and more recently on the right. The scale of these photos is a couple of miles across. The light colored areas in the 1935 image were grasslands or savannas. Then you see on the right, in the modern period, increased forest densities. This is a municipal watershed, so its health and stability is important to the city of Santa Fe. Loss of the forest cover here by extreme wildfires could result in filling municipal reservoirs with sediment, or even breaching the reservoirs, causing devastating flooding.
Now, I want to caution that these kinds of fire regimes and the causes of forest changes are not uniform across the West. This situation I have described is most common in forest types that formerly sustained frequent surface fires. High elevations, where you find spruce, fir, and lodgepole pine, for example, did not have frequent surface fires in the past. So for the most part, this is a change that is particular to the ponderosa pine-dominant and dryer mixed-conifer forest types. Nevertheless, this is a very extensive and serious problem across the West.

The 2002 Rodeo-Chediski Fire burned almost a half million acres and more than 400 homes in Arizona. (The Wallow Fire of 2011 in Arizona also burned more than half a million acres). Fuels and forest changes are a key problem in many of our landscapes, but the changes we are witnessing in recent years are most likely also related to warming temperatures and extreme droughts. Dr. Tony Westerling and a group of other scientists, including me, published a study in the journal Science in 2006, where we showed a striking correlation between rising temperatures across the Western United States and increasing numbers of large fires. This was especially true in the years when spring arrived earliest. There are particular years when the snowmelt occurs earlier and we have seen many more fires. Climate change – warming – is most likely involved along with other factors. For example, invasive species are a real issue in our lower elevations and deserts. African Buffel grass is now allowing fire to spread in the Sonoran desert for the first time, and people are also building homes in these landscapes.

It was interesting to see an editorial in the New York Times (October 31, 2010) about the Colorado River and Secretary Salazar’s initiatives on studying the Colorado River and water problems. The editorial even mentioned tree rings and the extreme droughts of the past they warn us about. One thing in particular that struck me when I saw this editorial was an advertisement alongside the column for the movie The Black Swan. This reminded me of Nassim Nicholas Taleb’s book. The essence of the Black Swan concept is that (1) high-impact, hard-to-predict, rare events have a dominant role in history and (2) people have a very hard time conceiving or accepting that such extreme events can or will occur. People thought there were only white swans in nature, until black ones were discovered in Australia. The point is that rare events – extreme events – are a characteristic of complex and highly interconnected systems, and therefore of economic, ecological and climate history. A first step in coping with Black Swans is recognizing their existence, and the next is to build for robustness and resilience in systems so that they may withstand or recover from the large impacts of extreme events when they occur.

To conclude, I think that to prepare for more Black Swans in coupled human-natural systems, including forests, we need to employ the philosophies of both John Muir and Gifford Pinchot. That is, our goals should include preservation, protection and restoration. Naturalness is still important, but we also need to consider utilization of resources and intensive management as a means of achieving ecological resilience. The fact is: we humans are now the stewards of the Earth’s atmosphere and forests.
Let me start with some basics: Fifty percent of the dry weight of wood is carbon. One cubic meter of wood—that’s about the size of a telephone pole—contains about a quarter ton of carbon, or the equivalent of about a ton of CO2 (carbon dioxide). Figure 1 is a picture of a million cubic meters of wood. It’s a salvage logging operation in Sweden after a massive wind-throw event. The intent was to clear the space for new trees to grow and to use some of that wood for purposes other than just decay. The wood pictured here contains about a quarter million tons of carbon. Humans are burning fossil fuels that emit 8 billion tons of carbon into the atmosphere every year. In terms of carbon, that amount is equal to half of the trees in Canada’s forests … this picture times thirty-two thousand. That’s enough wood to make a two-by-four that you can wrap around the earth at the equator. Not once or twice, but over 200,000 times.

The reason I’m telling you how much carbon we emit into the atmosphere is because it’s a precursor to understanding why CO2 concentrations are increasing. This is the so-called Keeling curve, shown here in Figure 2, that the late Charles Keeling developed in 1958 to measure the CO2 concentration on the northern hemisphere of a volcano in Hawaii. What we see is that CO2 concentrations in the earth’s atmosphere have been steadily increasing. We have, in fact, recently surpassed [an atmospheric CO2 concentration of] 391 parts per million, which is 40 percent above pre-industrial age CO2 concentration levels of 280 parts per million that have been reconstructed from ice cores.

What is more concerning is the rate of increase in our atmosphere, which in the 1990s was about 3.2 billion tons of carbon per year. Since then, we have had the Kyoto Protocol, the United Nations Framework Convention on Climate
Change, and numerous commitments to reduce greenhouse gas emissions into the atmosphere. In the period 2000 to 2009, the rate of increase has risen to 4.1 billion tons of carbon per year. In other words, we’re heading in the wrong direction at an accelerating pace. If we take a closer look at this curve in Figure 2, we see that the mean is increasing over time, but the monthly values are showing a very distinct seasonal pattern in the northern hemisphere.

If you want, we can observe the breathing of the earth. In spring, when leaves come out and plant vegetation in the northern hemisphere starts photosynthesis, the uptake of carbon dioxide from the atmosphere exceeds the releases; and we say the forests and the landscapes are operating as sinks. Then in fall and winter, when there is less or no photosynthesis and emissions from decomposition and decay exceed the uptake from photosynthesis, these systems operate as a source.

Although this is a schematic (see Figure 3), it is deliberate that the uptake arrow is greater than the release arrow because, if we look in detail at human perturbation in the global carbon cycle, we see a very interesting phenomenon. In the period of 2000 to 2009, we have been adding an average of about 7.7 billion tons of fossil fuel carbon to the atmosphere and another 1.1 billion tons from land-use change, which is from deforestation [mostly] in the tropics, the conversion of forest to non-forest land uses. The interesting thing to note is that, of this 8.8 billion tons of carbon, only half remained in the atmosphere. In other words, we humans have been getting a 50 percent discount in terms of the atmospheric CO2 concentration increases for our emissions. For every ton of carbon that we emit, half a ton is taken up by biological systems, mainly oceans and terrestrial systems around the world.

The big question is whether this 50 percent discount will continue in the future. In other words, if climate change and the things we are talking about today are detrimentally affecting the future function of forests as carbon sinks, then the rate of increase of CO2 in the atmosphere will go up greatly. Do this thought experiment: take away the sink of 2.4 billion tons of carbon that forests are contributing, and you will immediately see that the equation can only be balanced by having the rate of CO2 increase in the atmosphere go up. Worse, imagine if these forests were to become sources on a large scale — the rate of CO2 increase in the atmosphere would go up even more.

Central to the scientific questions we’re struggling with right now is this: What will be the response of forests, and terrestrial ecosystems more broadly, to changes in climate? Pierre Friedlingstein and colleagues did a comparison...
of a number of different models of how terrestrial ecosystems might respond and found that there’s a lot of scientific uncertainty; but, qualitatively, we can observe two possible responses. One is that, in a warmer world, trees grow better and there is more uptake of carbon from the atmosphere, what scientists call “negative feedback.” The other is that, with more warming, we’ll get accelerated decomposition, thawing of permafrost, release of carbon from peat and tundra systems, more forest fires, more insect attacks – what scientists call “positive feedback.” In other words, warming will feed the warming.

Now this isn’t just a scientific uncertainty, because the world is struggling to achieve a stabilization of CO2 concentrations in the atmosphere. The uncertainty among the models by 2100, the end of the century, is about 16 billion tons of carbon per year in fluxes; that’s twice the rate of current carbon emissions from fossil fuel burning. When we want to achieve a certain stabilization target, our mitigation effort will depend greatly on whether or not terrestrial ecosystems will help or hinder. In a world where the out-gassing of CO2 from terrestrial ecosystems exceeds the emissions from fossil fuel, we can reduce our fossil fuel emissions by a great amount and CO2 concentrations will still continue to rise.

We have already heard a bit about the mountain pine beetle, and I want to add just a few words about the impact of the beetle on the carbon balance in British Columbia. I know you have a problem here in the [U.S.] West. In British Columbia, the scale of the outbreak is much greater. We had extensive forest fires in the period 1880 to 1920 followed by natural regeneration of predominantly pines or pine-mixed forest. In addition, the successful protection against fires, combined with low harvest rates, has resulted in a landscape with large numbers of old pine trees. More recently, we have had warmer winters that allow higher overwintering survival rates [of mountain pine beetles], and warmer summers that allow higher reproductive success of the beetles, which have expanded their range northward and into higher elevations.

The area now affected in British Columbia is about 41 million acres, an area the size of Wisconsin. When a beetle kills a tree, it has two implications for the carbon balance. First, the tree is no longer removing carbon dioxide from the atmosphere. So, the rate of uptake is decreased, and it starts to decompose. So not only are we reducing the uptake, we are also increasing the release of CO2 into the atmosphere. In 2008, we published a paper in the journal Nature where we quantified the impact of that outbreak in British Columbia. The blue line that you see here on this
graph in Figure 4, shows the annual carbon balance of these forests if there were no beetles in the landscape. In the model, when we conveniently turn off the beetle, you can see that these forests are predominantly a small carbon sink, except in 2003 and 2004 when we had big forest fires in the area. Assuming average forest fire conditions in the future, which one can argue about, we find that, once we turn the beetle back on, the carbon balance in these forests switches from being a sink to being a substantial source.

Over the 20-year outbreak, the beetle impact is about a billion tons of CO2 added to the atmosphere. The annual values currently – we happen to be the peak of the outbreak – are about 73 million tons of CO2 per year. To put that in perspective, the CO2 emissions from all other sectors in British Columbia — burning fossil fuel, coal, natural gas, you name it — are about 65 million tons per year. So the beetle impact is greater than the CO2 emissions from all other sources in British Columbia, which, admittedly, is a large province with a small population density.

Understanding the direction and magnitude of feedback to climate change is essential. Climate changes will affect many processes, including growth, decay and disturbance, with large differences between ecosystems and regions around the Northern Hemisphere and the world. We’re currently not really able to predict the net impacts of all these changing processes together. However, what I dare to say is that there is an asymmetry of risk. As somebody said earlier, it takes a lifetime to grow a tree; it takes one bad event to kill the tree. An analysis that we have done for the boreal forest [of Canada] indicates that it is very unlikely that productivity increases in the forest can offset the increased losses associated with the changes in disturbance regimes. That is supported by everything we’ve heard and will continue to hear today. We need to have more monitoring and more modeling efforts to quantify and understand the magnitude and the direction of the feedback [to climate change].

One of the messages I want to leave you with is that forest and, more broadly, terrestrial ecosystem responses to climate change have the potential to provide positive feedback to future climate change through increased emissions that could completely negate the benefits of our mitigation efforts in all other sectors. In other words, if we let climate change advance too far, then terrestrial ecosystems could start to pump out vast quantities of carbon into the atmosphere. For example, the circumpolar tundra contains three times as much carbon in soil and peat lands than is in the atmosphere. If these systems start to respond in a massive way to climate change, human efforts to reduce fossil fuel emissions could be completely swamped.

I showed at the beginning of my talk that we have been receiving a 50 percent discount on all fossil fuel emissions, and about 27 percent of that can be attributed to the sinks in forests. Limiting climate change is the first important step towards helping us maintain the forest carbon sink. As I showed, climate change impacts on forests could increase atmospheric CO2 concentrations by triggering changes in processes – for example, widespread mortality, accelerated decomposition rates and more fires – that could substantially increase the atmospheric CO2 concentrations.

Lastly and very briefly, I think that what this all leads to is the question of what we’re going to do about it. We don’t have time to go into depth, but I do want to highlight that sustainable forest management and the use of wood and wood products as substitute for more emissions-intensive material, such as concrete and steel, can contribute to climate change mitigation efforts. When a ton of concrete is produced, one ton of CO2 emissions is created. And you can’t get very far with a ton of concrete in terms of building something. So understanding how we can use dead trees created by climate change, how we can use the opportunities created by climate change to grow new trees in regions where they may not have grown before, or where we can enhance productivity through other forest management options will be important to helping us de-carbonize the atmosphere. Forests and forest management will continue to play a role in the future in influencing the carbon cycle, but by themselves, they cannot overcome the problem of fossil fuel emissions.
By providing a global overview of this topic, I’m going to talk about why we are not alone here in Colorado in terms of forest die-off. The two main things this talk will do are illustrate worldwide patterns of drought and heat-induced tree mortality and discuss some of the scientific uncertainties that currently inhibit us from being able to predict future risks of climate-induced forest die-off.

Certainly hot and dry conditions in the past have been observed to drive episodes of forest health problems and tree mortality, illustrating that the causal linkages between severe drought and tree mortality are not unusual. They are really nothing new or surprising; but, at the same time, there are some places on this planet where trees are growing better recently than we’ve ever measured before. So it is certainly reasonable to ask: Is there is any reason for concern about the broad-scale forest die-off events we see today? Although in earlier talks today we’ve heard about particular examples of extensive climate-related tree mortality here in western North America, perhaps, at the global scale, this is being balanced out by more productive growth elsewhere.

Well, there is one particular climate trend occurring lately that is different than any other in the past thousand years: a significant warming of the world. An immense amount of research has been done on the topic of climate change, and a substantial scientific consensus exists that the planet has been warming rapidly in recent decades. This warming trend is projected to continue, along with a greater range in extreme climatic events such as severe droughts (IPCC 2007). Such climate changes could be driving increased tree water stress in many areas and thereby increasing risks of stress-related tree mortality. If so, we might expect to see patterns of greater tree mortality and forest die-off emerging in at least some forests.

In recent years, I have been working collaboratively with colleagues in the U.S. and abroad to document examples of drought-driven tree mortality on all forested continents and to assess whether any new trends were beginning to emerge. One result of these efforts is a paper, including twenty co-authors from around the world, published a year ago (Allen, et al. 2010). It is the first recent global overview of this phenomenon. One of our core findings is that there is no major forest type on the planet that is immune to the effects of drought and heat-induced tree mortality, with significant forest die-off observed from tropical rainforests of the Amazon Basin to boreal forests in Siberia and everything in between.

The map in Figure 1 shows the main climatic limitations to vegetation primary productivity. The bluish colors are where it’s limited by temperature. The reddish color is where it’s limited by water availability (note the deserts of the world). The greenish areas generally represent the tropics, where water and growing season length are usually adequate, but sunlight is limiting. So a broad range of different climate conditions limit vegetation productivity across the Earth. The superimposed dots indicate places we documented where there have been significant drought-related forest die-off events in the last 25 years. A key point is that drought and heat-driven tree mortality occurs widely across this whole environmental spectrum, and it can happen even in very wet places like Borneo and the heart of the Amazon Basin.

The 2010 global overview paper has satellite image maps of each of the six forested continents with numbers marking documented drought-induced mortality areas. Here, for example, are the maps for North America and Europe (see Figures 2, 3). The map numbers tie to continent-by-continent tables that list details and references for each mapped mortality event. The tables give specifics of what happened at any of the numbered map locations (e.g., type of forest and tree species involved, dates of tree mortality, size of affected area, etc.).
Also included here are a few photos illustrating examples of drought-induced tree mortality from around the world. The dead trees in Figure 4 are Atlas cedar (Cedrus atlantica) in Belezma National Park, Algeria, exhibiting wholesale die-off from severe drought between 2000 and 2008. Essentially the Sahara is moving north toward the Mediterranean Sea, and most of what is still green here is an evergreen oak (Quercus ilex) that remained alive after the taller cedar had died.

Note that in the global overview paper we only included recent examples that are securely documented in the (mostly English language) scientific literature, although apparently there are many other examples of drought-induced tree mortality known to local foresters and researchers around the world that currently are not reported in that particular way. For example, in Australia we were able to document recent drought-induced tree mortality only from Queensland in the northeast, where eucalyptus and acacia trees died across many millions of acres (see Figure 5); however, through interactions with various colleagues, I know of examples from southern and western Australia that haven’t been written up yet in the scientific literature. The pictured eucalyptus and acacia species in Figure 5 are evergreen, so when they look leafless in the photo, they’re dead.

In Asia, drought-related tree mortality has been occurring along the forest-steppe ecotone of inner Asia, and millions of acres in southern Siberia are being affected by various kinds of drought and heat-related tree mortality. Other
Asian examples of forest die-off extend from Turkey in the west across to China and Korea in the east, and southward down into India and the tropics of Borneo. Whereas El Niño climate events tend to bring wet winter weather conditions to the southwestern U.S., El Niño conditions often bring drought in the tropics. The strong El Niño in 1998 left a signature of tropical tree mortality from Southeast Asia to the Americas. In South America, the 1998 El Niño even caused significant mortality of southern beech trees (Nothofagus dombeyi) in the temperate forests of Patagonia in northern Argentina, while severe droughts in 2005 and 2010 have driven substantial tree mortality in the Amazon Basin.

In Europe, a lot of documentation exists from some regions, particularly around the Mediterranean where much good work is being done by strong research groups in Spain, France and Switzerland. Drought-related mortality of Scots pine (Pinus sylvestris) is observed in all of these countries (Figure 3), from the Pyrenees and Provence to the Alps, in both native forests and plantations. Spain alone has more than ten million acres of reforestations with various pine species, which are emblematic of similar landscapes all around the arc of the Mediterranean, where, in the past century, pine plantations have been established across extensive areas that have been desertified by intensive land uses over the past three thousand years. In the past two decades, we see signs of significant water stress, growth declines, and tree mortality emerging in these often-dense pine plantations, particularly associated with drought events and warmer temperatures.

Finally, in preceding talks, we’ve heard about examples of recent big forest die-offs in western North America, including sudden aspen decline here in Colorado and the huge lodgepole pine (Pinus contorta) mortality event in British Columbia. In addition, one of Werner Kurz’s colleagues just published documentation of aspen dieback and mortality affecting more than two million acres in Alberta and Saskatchewan, associated with warm drought in the 2000’s (Michaelian et al. 2010). Similarly, severe and warm drought affected the southwestern U.S. from 2000 to 2004, driving significantly higher levels of mortality regionally for most tree species. For some species, like ponderosa pine (Pinus ponderosa) and Colorado piñon (Pinus edulis), substantial mortality and even wholesale die-off was mapped across millions of acres (Breshears, et al. 2005).

For example, Figure 6 shows the Jemez Mountains near Los Alamos and Santa Fe, New Mexico in the fall of 2002 — all of those orange-colored trees are dying piñon. A repeat photograph of that exact same view 19 months later (see Figure 7) shows the skeletons of the dead piñon trees as numerous grey stems; the small green trees still present are the more drought-tolerant one-seed junipers (Juniperus monosperma). This die-off of the dominant piñon trees has caused a major alteration of the ecology of this landscape. Although a cohort of young piñon seedlings and saplings survived and continue to grow on this site, it will be literally decades before they will be mature enough to become seed sources for future piñon regeneration.
Now I’d like to briefly discuss some of the scientific uncertainties associated with climate-induced tree mortality. Three big uncertainties exist. First, we see that there are examples of significant of forest mortality being reported from many parts of the world recently, but maybe this is nothing unusual. Are new trends emerging globally? In the past two years there has been new research published showing increasing drought and heat-related forest stress and mortality in portions of southern Europe (Carnicer et al. 2010) and the Amazon Basin (Phillips et al. 2009, Lewis et al. 2010). And certainly in western North America, background tree mortality rates have increased recently (van Mantgem et al. 2009), and the magnitude and huge scale of climate-stress and bark beetle-related episodes of extensive forest die-off in western North America over the past two decades are apparently unprecedented in the historic record of the past 100-plus years (Raffa et al. 2008).

But what about at the global scale? Figure 8 displays patterns in the scientific literature on this topic from 1984 to the present, as a percentage of all forest related scientific references. We see that there is a very strong trend of an increasing percentage of references that are looking at forest mortality associated with drought. While this does not prove that more forest mortality is occurring on the ground, it does mean that more scientific interest and attention exists on this topic.

For example, a paper came out last summer that used satellite imagery across the planet to look at terrestrial vegetation net primary productivity (NPP), which is basically land plant growth averaged for the past 10 years across the Earth’s land surface (Zhao et al. 2010). The authors found that overall NPP had declined globally over that 10-year period because of drought stress across large parts of the earth, which was contrary to many projections that, with increasing CO2, global NPP would increase. While there are hints that worrisome trends in global forest health may be emerging, we cannot yet determine definitively if worldwide tree mortality rates and forest die-off events are rising, because we lack long-term measurements of forest health trends at a planetary scale. Accurate documentation of global forest mortality patterns and trends requires the establishment of a worldwide monitoring program that will likely combine satellite remote-sensing approaches and ground-based measurements in a coordinated and consistent manner.

A second big uncertainty comes from the difficulties in determining the physiological stress thresholds of tree mortality well enough to rigorously predict mortality in computer models that link climate to tree growth and death. Basically, as ecologists, we know how to grow trees fairly well in computer models, but we don’t know yet how to kill them reliably in quantitative, process-based ways (McDowell et al. 2011). Trees have a variety of ways to buffer themselves from stress, and they commonly die gradually or incrementally, challenging our ability to precisely determine how or even when they died.

For only a few tree species do we know in a controlled laboratory situation how much water stress an individual tree can take before it dies. In uncontrolled real landscapes, many interacting factors further complicate understanding and modeling tree mortality responses to drought and heat stress, ranging from diversity in site conditions (slope, aspect, soils, variable temperature and precipitation patterns) to competition with other plants and feeding impacts from animals. Actually, in many cases we are unsure whether drought-stressed trees die from direct desiccation effects, indirect starvation as they can not photosynthesize carbohydrates adequately when severely water-stressed, from the primary or secondary effects of attacking insects and diseases (McDowell et al. 2011), or from some combination of these processes.
Scientists are now just beginning the experiments needed to better document these physiological responses and mortality processes to determine how even a few specific tree species respond to particular kinds of stress. Because we currently lack the knowledge needed to accurately predict major episodes of tree mortality, we continue to be surprised when a big forest die-off event occurs. Another reason why we’re taken by surprise when extensive tree mortality happens is because it commonly manifests as a non-linear threshold response to a variable climate. A drought-stressed forest may look relatively healthy for some extended period of time, until a tipping point of some sort is reached. Then trees can suddenly begin to die en masse.

Until we better understand the various non-linear threshold processes that underlie tree mortality, projections of future tree mortality risks in response to climate variability and change will remain quite uncertain. But given that the best current global climate models show that by 2100 many of the world’s climate patterns will shift somewhat, it is reasonable to expect these climate changes to drive substantial shifts in the distribution of most major ecosystems, including forests. And from the examples of drought and heat-induced forest die-off recently documented around the world, one manifestation of the expected ecosystem shifts is likely to be substantial climate-induced tree mortality in at least some regions.

Finally, a third major scientific uncertainty I want to mention is our limited knowledge about diverse feedbacks between forests and the overall Earth system (Lenton et al. 2008, Adams et al. 2010). Forests cover about 30 percent of the world’s land surface and provide many important ecosystem services, including capturing and sequestering about one-quarter of the excess carbon that humanity releases into the atmosphere every year through tree growth. But there are risks that this huge pool of forest-stored carbon might not be stable if growing climate stress drives widespread tree mortality, and global forests could release a lot of this stored carbon back to the atmosphere, potentially becoming a further positive feedback for greenhouse gas concentrations and associated climate warming.

Forests are important in modulating the water cycle at scales from local to global, and forests partly drive how much sunlight is absorbed at the Earth’s surface, and how much is reflected, affecting planetary heat fluxes. Any major changes in the world’s forests will have big feedbacks to the whole earth climate system. Another related topic area that we don’t know enough about includes the feedbacks and interactions among climate-induced forest stress and other tree-killing processes like fires and insect outbreaks. Given these various uncertainties, additional monitoring of global forest health and new research are needed to improve scientific certainty regarding risks of future climate-induced tree mortality.

In conclusion, let me say that forests are extremely important to people as well as to the planet. The earth is graced with a great diversity of forests that are essential to local and global ecologies and economies. Forests and even unique individual trees also are widely revered by societies for many less tangible reasons, including the timeless sense of continuity and enduring character they provide to particular regions and local landscapes. As mature trees typically can live much longer than any person, so forests often seem immutable, essentially permanent, with any natural changes so gradual as to be imperceptible. But we see that climate stress can cause big forest die-off events to emerge in just months or a few years. Because people care about forests at many levels for many reasons (see Figure 9), a focus on forests is one good approach to get people to pay attention, sooner rather than later, to the actions we all need to take, individually and collectively, to ensure the ongoing continuity of healthy forests.
Dr. Joyce’s research has focused on quantifying climate change impacts on ecosystems, wildlife habitat and forests and also on developing adaptation options for their management. She is a climate change specialist for Resources Planning Act assessments in the Forest Service charged with identifying and coordinating analysis of the potential effects of climate change on U.S. forests and rangelands. She has contributed to various publications and studies on the first synthesis of management options available for national forest managers incorporating climate change considerations. She received her Ph.D. from Colorado State University, and was recognized with the Forest Service Deputy Chief’s Distinguished Science Award in 2010.

What have we read so far in this e-book? Ecosystems are changing in response to observed changes in climate, extreme events, and disturbances such as fire and insects. We read not only that these changes are occurring but that we should expect them to continue – changes in temperature; more extreme events; and more disturbances such as fire and insects that are not like the past. Key point: these changes in climate and ecosystems are now part of the environment in which resource management occurs.

Resource managers base decisions on experience, an ever-developing field of scientific information and the local climate. Imagine driving from Aspen in the mountains to Fort Collins on the northern plains of Colorado. The tree species change from spruce and fir trees to ponderosa pine and then to only grasses, no trees. The vegetation differences are the result of different climates. Resource management in the forests around Aspen is different when compared to the ponderosa pine forests in the foothills and even more so when compared to the grasslands outside of Fort Collins. Various kinds of resource management activities used in these ecosystems are influenced by the climate in these ecosystems, such as when and what types of logging occur, how and when areas are protected for animals breeding, when and what type of prescribed fire is used and what size the road culverts are.

We can think of these management activities as tools in a toolbox. These tools have been developed based on the experience of natural resource managers and research scientists and reflect the climate in a given area. Because the toolbox reflects the climate in each area, we might ask, “Are the current tools in the natural resource management toolbox appropriate for managing our National Forests under climate change?”

Adapting to climate change typically has two goals: reducing the vulnerability of ecosystems and human communities; and enhancing the resilience of ecosystems. Let’s look at the first goal: reducing the vulnerability of ecosystems and human communities. We would say that an ecosystem is vulnerable when it is unable to cope with the adverse effects of climate change. Scientists have established that, over a long period, ecosystems have adapted to a certain frequency and intensity of fire. Thick bark on ponderosa pines gives it the adaptive capacity
to withstand periodic surface fires. Climate change will likely alter the kinds of fires and how frequent they occur. Under that future, ecosystems that have evolved over time to be resilient to fire could now be vulnerable to these different fire regimes. Whether that happens in your area is a function of what is happening to climate in your area. Is the temperature changing? According to the Colorado Climate Report, the temperatures in Steamboat Springs, Grand Junction, and Montrose have warmed over the last 100 years. Understanding what the changes are in your area begins the conversation on how your ecosystem or community may be vulnerable.

What have we learned from past natural resource management and extreme weather events? Lake Tahoe in Nevada, noted for the clarity of the lake water, is surrounded by forests, some managed by the U.S. Forest Service. Winter storms are a regular part of the climate here. The standard practice when any vegetation management treatment is done is to have the erosion protection devices in place before winter storms begin, more specifically by Oct. 15. The erosion protection devices are a tool in the natural resource management toolbox. These winter storms can be very wet. In 2009, a winter storm was forecast in early October, the first of the season. All accounts pointed to this first storm being a large one. Indeed, it was. 3.2 inches of moisture fell on October 14, more than 3 times the average for that day based on 101 years of weather data from the Tahoe weather station. Key point: the date, October 15, reflected an understanding of when winter storms typically, normally, usually start. Instead of looking just at the calendar, now we might need to look at the forecast as well as the calendar, and in so doing begin to determine if the dates associated with our resource management need to be changed. Learning from experience and iteratively incorporating lessons into future resource management is adaptive management in its broadest sense.

Let’s look at the second goal: enhancing the resilience of ecosystems to the changing climate. We would say that an ecosystem is resilient when the same plants and animals can return after a disturbance such as wildfire. Stresses such as air pollution, invasive species, and fragmentation of habitat can reduce the ability of an ecosystem to return after a disturbance. The goal of enhancing the resilience of ecosystems would mean an attempt by resource management to reduce these stresses — reduce air pollution, remove or reduce the invasive species, and attempt to reconnect habitat for wildlife.

We have to keep in mind that the changes will continue and that these changes are directional. Key point: the temperature is warming, yes it will be variable, but the trend is directional. What does directional mean? Think of a balloon. Press your finger into the balloon, just a little and then let go. The balloon returns to its original shape. Press your finger into the balloon again, further and further – this is directional change. The balloon can only withstand so much directional change. For ecosystems, directional change in temperature means that at some point, the plants and animals on the landscape we know today may not be the plants and animals that will be best suited, adapted, to that landscape under climate change. We are seeing changes on the landscape today where plants and animals are not returning to develop the type of ecosystem before the disturbance. Plants and animals are reactive in response to climate change; they do not anticipate. Humans can anticipate. Preparing for these events is a necessary step in enhancing our adaptive capacity and it is also our greatest challenge.

In the West, changes associated with climate are very likely to be abrupt — a major fire, a drought, an insect outbreak, or a combination. When these abrupt changes occur, it may be important to be ready with a strategy for facilitating the new ecosystem conditions. Here management must be flexible, perhaps experimental, and we must learn with every step we take. Even outside of these events, it may be necessary to anticipate. As we learn more and begin to understand that the plants best suited to our landscape will be different, we may to begin
managing transitions to these new ecosystem conditions. In these situations, managing for adaptation means promoting efforts that sustain desired long-term ecosystem functions, such as maintaining soil productivity and health, maintaining watershed health, hydrological cycles, promotion of native flora and fauna, and maintenance of amenities that human communities depend upon from the National Forests, even in the face of eventual loss of the plants and animals as we know them now in many or most areas.

Much scientific information is available. My colleagues and I have found the most successful way to weave this scientific information with the on-the-ground experience of natural resource managers is a science-management partnership. This partnership can take many different forms from a one-day workshop, to a yearlong arrangement.

This partnership provides a place to ask the question about whether we have the tools in the natural resource management toolbox to reduce the ecosystem vulnerabilities and to manage the ecosystems for resilience, and to begin the conversation about managing the transitions to novel and new ecosystems. The key point here is that it is not so much talking as it is listening. Through these conversations, new ways of looking at natural resource management emerge. Can current tools be used? Can current tools be applied in new ways? Do we need new tools?

Rather than thinking about climate change as a problem, we might envision this as a puzzle. Each of us has a piece of that puzzle and all of our pieces are needed in order to create the picture of the puzzle. We know part of that picture. Temperature is warming and will likely continue to warm. There will be more extreme events, and disturbances such as wildfire and insect outbreaks will be different from our historical past. The resource manager must begin to contemplate whether the current tools in the natural resource management tool box can still be used, could be used in a new way, and what new tools are needed. By studying new questions, it helps us understand how climate and ecosystems interact. Scientists have the responsibility to bring that new information into natural resource management.

The National Forest, as well as the National Park, the Bureau of Land Management and the National Wildlife Refuge, must look across the boundary lines. The bark beetle outbreak in Colorado has taught many local, state and federal agencies, as well as private landowners, that these altered disturbances do not stop at the property line. The magnitude of such a large-scale event requires a coordinated response across the landscape. The greatest challenge is anticipating these large-scale events, managing them and adapting to large-scale changes.

The public must also be involved, and you can get involved in many ways. You can be the eyes on the landscape. You can be a volunteer observer in the CoCoRaHS network – the Community Collaborative Rain, Hail and Snow Network – measuring and mapping rain, hail and snow. This network aims to provide the highest quality data for natural resource management, education and research applications. Or you can be a volunteer observer of the National Phenology Network. What is Phenology? It is the recurring plant and animal
life cycles, such as leafing out and flowering. Scientists know that these events are sensitive to climatic variation and change. Observers watch for when a flower blooms, or when insects emerge, or birds migrate. As an NPN observer, you can help scientists identify and understand environmental trends so we can better adapt to climate change, and share your concerns with natural resource managers and scientists.

Each of us has a piece of that puzzle and all of our pieces are needed in order to create the picture of the future of National Forests and enhancing our adaptive capacity.
I present myself as a non-scientist. As educators and land stewards at the Aspen Center for Environmental Studies (ACES), we lean on scientists, but we are not scientists in the purest sense. I’m going to talk about two stories that I think contain some hope. I’m going to share a couple of stories motivated by a can-do, let’s roll up our sleeves, wade in, and try to make a difference attitude. The stories have to do essentially with water: using water to restore ecosystems and to sequester carbon. We think a lot about water. We do a lot of outdoor plumbing and we have beavers that are always trying to flood the world. We’re trying to keep the beaver and also provide for biodiversity in each of our sites.

To jump to the first project: about a dozen years ago, the Forest Service asked ACES to be the volunteer project coordinator of the repair of a peat bog on Smuggler Mountain. On the top of that mountain, a series of peat bogs formed 12,000 years ago after the last glaciation were leaking because they had been ditched and drained for mining in the 1940’s. They weren’t functioning well as ecosystems, so we went in and repaired the leaks. We did it fairly quickly and efficiently and I take a lot of pride in having recovered that landscape (see Figure 1).

Incidentally, while we were doing that work, two biologists from Tibet were helping us. We had no idea if they had any idea what we were saying. They had learned English a couple of weeks before they arrived. After they went home we learned that they had understood our wetland reclamation project and its value. They went back to Lhasa and the Lhalu Wetlands (meaning the lung of Lhasa) in Tibet. The people of Lhasa regard it as a very important ecosystem. Yet of the 3,000 acres, half of that landscape had been dried out. It was covered with cattle and wasn’t functioning well as a wetland. The Tibetan biologists went back and said, “you know this just isn’t right, we need to re-wet this. We’ve seen how this is done.” In the first year, they recovered about 10 percent of what had been lost. They have about another 1,500 acres to continue their work at re-wetting that wetland.
After finishing the work at Warren Lakes, we became aware of the peat dome of Indonesia, which you may know is the third largest contributor of anthropogenic carbon to the atmosphere after the United States and China. We went back and took a look at the work we did and discovered that not only had we recovered these wetlands and encouraged the recovery of a much bigger wetland in Tibet, but we also managed to sequester a fair amount of carbon. Doing the numbers and as much research as I could, I discovered that what we have sequestered at Warren Lakes, which is 50 acres, is somewhere between 500 and 3000 tons of carbon a year for about a 100 years. We at ACES feel pretty good about that, and it was inadvertent. At Lhasa, the numbers suggested that 180,000 or 200,000 tons of carbon is sequestered annually, again for a long time.

There are things that people can do that are fairly simple. I heard in an earlier presentation today that $2-300 per ton was the cost for carbon sequestration with scrubbers. My numbers for Warren Lake suggests the cost was about 20 cents per ton, if you stretch it over 100 years.

ACES has a 160-acre site on the Fryingpan River that we’re regarding as our future site for green technology training (see Figure 2). We have several levels of training. The first level that I’m coining a new term for is Green Leafy Technology. That’s not what you might think. It’s like insulating your house before you put the solar panels on the roof, using the environment as a source of carbon sequestration and repairing ecosystems. We’ll also employ other technologies – installing hydro, solar and heat pump technology – and we’ll engage students in a field station setting.

The Native Americans whose ancestors lived here until just a short time ago comprise another student audience we plan to engage at the ACES Fryingpan site. They and other groups will come and be trained at this site, where they’ll get hands on experience installing green technology – from the Green Leafy Technology of ecosystem restoration to the hard, traditional green technologies. We’ll be contributing to a new generation of green technology experts who can apply their skills towards building a more hopeful future.

Figure 2: The Aspen Center for Environmental Studies Spring Creek site. Photo credit: Tom Cardamone
References


