

Forest Management for Mitigating Drought Impacts

Amanda Cucchi: [0:05] Welcome to the US Fish and Wildlife Service's National Conservation Training Center in Shepherdstown, West Virginia. My name is Amanda Cucchi, and I will be your host today.

[0:14] I would like to welcome you to our webinar series held in partnership with the US Geological Survey's National Climate Adaptation Science Center.

[0:22] Today's webinar is titled, "Forest Management for Mitigating Drought Impacts." We are excited to have Dr. John Bradford from the US Geological Survey with us today.

[0:32] I'm going to pass the mic over to Dr. Abby Lynch, a fish biologist at the National Climate Adaptation Science Center, who will introduce our speaker today. Take it away, Abby.

Dr. Abigail Lynch: [0:43] Thank you. Hi. I am Abby Lynch. I'm a research fish biologist with the National Climate Adaptation Science Center. It's my pleasure to introduce Dr. John Bradford, who is a research ecologist with the US Geological Survey's Southwest Biological Science Center.

[1:00] John studies the impact of global change on terrestrial ecosystems, focusing on the understanding of how changing climate conditions and when these practices influence terrestrial vegetation structure and composition.

[1:13] His interests tend towards large spatial and long temporal scales and integrate with research results from manipulative and observational experiments with simulation modeling to develop applied insights at scales from plots to landscapes to regions.

[1:31] John's current research projects include quantifying past, current, and future patterns of drought, and implications for sustainability of dryland plant communities.

[1:41] Welcome, John.

Dr. John Bradford: [1:43] Thanks, Abby. Thank you for hosting us. I really appreciate it.

[1:46] The work I'm going to talk about today is a part of a longstanding collaboration between a fairly large group of people, most of which are shown on here. I do want to highlight a few folks that have been really an integral part of this for, I think, it's over a decade now.

[2:03] We've been working on these same topics and some of these same long-term analyses, in particular, Brian Palik with the Forest Service in Northern Minnesota, Shawn Fraver, who is now with University of Maine, and Tony D'Amato at the University of Vermont now.

[2:18] The four of us really started these ideas of using these long-term forest management experiments to provide some insight about the potential impact of climate change.

[2:29] I'm here in the Southwest Biological Science Center with the USGS in Flagstaff, Arizona. My work, including the stuff I'm going to talk about today, really focuses on trying to think about the challenge of climate change and the challenge of increasing drought, and what that means for terrestrial ecosystems.

[2:45] It's really apparent that the challenges represented by climate change are quite clear. We see a lot of increasing evidence for long-term directional changes in temperature, long-term increases in the eco-climatic variability, and that has a lot of expected impacts on ecosystems.

[3:04] The solutions are relatively rare. They often are these generalized ideas, like, "Well, we should manage for a change," recognize things are going to be different than that. That's good.

[3:14] We should maybe develop strategies that hedge our bets so that no matter which direction things go, our systems will continue to function. That's also nice, but they may not be really as useful as we'd like to get in terms of developing specific strategies.

[3:28] A lot of my work really focuses on two things. One, trying to constrain the uncertainty about the trajectories that we expect, both with respect to what are the conditions that are relevant to ecosystems and what directions are those going.

[3:41] Also identifying, as much as possible, some specific strategies that may be useful for promoting sustained resistance and resilience. It's really that last point that I'll talk mostly about today, which is thinking about specific strategies.

[3:55] Really, the key questions I want to think about both relate to the potential benefits of forest thinning, for promoting resistance and resilience to future droughts and future weather extremes, in general.

[4:08] There's two questions here that I want to talk about. One is how does forest thinning alter the vulnerability of tree growth to drought. This is going to be probably the lion's share of the talk. This is the big long-term experiment that the Climate Adaptation Science Centers were generous enough to fund in the past.

[4:25] This work really involves using some long-term forest management experiments. I'll talk more about that in a minute. The nice thing about this is it represents really broad climatic gradient. We can look for the consistency and generality of some of the ideas.

[4:37] The second one is a little more specific to our neck of the woods down here in the Southwest. It's thinking about to what extent can thinning promote sustainability of forest in these dry areas. In particular there, I'm going to look at both tree mortality and regeneration patterns, which...There's a lot of expectations that are going to be pretty heavily impacted.

[4:56] Let's start with the overall growth topic. This work really has been utilizing and taking advantage of some of these long-term, what they call growing stock level experiments. These are experiments that manipulate forest density. The amount of basal area per unit ground area that exists on a site.

[5:15] These were originally set up by the Forest Service typically all over the country in various places. They have treatments that might expand from an un-thinned control. That's extremely dense down to less than stands all the way down to quite low-density forest stands.

[5:31] A lot of them also have clear-cuts as well. These growing stock level experiments have been one of the really well-replicated, long-term experiments that the Forest Service has set up.

[5:44] They maintain these stands. Most of them were set up in the '50s or '60s. They randomly assign treatments, which is really forward-thinking for that time. They replicated their treatments, so it's really this gold mine of potential insights.

[5:59] They're originally designed to evaluate growth and yield, so the timber benefits of different thinning regimes. That was certainly very useful at the time. They also represented real opportunity, because they are a gradient in competitive intensity.

[6:11] The higher density stands keep trees in environments that have a lot of competition for resources, including water during drought. That's useful for evaluating the potential influence of competition on the way that these systems respond to droughts and other events and looking for interactions between density and drought events.

[6:34] The other big picture thing to keep in mind is that in wood forests, the potential for thinning is one of the most obvious management strategies that we could adopt. Having a really good handle on where, when, and how much thinning can be beneficial is an obvious thing that would be very useful to know.

[6:52] In all these sites, I'm not going to talk a lot about our methodology. We developed annual growth chronologies for these forest stands maintained at different densities using dendrochronology.

[7:02] We cored a whole bunch of trees and cross-dated them and developed chronologies. Then related those inter-annual patterns and growth to fluctuating drought conditions and then looked at the influence of density on that.

[7:14] This work really started, as I said, for more than a decade ago now with just one site up in Northern Minnesota, the Birch Lake red pine plantation. As I said, we established measurement plots and cored all the trees in relatively large measurement plots.

[7:28] We're able to develop chronologies that look like this where you've got inter-annual variability, and this is tree growth. This is per tree as shown in this particular plot. It fluctuates through time.

[7:38] Then around here is where the experiment was originally set up. You see growth tended to increase on a per-tree basis. The most in the low-density stands, because they have the least competition. There is less growth in the high-density stands.

[7:51] These inter-annual patterns provide a lot of ability to look at how this relates to drought. We started out with a relatively simple analysis, looking at a measure of resistance and measures of resilience.

[8:03] Resistance is the magnitude, the extent to which growth was maintained during a drought event. Higher values mean greater maintenance of growth during the drought. Resilience is the magnitude to which growth was recovered after the drought event.

[8:21] For both of those metrics, I'm showing resistance on the left, resilience on the right as a function of basal area routine. This is low-density on the left and higher density on the right.

[8:31] You can see in both cases, we found evidence that the higher the density, the lower the resistance and the lower the resilience. This suggests that there really was a pretty clear and demonstrable effect of density on the way that these stands respond to drought.

[8:46] We then expanded this to some other sites, including one in South Dakota and one down here in Arizona, where I am. These are both red pine stands. The nice thing about these is they both included control stands that were never treated.

[9:00] You can see those lines pass along the very bottom that it did not change when the experiment was set up. We replicated that same framework of looking at how these systems respond during known drought events. We really focused in on when we knew these sites experience the droughts.

[9:16] What I'm showing here is the Minnesota site across the top, South Dakota in the middle, Arizona across the bottom. In all cases, the x-axis is from low density on the left to high density on the right. In this case, we've standardized the densities using relative density.

[9:33] Resistance is on the left. Resilience is on the right. For each of those, I'm showing two droughts. One drought in the left column of each pair that is early in the experiment to see if maybe there are effects that initially occur.

[9:46] After you maintain the basal area densities for several decades, maybe those effects tend to disappear. The big picture here is that in almost all cases with the exception of the later drought in Minnesota, we do see that the higher density the stands are maintained at lower overall resistance and resilience in growth they have during drought patterns.

[10:06] This really suggested that there's something here. There's something worth exploring in a much broader basis.

[10:13] We then started looking at what other sites we could try to include. That's where we expanded this to what we have now, which is eight sites, ranging from three of them I've already mentioned here. The one in Arizona, South Dakota. We're going to have two now in Northern Minnesota that are both red pine.

[10:30] One northern hardwood in Northern Wisconsin. An oak site in Ohio. A hardwood site in New Hampshire. A coniferous site in Maine as well. These represent a pretty dramatic aridity gradient as expressed by the colors in here.

[10:46] Just to remind you or let you know, I'll keep these colors for these sites throughout the talk, so that the redder side is always the hottest, and this blue side is always the hottest and driest. This represents a really broad range of climatic conditions. All of these have the same replicated, controlled experiments, looking at density over several decades.

[11:09] It's a pretty rich data set. We were able to collect cores, characterize inter-annual tree growth at the stand level across this record, and cross-dated over 6,400 trees. A really tremendous effort. This took resources and support from a number of different sources.

[11:27] The National Climate Adaptation Science Center was very helpful in providing the resources to really pull all this together, and do some analysis about the generality of patterns that we see, so we can learn about how density influences the way that these stands respond to drought. That's what I'm going to talk about now.

[11:47] Just to let you know, one of the challenges in doing this was that these stands all have different growth levels. The ones in the hotter, drier places generally grow less than the ones in the wetter places. We standardized all of our metrics.

[12:00] We standardized drought by using the Self-Corrected Palmer Drought Severity Index. We standardized density by putting all these in a relative density basis. We standardized growth by de-trending and standardizing each one, so that a good growth year means the same thing in all sites. Unusually dry year also means the same thing, at least as much as we could, across all sites.

[12:22] This developed a pretty large data set. We've done a fair number of things with it. What I'm going to talk today about are attempts to define and evaluate the responses for three specific metrics. The first is what we call the forest growth response to drought.

[12:40] This is just quantified as the slope of growth as a function of drought. How much does growth decline as conditions get drier? I'll talk about these again as I go through them. The second thing we wanted to explore was the explanatory power of drought versus density.

[12:55] This is the R squared of the proportion of variation in growth that can be accounted for by drought, versus the proportion that can be accounted for by stand density. The third thing we wanted to look at was the density impacts on growth response.

[13:10] This is the difference in the slope of growth versus drought between a high and a low-density stand. How much does density itself alter the way that the forest responds to drought? This all hopefully describes a little bit how we quantify these. We didn't want to just have general ideas.

[13:28] We wanted to actually develop things we could quantify across these broad gradients. I'm going to walk you through each of these. Show you a little bit about what we expected and what we found, in terms of broad patterns in these responses.

[13:38] The first one is forest growth response to drought. Again, this is just the slope of how forest growth shown in the Y axis here relates to drought. Generally, you would expect growth to decline during drought periods. Our hypothesis would be that it would decline more in a dry site or in a particularly dry period at each site.

[14:00] For each site, we broke the long-term several-decade chronologies down into 20-year periods, and looked at how these responses varied through time as well. We expect it to be less

responsive in either humid sites or low-drought severity periods. You have a greater negative slope when things are dry, or in dry places.

[14:22] Our hypothesis is greater response in dry places and during dry times. First, we'll look at the broad spatial patterns and average growth response to drought. We find that growth does decline as a function of drought in almost all the places.

[14:41] There's a couple of the sites in the intermediate levels that really didn't display very consistent patterns. Most of the sites had clear negative relationships, which is what you'd expect. There's really no evidence that those negative relationships are any steeper in the dry sites. This was a bit of a surprise.

[14:54] We thought that certainly the Arizona site would have a greater decrease in its growth during dry conditions than some sites in the northeast. This was certainly a surprise. This suggests that really, drought has a pretty substantial influence on growth in all of these sites.

[15:09] That was our first surprise in looking at these data. We also looked, as I said, at how the growth response throughout varies through time at each of these sites. What I'm showing here, each of these panels is one of the Experimental Forests from arid sites in Arizona here, moving to more intermediate conditions, and then down in the lower right to the wetter sites.

[15:29] What we're looking at here is how the forest growth response varied during the average drought severity during 20-year periods. When a site was in especially dry conditions, that's on the right. When it was on unusually wet conditions for that site, it's on the left. We would expect relationships to have greater negative slopes when things are especially dry.

[15:51] We did observe that in some of the sites, which include these two drier sites. We also observed exactly the opposite at some of the other sites, including the Cutfoot Experimental Forest, the Northern Wisconsin hardwood forest, and the New Hampshire Bartlett Experimental Forest, where we actually see the opposite.

[16:09] Growth was most responsive, the largest negative slope, when those sites have relatively wet conditions. This is something that was also a little bit of surprise, and some nice differences across these sites.

[16:22] The second metric that we wanted to look at was to try to understand the explanatory power of drought versus density.

[16:29] This is the proportion of variation in growth that's explained by either drought or density. This one's a little bit harder to convey in a nice little diagram, but it's shown here. This is forest growth as a function of drought.

[16:40] The way that this could be conveyed is that in a relatively humid site or a low-severity drought period, you might have high-density and low-density stands both declining, but perhaps there's a larger difference between high density and low density.

[16:52] Your density impact is greater, and your drought impact is overall less, whereas your arid site might look more like this, which you have a higher R squared for drought than density.

That was the hypothesis we expected. We expected greater explanatory power for drought, when conditions are dry or in dry places.

[17:13] We'll look at the broad patterns across, in terms of average influence of drought. This shows mean explanatory power over the whole several decades of the study as a function of aridity from wet sites to dry sites. We do see that the circles are the explanatory power of drought. The axes are the explanatory power of density.

[17:36] We do see a significant increase in the explanatory power of drought as you move from wet places to dry places. A higher proportion of the variation in growth is accounted for by drought, kind of what you'd expect. We do see some of the sites on the wetter side that have a large influence of density, but that wasn't actually a significant relationship across this gradient.

[17:57] Some evidence of what we expected, but not completely what we expected.

[18:00] When we look at the inter-annual patterns in the explanatory power, in this case, I'm just showing drought. This is, again, the sites from relatively dry to relatively wet. We would've expect increases in the drought and influence under dry conditions.

[18:17] We only saw that in the two driest places. The rest of them showed no relationship. One side actually showed the opposite as you get toward the wetter site. Certainly, there's some difference in the way that these systems respond to fluctuating conditions. The dry site behaves as you might expect. The wet sites appear to be doing some other things.

[18:39] The last metric that we looked at is perhaps the most relevant one, the density impact on growth response. This is the difference in the slope of growth versus drought between high and low density.

[18:51] The way this could be conceptualized, we have forest growth here as a function of drought. In the humid site, you might have high and low-density stands both declining. The high-density stand would presumably decline more. The low-density stand would decline less.

[19:06] Also true in the arid site. The difference between high and low density, we expect it to be lower in humid site and higher in the arid sites where drought is presumably more influential. That was our basic hypothesis that we're working with. We're expecting greater density impacts in the dry places and during the dry times.

[19:26] Looking at the medium density impacts through time of the whole experiment, we do see some of the values that we would expect where you have a positive relationship between density and the slopes. Values above zero here just mean that when you have higher density, you have a larger slope, which means you have the expectations for decline.

[19:47] That was mostly what we expected, but there was no pattern across these stands, which is a little bit surprising. We certainly thought that the density would have a bigger influence in moderating those effects in the dry sites. We didn't really see that. That was a little bit of a surprise.

[20:04] When we looked at the same patterns through time, from the arid sites to the more humid sites, only in a few other sites did we see anything that supported our expectation. In a lot of

places, we didn't. Certainly, in the driest sites that suggest that when conditions are unusually dry, that density impacts are the largest. You have the largest difference between growth in high versus low-density stands.

[20:28] This is a lot of results that I've just dumped upon you. A little bit complicated. I'll try to simplify it a little bit in a way that's maybe it'll be easier to understand.

[20:39] In a nutshell, our results suggested that drought decreases growth in all areas, including the wettest places in the northeast. In fact, we didn't find any evidence for differences in slopes between the wet sites and the dry sites. That was one thing that we're a little bit surprised by.

[20:55] We also found that the explanatory power of the dry sites was higher for drought. You have a tighter relationship between growth and drought for the dry sites that might be, the red, whereas the blue [indecipherable] represent a wetter site where there's more variability.

[21:11] This is maybe because there's more complicated and varied influences over growth in the wetter sites. Maybe insect outbreaks, potentially, late frost events may have a greater influence there, whereas it's maybe the controls in the dry sites are either simpler or more easily encapsulated by just drought itself.

[21:36] Probably the most interesting thing we did find is some evidence for this interaction in the way that systems respond to drought, such that low-density stand tend to have less growth declines during drought than high-density stands, which is what we expected, but we didn't expect it to be as consistent across sites.

[21:58] We found this effect essentially everywhere. The magnitude of the difference in slopes was really no greater in the dry sites than the wet sites, which surprised us quite a bit.

[22:09] Maybe it's the most compelling result from all the work. This interaction really represents the fact that density manipulation can alter the way that systems fundamentally respond to drought conditions. We also dug into that a little bit more and looked at the relative influence of drought versus density and the prevalence of having a significant interaction through time in all the sites.

[22:34] What I'm showing here is all eight sites from the driest sites, over here, the intermediate sites, and the wetter site over here, showing you the stack bar that shows you the overall proportion of growth variation that's explained in each 20-year interval throughout the whole experiment, with the proportion that's attributable to drought in the red lines, and in density in the green bars.

[22:56] You can see the relevant influence, drought versus density.

[22:58] Across the top, we put a little star for every 20-year interval where there was a significant interaction between density and drought. That's what I think that's the crucial thing that illustrates importance of the way that density plays a role here.

[23:12] You can see that in the driest site here, it's about 82 percent of the time, including all the times recently, all the 20-year intervals. There's a significant influence of the interaction between density and drought.

[23:24] There's a few key points from this. Drought is consistently important in the dry areas, all this red or brown bars up here, whereas density becomes more consistently important in the wetter locations.

[23:39] It's worth noting that the density by drought interactions are quite common. Even the wetter sites have about half of the time where they have a significant density by drought interactions. About half of the intervals there.

[23:52] There was clearly a role being played by density in a way that these stands were responding to drought. It's especially influential during the dry periods here at Fort Valley. That's something that we're trying to dig into a little bit more and try to understand some of the mechanisms about how is it that density alters the way that these stands respond to droughts.

[24:11] We're working with one of the experimental forest down here in Arizona, looking at some of the different densities, from low density, to intermediate, to this unpinning control that's really a doghair thicket with a lot of mortality.

[24:23] We're trying to understand, in particular, the extent to which these vegetation differences alter the actual patterns of soil moisture, and thus alter the magnitude of the drought itself.

[24:34] To do that, we've instrumented these sites. We've installed moisture sensors. We've had them in there a few years. We combine that with some long-term water balance modeling to assess the soil moisture patterns. That's what I'm going to show you here.

[24:46] On the left, we have average soil moisture for a low-density stand. This is from the soil surface, up here down to about a meter at the bottom. This is throughout the year. This is average seasonal patterns of soil moisture by depth, with wet conditions in green and dry conditions in yellow to white. You have low-density stands and high-density stands.

[25:06] They look relatively similar. I want to draw your attention to this period here in the pre-monsoon, relatively deep soils. There's clearly drier soils in the high-density stands. There's greater drought stress being imposed by the vegetation itself in these locations. This potentially underscores an important pattern to recognize when we're trying to project these impacts into the future.

[25:34] We also look at the variability in soil moisture, which is shown on the right, the same seasonal patterns across the bottom here, and depth from the surface to the bottom. Now, we've got the variation in soil moisture, from high variation in red, low variation in white. The surface soils are highly variable through time. The deep soils are less variable.

[25:55] Again, if you focus on some of these earlier periods of deep soil moisture, the low-density stands tend to have relatively low variability in that time. That's a crucial time for storing moisture to get through the season. It suggests that the low-density stands tend to have low moisture and less variable, more reliable moisture, especially in the spring time.

[26:16] The high-density stand that's more variable is going to experience greater drought and greater growth declines when conditions are dry.

[26:23] We also look at, are right in the midst of some analysis, trying to identify the most influential depths and times of soil moisture for accounting for tree growth. This now showing the correlation between soil moisture on an annual basis at any time, depth and forest growth for the several decades at these sites for low density and high-density stands.

[26:49] You can just see there's tremendously high correlation in this growing season, early growing seasons period in the high-density stand. This suggests that the declines in the moisture in that time and depth are really driving down growth in these high-density stands, whereas the low density is relatively buffered from that.

[27:06] If you look even more closely, you can see that the most influential time in the high-density stand is more shallow in middle of the growing season, whereas the low density responds to this deeper soil moisture storage early in the season. This suggests fundamentally responding to the system in different ways.

[27:22] We're working now to combine these with some assessments of some atmospheric demand and severity of vapor pressure deficit, for example, to develop metrics to account for forest growth and understand how thinning moderates the adverse impacts of drought.

[27:41] This is particularly relevant in this northern Arizona landscape. Some of these forest restoration projects that are really taking place nationwide, one of the largest ones are the Four Forest Restoration Initiative, which is occurring in this large patches of northern Arizona.

[27:59] Most of these restoration experiments were set up to promote fire behaviors and stand structural conditions that are more consistent with the natural range of variability for these forests. They weren't done to think about the potential benefits of creating drought resistance and resilience.

[28:17] We're working with the Nature Conservancy and Forest Service here in northern Arizona to try to understand the potential co-benefits that these thinning treatments may have for promoting greater resistance and resilience.

[28:29] That's a nice segue into the second question that I wanted to think about, which relates to understanding forest sustainability in the southwest and the role that thinning can have on that.

[28:38] A lot of our forest down here are pretty well-represented by this photo from southern Utah. These forests exists in the high elevation areas often surrounded by a mosaic of grasslands and shrublands that are already quite dry. Many of them existing at the edge of their drought tolerance limit in these sky island context. There's a lot of expectations that they're going to be really vulnerable in the future.

[29:06] There's one study, one study from Cook from a few years ago projected soil moisture conditions in the 21st century and suggested that there's a real hotspot and potential declines in soil moisture right here in the southwest where a lot of these forests may be especially vulnerable.

[29:21] In fact, they understood that we may be experiencing soil moisture conditions this century that we haven't really experienced for at least 1,000 years. There's lots of reasons to be concerned about the sustainability of these forests.

[29:32] We're digging into this from the particularly, hopefully practical point of view to think about what role and what impact does this density manipulation have in moderating these effects. What impact does the density have on moderating climate impacts on tree mortality, and likewise on tree regeneration?

[29:51] I'll just give you a few highlights from some of this work starting with mortality. Mortality has been pretty well-recognized. Craig Allen had a great paper several years ago demonstrating high tree high mortality rates driven by drought in all over the world, especially in the southwest US.

[30:08] The basic idea is as a result of climate change into warmer and potentially drier conditions, the climate space in which your forest exists may shift in the conditions that tend to promote mortality. They may cross this mortality threshold when we start to see really widespread mortality.

[30:27] This certainly garner a lot of attention justifiably, but we're still curious about the potential benefits of thinning. There hasn't been very much work looking at the influence of forest. We did a little bit of work originally in some of our sites up in northern Minnesota. There has been one paper we've been able to find looking at effects in Europe, but neither of those are particularly the dry forests that we have in the Southwest that are going to be most vulnerable.

[30:51] We wanted to explore the question of can density reduction minimize drought-induced tree mortality. To do this, we've had a couple of studies, but the one I want to talk about today has been using the forest inventory and analysis data.

[31:05] We looked at three species for this. I'm just going tell you. I'll just show you some results from ponderosa pine, which is probably the most common tree species down here in our neck of the woods.

[31:15] We collected data from FIA plots from all over the Southwest and evaluated the way that tree mortality responds to the extreme conditions that were experienced between repeat measurements of the inventories.

[31:30] Maybe it's a lot of a complicated thing here, but I'll walk you through the implications here. What we're showing -- just ignore these lines here and focus on the color of the dot -- each dot is an FIA plot for ponderosa pine in the region.

[31:49] The colors relate to the estimated mortality rate from low mortality in green to high mortality in red. They're shown in the climate space that relates to the maximum annual temperature that was observed between the measurements, so the interval maximum annual temperature.

[32:06] How extreme was temperature? Likewise, the interval minimum spring precipitation. How dry was the driest spring between the times that these plots were measured?

[32:16] For all the species, we did some model selection to identify the best variables for both precipitation and temperature. Then we show the plots on that space to give you a feel for how mortality plays out across the climate space in which the species exist.

[32:33] You can see clearly there's higher mortality in the sites that experienced low precipitation and high temperatures during that interval. These black lines here are just isolines.

[32:44] They give you a feel for where the density of these plots are, so most of the plots, which are a little bit hard to see from just the dots themselves. Most of the FIA plots are in this area right here where the black lines are.

[32:56] Then this lighter blue and darker blue show you where the climate conditions of these FIA plots, this whole population, is expected to move in the middle and the end of the century.

[33:08] You can see clearly the plots are moving to the right to warmer temperature, extreme conditions, and then even further warmer by the end of the century. There's some variability in the projections for precipitation.

[33:21] Just this trend to the right really underscores that these plots are likely to experience pretty dramatic increases in expected mortality rates. I'll show a little bit about what those look like.

[33:33] We also wanted to look at the influence of density. The way we did that was to include a term in our models that related to the basal area of each plot, which is the total density. This is a little bit of an obtuse figure, but this is the posterior estimate of the distribution for the coefficient for basal area.

[33:51] What does this mean? This positive value -- this line here -- is zero. The positive value here just suggests that there's a very clear signal that basal area is positively related to mortality.

[34:02] Said another way, the more basal area on a site, the more likely the trees are to experience mortality. This is considering all these other variables that went in climate-wise.

[34:15] Basal area has a very clear and consistent effect. We found this in all our species. What I've done there is take the full model and estimate annual mortality rate under historical recent current conditions in the middle of the century and the end of the century.

[34:31] You can see for each of these time periods, we've got three different potential basal area treatments. One is what would happen if we kept these stands at low basal area, the other at medium basal area or high basal area.

[34:42] For each time period, you see there's some difference under current conditions. We clearly do see higher expected mortality when basal area is high. That difference becomes even more pronounced as we move into the future and overall mortality goes up.

[34:56] This suggests that there is some potential for moderating expected mortality increases by reducing density. Some of the big picture from the mortality stuff is that we found that tree mortality tends to be higher in all the species when the hottest year was unusually hot.

[35:14] This is consistent with a lot of studies suggesting that the heat stress combined with drought is really influential. We also found that the winter and spring precipitation is very important. It's going to be higher when winter and springs are very dry. Summer and actual monsoon, precipitation in the region was not particularly influential. Mortality tended to be higher when stand density was high.

[35:35] Thinking about the future, this suggests that climate change is likely to increase mortality. A lot of other folks have found similar results. What potentially new about ours is it does suggest that density reduction has the potential to help mitigate some of this future mortality.

[35:50] Last thing I want to talk briefly about is the influence and importance of tree regeneration. This is something that has received a lot less attention but may be a little bit of a surprise.

[36:02] It's possible that the future sustainability of these forests in the Southwest may be as influenced by regeneration patterns as it is by mortality patterns. If you have stands that experience even really dramatic mortality but they have regeneration, then presumably you'll still have a forest there in the future.

[36:19] If regeneration fails, then eventually your sites will just start to blink out of forest and become something else. Grasslands and [indecipherable], for example. This is a picture from a site just outside of Flagstaff burned in the mid-90s.

[36:33] It was ponderosa pine all the way up this hillside before this burned, and it just hasn't come back. There hasn't been any effective regeneration in this site. This underscores the potential that regeneration failures may have for altering our landscapes in the Southwest.

[36:49] The way we've been approaching this is to try to understand at some detail the controls. By that, we mean temperature, soil moisture conditions that define success for tree developmental stages that overall determine regeneration.

[37:01] It's a relatively complicated process. We have developmental stages, including flowering and cone development that are really the extent to which the existing trees have the resources to produce flowers and cones. This is really variables that relate to growth suitability for existing trees.

[37:18] Then there's three stages that really relate to the seedlings themselves -- the ability to germinate, the ability to survive in the first year, and ability to survive in years two to five. It's as far as we tried to understand this.

[37:29] Those later stages for the seedlings really relate to avoiding the severe drought that kills these young small seedlings. We took these insights about what controls regeneration, again just focusing on ponderosa pine in this case. We projected what the future holds for this.

[37:48] What I'm showing here is plots for the overall suitability score for these five stages -- flowering, cone development, germination, seedlings, and then seedling survival the

first year and survival in the years two to five for three time periods -- historical time period in blue, a middle of the century, and the end of the century in red and yellow there.

[38:09] You can see that some of the variables that are most influential over cone development and flowering actually make it more favorable in the future. One thing to note is this is not just the Southwest. This is sites all over the Northwest as well.

[38:23] Let me explain why there are some real potential for increasing established tree growth that's a little bit different from some of the other studies. If you look at the ability of seedlings to survive and particularly to survive years two through five, it dropped off quite dramatically.

[38:39] This process is already really episodic. These results suggest that as aridity increases and temperatures rise, the likelihood of having a two to five-year period where you don't experience a severe enough drought to kill a seedling is really going to be going down by the end of the century.

[38:55] This underscores some challenges, but we've also used some of these long-term experiments just to bring this around full circle and wrap up. We used some of these long-term density manipulation experiments and looked at regeneration patterns within them.

[39:08] This is one, again, for the Fort Valley Experimental Forest from a clear-cut all the way up to an unthinned doghair thicket. This is the density of seedlings in 2014 and '15. We had a big crop, a big seedling event here in 2013.

[39:22] It was unusually a wet year at the right times for these seedlings, so we've been tracking these cohorts ever since then. You can see that these intermediate to low densities treatments but not the clear-cut itself tend to have the highest density of seedlings.

[39:37] When we look at the actual survivorship curves for this -- this is survivorship from 100 percent dropping off to time as we measured in different times -- it is these low basal area treatments but not the clear-cut that actually have the greatest long-term survival.

[39:54] This suggests that really these low basal area treatments enhance both the seedling density and the potential survival. Just to give you a feel for what this looks like, this picture on the left is a clear-cut.

[40:09] These two here are the 7 and 14 m²/ha. It's these intermediate to low densities where you have some trees but not these really dense trees over here. We think this is maybe because there's a lot of grass competition in the clear-cuts.

[40:25] We have also a lot of solar radiation that really heats the temperatures of the surface soil up. That probably imparts stress upon the seedlings. There's some shade in these immediate treatments, but there's also some access to mineral soil.

[40:37] These seedlings really need to get access to mineral soil to develop their root systems. These high treatments, in addition to being relatively dry, they tend to have a large thick litter layer that prevents the seedlings from accessing the mineral soil that they need.

[40:54] There seems to be a sweet spot here for potentially promoting regeneration. This may help inform some of the restoration treatments that may be most effective for trying to maximize long-term regeneration.

[41:08] I'm just going to wrap up with a few take-home messages. Then we have left some time for questions. First, from our growth studies, we found a few consistent patterns that appear to hold true across these really broad climatic gradients.

[41:21] One, drought decreases forest growth. It does it everywhere. It actually didn't decrease it anymore in the dry places than it did in the wet places. That was a big surprise. Then reducing density also mitigates those growth declines.

[41:33] Again, this happened just with a magnitude just as dramatic in the wet places as the dry places. This suggests that even in the relatively mesic and humid forests, there may be some benefits to managing at lower densities in terms of imparting drought resistance and resilience.

[41:50] In the dry forest, we see pretty clearly that the benefits of density reduction are most pronounced during dry periods. This is useful, because it's going to be the episodic extreme droughts that are likely to impart mortality.

[42:05] The density reduction treatments may be especially useful for helping mitigate some of those adverse effects. Some of our ongoing work and some of the directions I'm really hoping to go relate to the idea that the stand density alters the severity of the drought by actually influencing the soil moisture conditions themselves.

[42:21] We're digging more into those mechanisms. There's a lot of opportunities to develop metrics that relate both soil moisture and water availability to atmospheric demand and try to represent the kind of stresses that we know from physiological studies are very detrimental to trees.

[42:37] In the Southwest in particular, climate changes are likely to increase both mortality, and it's likely to decrease regeneration. Managing for lower force density has the potential to decrease both the mortality and promote greater regeneration during the favorable times when that happens.

[42:55] We're also actively pursuing some projects where we're trying to build empirically driven and sensitive population models that represent the influence of fluctuations in climate change on the population dynamics of these forests.

[43:12] We're trying to represent both mortality, regeneration, and growth and get the big picture of where these forests are going and include density as one of the terms in those models. That really provides some insight into the relative benefit of trying to maintain high or low-density stands. With that, I will stop and take any questions.

Amanda: [43:31] Joshua Freeman was wondering, were there increases in all stands treated in average soil moistures?

Dr. Bradford: [43:37] The only site that we have looked at soil moisture explicitly is the Fort Valley Experimental Forest down here in Arizona. We do see increases in soil moisture in

sometimes a year in those sites, but I haven't looked at it in most of the places. We just haven't had the resources to start instrumenting those sites with soil moisture sensors.

Amanda: [44:03] Joel had a question. What are the relative magnitudes of BA reduction required to achieve mortality reduction? Would we have to reduce BA by 50 percent or reduce mortality by 15 percent?

Dr. Bradford: [44:19] The best thing I could suggest is to look at that paper where I presented those results. We do show an estimate and provide quantitative estimates of mortality rates under reduced density and the reduced density that we had.

[44:33] We report what those values are in basal area for the different species. I don't recall them off the top of my head, but they're in that paper, that Bradford and Bell 2017 paper. I could communicate with them if you want to send them an email.

Amanda: [44:46] How much do the differences in growth response depend on species-specific adaptation?

Dr. Bradford: [44:52] I'm not sure that I have a good answer for that, because all the metrics that we looked at for this study so far have been at the stand level. There is a tremendously rich data set that we represented here.

[45:04] For some of the sites like the Black Hills, Fort Valley, some of their mid-time plantations, they're essentially monospecific. For some of the sites in the Northeast and the northern hardwood sites, there's a lot more diversity.

[45:17] We haven't dug into those species-specific effects yet. It's just something we haven't had a chance to do, so I don't have a good answer to that. We have some here. Should I say them back or should we just sign off and I can talk to these folks here?

Amanda: [45:30] Yeah. You can definitely say them back.

Dr. Bradford: [45:35] Jody?

Joy: [45:35] I was wondering. We have a lot of people in this campus that are involved in basic data collection. Do you want to comment on the value of having long-term monitoring data for your work?

Dr. Bradford: [45:46] Yeah. The question was the folks here that are in the room include a mix of people from the USGS, as well as the park service and probably some other entities. A lot of which are involved in long-term monitoring efforts.

[45:59] The question was would I like to comment on the value of this long-term monitoring for these studies. I would have to say that it's essential. This work that we did would simply not have been possible if the forest service hadn't set up these long-term forest experiments in the '50s and '60s and set them up in such a thoughtful way.

[46:19] Some of the stuff I showed about mortality would also not have been possible if we didn't have the forest inventory and analysis of data that are maintained. From my point of view, those data observed are essential.

[46:31] I'm really grateful to the forest service experimental forests and all those scientists more than half a century ago. I don't know who set those experiments up and allowed us to have 50 and in some cases 70 years of annual measures of growth under different competitive environments. It's really cool. We have one more question here.

Audience Member: [46:49] [off-mic question] .

Dr. Bradford: [46:53] That's a good question. The question was about how do the understory plant communities respond to the density treatments. How does that respond to vary across the climatic gradient? What role does that play in terms of the drought response?

[47:11] The response of the understory varies quite a bit. Here in Arizona, thinning the trees largely results in an increase in grass cover. It's a grass-tree mix. In many of the sites in the more humid places, they tend to get more shrubby material.

[47:27] Hazel in Minnesota really becomes a big issue. Then there's a lot of shrubs or understory trees that tend to come up in growth in some of the wetter places. In some places, you get a lot more woody plants. Other places you get grasses.

[47:43] There is potential that the ingrowth of the woody plants may have a greater competition, so you may need to do more frequent return entries to maintain your lower density in some of the wetter sites, whereas it may be easier down here.

[47:59] As we show with some of the generation patterns, when you get few enough trees, you may get enough grass that it competes with those crucial times of development. You probably don't want to have a plan to do clear-cuts everywhere, because that won't help with things like regeneration. I don't know if that helps, if that answers your question.

Audience Member: [48:18] John, I assume all of these forests you stated were cut down from their virgin condition at some point in the past. Then these are regenerated or they are replanted. Was there...

Dr. Bradford: [48:27] That is a mix actually. Most of them, including the one here, were naturally there from natural origin. One of them, the very first one I talked about, the Birch Lake plantation, that was planted, but that's relatively unique.

[48:41] Most of them are from natural origins, so they define the relatively homogeneous [indecipherable] , identified treatment plots, and then randomly assigned treatments within that. For most of them, I'm going to go back and show you.

[48:56] I didn't show you some of the figures, but we did look at were there differences in growth response prior to treatment in those stands using the same vendor phenology we'd look way back to before they set them up, and we didn't see effects of that.

[49:08] You could see some of the controls. Not the controls there. The pre-growth patterns. Is it here? This one. If you look in here, you can see these stands go back all the way to here. They were growing. The same trees were growing well before the experiment was set up.

[49:33] Then the experiment was set up. You started to see a large divergence in growth rates after the experiment was created, because then you are more altering competition and creating better growth conditions for some versus others. Does that help?

Audience Member: [49:46] Yes. I might have asked this in the beginning but do you think these are one-time treatment or are they maintained?

Dr. Bradford: [49:54] They're maintained. They go in about every 10 years. Some places a little bit more, but they keep going back in and thinning back down to the target level. They're not perfectly consistent through time.

[50:06] The basal area creeps up, and it goes down. It creeps up and goes down. Then our model to use the actual basal area in the year in each year.

Audience Member: [50:14] I'm thinking about all the vital rates you're talking about. It seems like you get convergence back to a certain types of data. The lower ones both have higher survival and having higher improvement.

[50:28] If you're thinking about scaling this up to management where maybe you're not going back every 10 years, is there a certain extent that there's a time period over which you converted back to the similar forest?

Dr. Bradford: [50:43] Yeah, there is. The question was given that these treatments, these experiments were maintained with repeat entries about every decade or so, what does that suggest about, I guess, the feasibility of doing this on operational scale of broad landscapes.

[50:53] Now, we probably want to target relatively low densities so that they have time to grow up into and even through the target densities and then have to enter them again in maybe 40 years or something like that.

[51:06] Of course, that's going to be easier in the floor going places that are the driest sites and probably harder to maintain in some of the wetter sites where the growth is just faster.

Amanda: [51:14] It looks like we have a few more questions that we have in the chat box. Michael sent in, "Can you talk a bit about how heterogeneous density structure across the landscape might be important for these density-drought, growth-mortality relationships? That is, how does this scale at which we measure density matter?"

Dr. Bradford: [51:34] Yeah, that's a good point. There's a lot of focus in the restoration plans down here, for example, on promoting and creating heterogeneity in the stand structures both within and among landscapes.

[51:47] I think it is pretty important. I'm not as certain about the influence of the heterogeneity on the sites and the weather locations. Down here, you want to have variation because that will

create a lot of microsites that might be able to capitalize on opportunities for regeneration or differentiation in growth.

[52:07] That's essentially one of those potential bet hedging strategies where you have trees within your population growing in these different conditions that you can create.

[52:15] It's important to include that. I wouldn't advocate for a homogeneous treatment to one level. I think that the evidence is pretty clear that reducing density and creating some of the patchy combi treatments that are common here will be beneficial. Hopefully, that's addressing the question.

Amanda: [52:33] Another question was, did you find that the tree stand age has an effect on growth response? We have seen that the younger trees have greater transpiration demand. Would those be more susceptible?

Dr. Bradford: [52:45] That's a great question. Actually, in the very first study, where we looked at the study, which is shown on this figure right here, if you're still looking. What I'm not showing in that is we looked at three droughts in this original Birch Lake plantation. One drought before the treatment were initiated and that showed no effect, which is good.

[53:05] Before we put the treatments in, they were all the same. This is the drought that was relatively early in the treatments. Surely, after they had started being treated, it has a clear effect. Then, we looked at a late drought at this site, we didn't see an effect of density. There was no relationship.

[53:24] This particular site for this one effect showed what the question was suggesting, where there's the greatest influence of mitigating drought effects in the younger trees or, at least, in the trees that were in the earlier treatment.

[53:38] That's part of why, in this study, we looked at an early drought and then a late drought for each combination. We didn't see any more evidence of that decrease in the effect in older stands or in stands that had been treated for longer periods of time. That's why I didn't dwell on it anymore. We didn't see that effect. We didn't see the effect decline with age.

[54:00] When we look all the way down to this figure, where we look at the proportion of growth variation that's explained by drought and density, I don't really see any evidence in here that it's declining over time, in terms of density or drought influences. It's a little bit hard to disentangle the trajectories we've also been experiencing in climate conditions.

[54:22] Climates have been warming. That may be playing a role as well. The short answer is we saw some age or at least time-related effects in the very first site we looked at, but we didn't see those anymore after we kept looking. It's something on our mind, but we haven't seen a lot more evidence for it.

Amanda: [54:40] Great. It looks like we got one more question from Joel. "Do you have any comments on the importance of the spatial arrangement of trees for a given stand density? I wonder about the effects of forest geometric arrangement on soil microclimate, such as shading, as well as root competition by differentially spaced trees."

Dr. Bradford: [54:58] It's a good question. Most of these treatments are imposed in a way that has relatively uniform spacing. I don't have any specific results that I can point to from any of these analyses that suggest that maintaining heterogeneity would be better. I certainly would be inclined to be biased that direction, to be honest, that promoting heterogeneity in your arrangement of trees will be beneficial.

[55:26] That is, as I mentioned earlier, one of the explicit parts of the treatments for restoration in the dry forest down here.

Amanda: [55:34] I think that might be all of our questions. On behalf of the US Fish and Wildlife Service, and the US Geological Survey's National Climate Adaptation Science Center, I wanted to say thank you to Dr. Bradford, for taking the time out of your busy schedule to be with us today. Thank you as well to all of our attendees who are here on the webinar today.

[55:53] This was the first in the 2019 Science You Can Use webinar series that is held in partnership with the NCTC, NCASC, and Association of Fish and Wildlife Agencies. Very cool we got to be a part of it. We will see you next time for the latest webinar. Bye, everybody.