Spruce Beetle Climate Model

https://northernclimatereports.org/

Project background

Funding and direction

This project was a collaborative effort ("Applying Climate Change Modeling to Selected Key Factors in Ecosystem Health and Adaptation in Alaska") funded by USGS via the Alaska Climate Adaptation Science Center, 7/1/2021 - 6/30/2024. It was undertaken by the Scenarios Network for Alaska and Arctic Planning (SNAP), a research group within the International Arctic Research Center (IARC) at the University of Alaska Fairbanks (UAF) in conjunction with partners and advisors at USGS and USFS. The Principal Investigator was Dr. Nancy Fresco (nlfresco@alaska.edu).

Overarching objective

Alaska's high-latitude setting places it at the front lines of environmental change. Rising temperatures, altered precipitation regimes, and associated shifts are rapidly altering ecosystems and associated human systems. The ability of Alaska's land managers and communities to predict these changes will profoundly affect their ability to adapt. SNAP applies its expertise in climate science, climate modeling and downscaling, and landscape ecology to better understand the manner by which these changes affect ecosystems and human populations. The objective of this project was to apply SNAP expertise to a real-world landscape-level climate-linked ecological issue of immediate interest and concern to Alaskans.

Project initiation and delineation

The project was initiated via communication with agency partners who have a direct interest in linking climate variables with key observed or suspected landscape change.

The issue that was selected to meet an identified need was modeling linkages between climate variables and spruce beetle *(Dendroctonus rufipennis)* outbreaks in forested regions of Alaska.

Large beetle outbreaks have occurred periodically over the past fifty years, particularly on the Kenai Peninsula, with a peak in the mid-90s (Figure 1). Recent heightened beetle outbreaks, particularly in the Matanuska-Susitna Valley, are now causing concern. These outbreaks, although linked to many factors, are at least partially driven by climatic conditions.

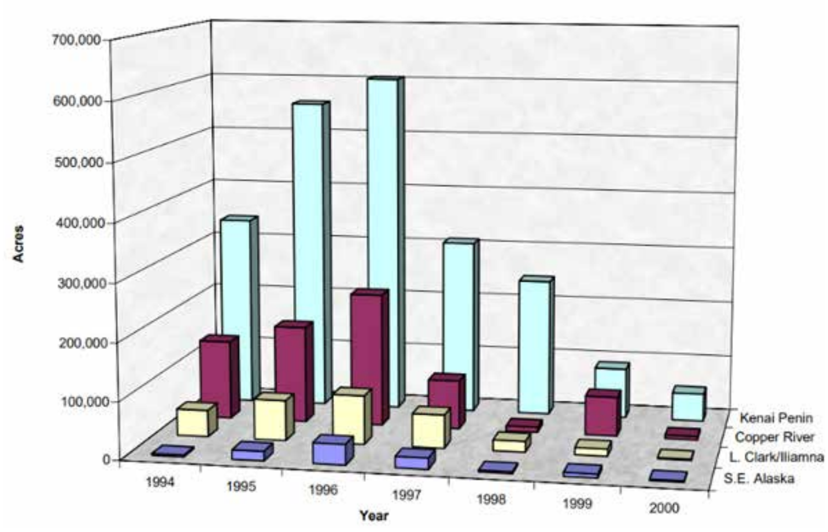


Figure 1: Peak years of historical bark beetle activity in Alaska. From FS-R10-90-C1.1990.

The initiation of historic spruce beetle outbreaks has been mainly attributed to blowdown, logging activities, and other disturbances that produce an abundance of suitable host material; when beetle populations surge in such host material, they then attack live trees. However, such forest conditions and disturbances do not always result in outbreaks. Climate is also a factor.

The fact that outbreaks are correlated with warmer weather is well documented, and some research efforts, including lab studies, have pinpointed the effects of specific climate variables on beetle survival, maturation, and breeding. However, no comprehensive model exists linking climate to beetle populations. As such, projections linked to future climate have not been possible.

Participants

Once this modeling effort had been identified, the next steps included identification of key subjec***t***-matter advisors and core team members. These included Michael Shephard, Jessie Moan, and Sydney Brannoch (entomology and land management, USFS); Jeremy Littell (climate modeling and ecology, USGS); and the SNAP team. Within SNAP, Nancy Fresco took the lead on research and model development, Kyle Redilla led the model creation and coding and contributed to the ecological analysis, Bruce Crevensten assisted with project management and data/tech management, and other team members (Bob Torgerson, Craig Stephenson, Carolyn Rosner, Michael DeLue, and Charlie Parr (UAF/IARC) created and contributed to the online interface that hosts the tool, products, and data.

Specific project goals

This project aimed to create a model that would assess the past, present, and future relationship between climate and beetle outbreaks in Alaska. Specifically, we examined the level of protection from outbreaks afforded by prevailing climate conditions, and projected how this might change over space and time, across forested regions of the state.

The intent of the model is not to pinpoint precise locations of future outbreaks. Such predictions would be too temporally and geographically fine-scale to determine from existing datasets, and more importantly, would neglect the many aspects of forest growth, health, and management that contribute to vulnerability. Instead, the model defines three levels (low, medium, high) of relative climate-related protection from outbreaks, validated against historical data. Model outputs are intended to help inform forest management, broader land management, and climate change adaptation strategies.

Approach

The team determined that model outputs would ultimately be shared via a user-friendly online interface. The team agreed that the **Northern Climate Reports** tool would be an ideal platform, given its ease of use and links to other climate variables of interest to potential users.

As with other climate-linked variables included in the tool, beetle model outputs include model runs based on multiple possible climate futures derived from different downscaled climate models (GCMs) and greenhouse gas concentrations (RCPs). Appropriate climate datasets for the project were selected by the SNAP team in consultation with Jeremy Littell.

Extensive literature review was necessary to find the best existing information linking bark beetles to climate variables (see Sources). Based on this literature review, the team undertook iterative model creation and validation as described below.

Ecological background

Reproduction and life cycle

Understanding key aspects of the life cycles of spruce beetles is crucial to effective modeling of the relationship between these life cycles and climate variables. This includes understanding maturation, overwintering, and breeding.

Newly adult beetles fly to a new tree in the spring (referred to as "flight"). The date of beetle flight has been recorded as occurring at approximately the first instance of temperatures of 16°C or warmer. Females then lay 20-30 eggs, which hatch on that tree. If there are enough warm days in the remainder of the summer, the new larvae reach adulthood at the end of the summer, and overwinter as adults; these are "univoltine" beetles. If these heat requirements are not met, beetles over-winter as late-stage larvae ("instar IV"); these are "semivoltine" beetles. Parameters for univoltinism have been experimentally identified based on the number of hours above 17°C accumulated between 40 and 90 days pos***t-***flight (first instance of 16°C). Univoltine beetles breed the next spring, when they are one year old. Semivoltine beetles don't breed until two springs later, when they are two years old.

Since approximately half of each egg clutch is female (~12.5), the theoretical maximum population growth would be about 1,250% annually. This matches the most extreme years of the most extreme outbreaks, in terms of increase in damaged acres from one year to the next. The theoretical "steady state" survival % (from egg to breeding) would be approximately 0.08, 8%, although this is complicated by the fact that adults can survive to breed again in subsequent seasons. While imprecise, these numbers were helpful in model calibration.

Predation

Although not climate-linked, understanding predation is necessary to understand the relative success rates of univoltine and semivoltine beetles. Predation, primarily by woodpeckers, is very high for larvae, and very low for adults. Thus, univoltine beetles have two advantages: 1) less time in the larval stage and 2) no time as larvae during winter, when woodpeckers have few other food sources, and may subsist on a diet that is as much as 99% beetle larvae.

The literature shows that a wide range of predation rates are possible, from 19% up to 98%. These vary based on many factors, including beetle density, with the highest rates at moderate densities, because at low densities woodpeckers are not drawn to the site, and during major outbreaks woodpecker reproduction cannot keep up with beetles (even though woodpecker numbers may increase 50-fold).

Habitat

As already noted, this modeling effort did not consider non-climate-related factors. Climate-linked factors must be viewed in the context of beetle habitat.

To help avoid presenting completely spurious or confusing results, model outputs are shown only for forested areas of Alaska. Based on expert opinion from project partners, we selected the USFS forest/non-forest map. However, even when limited to forested areas of the state, habitat variability is high.

Alaska's forests include coastal rainforest, boreal forest, and transitional forest. D rufipennis attacks white spruce *(Picea glauca)*, Sitka spruce *(Picea sitchensis),* and the cross between these two species, Lutz spruce *(Picea lutzii).* The percentage of these three host species varies enormously across the forested extent of Alaska. In the Tongass National Forest in Southeast Alaska, Sitka spruce occurs alongside western hemlock, western red cedar, and Alaska (yellow) cedar. This forest type has not been observed to be susceptible to beetle attacks. In contrast, the Chugach National Forest in southcentral Alaska, where beetle outbreaks have been severe, is primarily Sitka spruce and white spruce. Alaska's extensive boreal forest includes susceptible white spruce, but also black spruce, quaking aspen, paper birch, balsam poplar, and larch.

Within the context of this wide range in forest types, habitat variability is also dependent on forest age and health. In fire-driven boreal ecosystems, young forests are made up primarily of fast-growing hardwoods, only overtaken by white spruce or black spruce after several decades. In all forest types, beetles prefer dead and dying trees – spruce downed by some combination of age, other disease or infestation, and windthrow or other disturbance. Only when climate and other factors allow for larger outbreaks do beetles attack living trees—usually old, large-diameter spruce.

Climate data

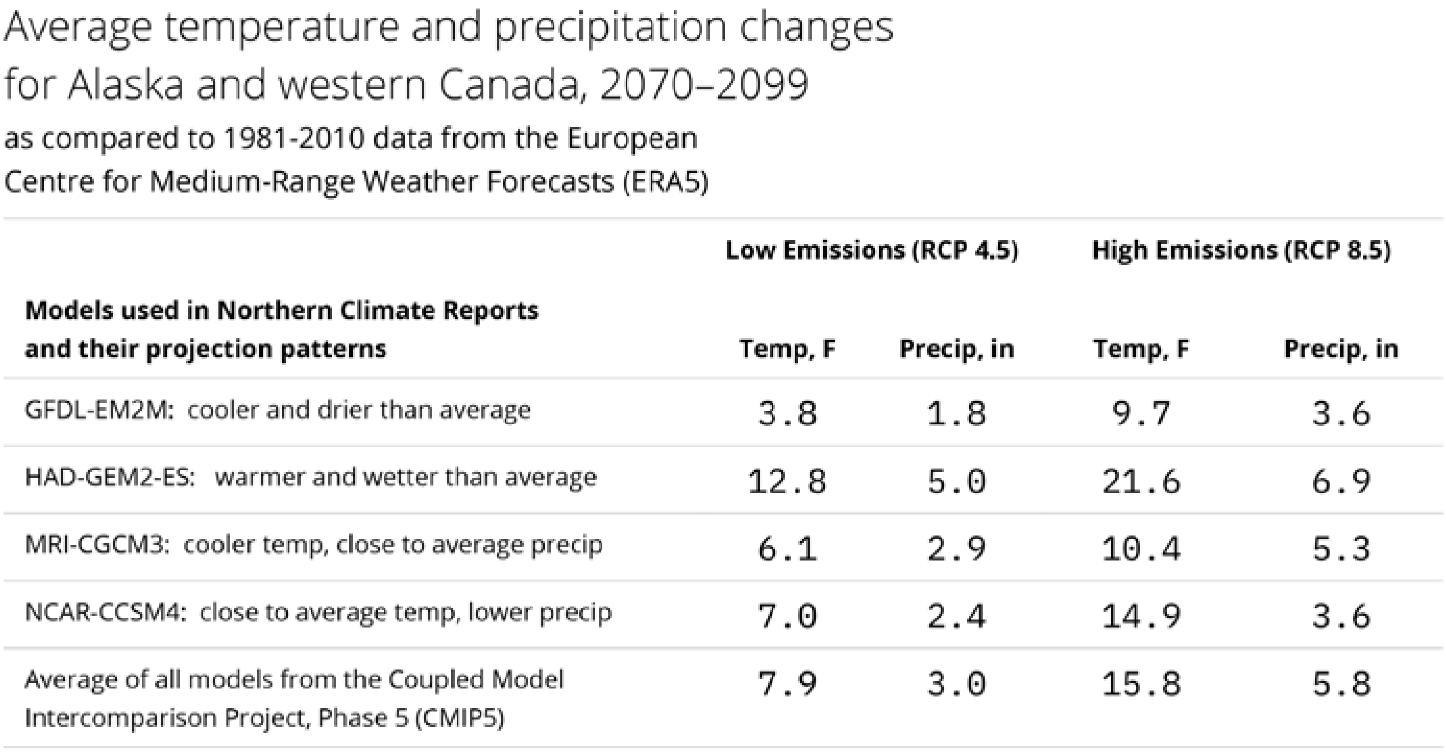
Historical

HIstorical data used in this model came from the Daymet dataset. Daymet is a research product of the Environmental Sciences Division at Oak Ridge National Laboratory, and is supported by NASA through the Earth Science Data and Information System. Daymet provides 1 km x 1 km gridded estimates of daily climatology by statistically interpolating and extrapolating ground-based observations.

Projections

As explained [here,](#) best practices for climate projections include selecting more than one model, more than one greenhouse gas scenario, and more than one future decade.

Based on expert advice from Jeremy Littell, climate projections were selected from four different models, as shown in the table below. Model outputs are dynamically downscaled for the Alaska domain. **SNAP datasets are available online.**



Average temperature and precipitation changes for Alaska and western Canada, 2070–2099

as compared to 1981-2010 data from the European Centre for Medium-Range Weather Forecasts (ERA5)

	Low Emissions (RCP 4.5)		**High Emissions (RCP 8.5)**	
Models used in Northern Climate Reports and their projection patterns	**Temp, F**	**Precip, in**	**Temp, F**	**Precip, in**
GFDL-EM2M: cooler and drier than average	3.8	1.8	9.7	3.6
HAD-GEM2-ES: warmer and wetter than average	12.8	5.0	21.6	6.9
MRI-CGCM3: cooler temp, close to average precip	6.1	2.9	10.4	5.3
NCAR-CCSM4: close to average temp, lower precip	7.0	2.4	14.9	3.6
Average of all models from the Coupled Model Intercomparison Project, Phase 5 (CMIP5)	7.9	3.0	15.8	5.8

Model Summary

The model incorporates three separate climate-based factors:

1. Beetles' rate of maturation in response to cumulative heat
2. Fall survival based on rate of cooling
3. Survival of winter extreme cold with or without insulating snow

These factors are combined to calculate the overall climate-related protection for a given location and year. Outputs are presented via maps summarizing risk across past (1988-2017), current (2010-2039), near-future (2040-2069), and distant (2070-2099) time periods.

Past outbreaks have generally occurred when climate conditions have been consistently favorable to beetle population growth over several years. Our model is thus calibrated to predict the least climate-linked protection and when a given time period includes multiple years favorable to beetle population growth.

This model provides outputs for forested regions of Alaska as defined by the US Forest Service. It does not include important non-climate-related factors that may affect outbreaks, including

- The presence and percentage cover of white spruce, Sitka spruce, and Lutz spruce, the Alaska tree species most at risk of beetle infestation.
- Forest age and successional stage
- Forest health, including other stressors, pests, or blights
- Forest management, including fire management, harvest, and pest control
- Past and ongoing beetle outbreaks, including potential spread from nearby regions

Detailed model logic flow

Overall parameters and assumptions

1. The overall goal is to model three levels of climate-related protection from beetle outbreaks (low, medium, high).
2. All map pixels operate independently. The model does not account for beetle spatial spread.
3. Each time-step is also independent, in that the model outputs risk levels year by year, not cumulatively; however, protection levels are associated with the frequency of protective years across longer time periods.
4. The model accounts for beetle survival and reproduction based on impacts of climate only, and includes non-climate components only where there is a crucial connection to climate.
5. The model accounts for two summer-climate-driven pathways to beetle maturity, univoltine (maturing in one summer) and semivoltine (overwintering as larvae).
6. The model also accounts for beetle survival through two climate-driven challenges: autumn cooling and winter extreme cold.
7. Each of these three pathways are mathematically defined based on the best available literature.
8. Due to semivoltinism, in order to calculate discrete, single-year values for climate-related beetle risk, the model incorporates two years of data for each single-year output.
9. A beetle cohort is composed of all newly hatched larvae in spring.
10. In order to reproduce, univoltine beetles from a given cohort have to survive the following:

    - One summer of woodpecker predation as larvae
    - One fall cooling period as adults
    - One winter as adults
11. In order to reproduce, semivoltine beetles from a given cohort have to survive the above, plus:
    - One summer and one winter of woodpecker predation as larvae
    - One fall cooling period as larvae
    - One winter cold as larvae
12. All survival factors are assumed to be multiplicative.

Summer model component

1. The summer model is focused on calculating the percentage of beetles that are univoltine as opposed to semivoltine.
2. The percentage of beetles that are univoltine in a given cohort is denoted as ***u***, and the percentage that is semivoltine is therefore (100-***u***).
3. Let ***h*** (heat) be defined as the number of hours above 17°C accumulated between 40 and 90 days pos***t***-flight (first instance of 16°C). Note: total hours, not degree-hours
4. In the case where the only data available are daily minimum and maximum temperatures, (***tmin*** and ***tmax***), ***h*** was computed as
    - max((24 * (***tmax*** - 17) / ((***tmax*** - 17) + (17 - ***tmin***))), 0) in the case of ***tmax*** > 17 and ***tmin*** < 17
    - 24 where ***tmin*** > 17 and ***tmax*** > 17
5. Let ***h*** map to ***u*** with the following rules based on Hansen 2001:
    - If ***h*** < 40, ***u*** = 0 (no beetles are univoltine)
    - If 40 < ***h*** < 225, ***u*** = [(h-40)/7.4] (0% to 25% of beetles are univoltine)
    - If 225 < ***h*** < 412, ***u*** = 25 + [(***h*** - 225)/2.5] (25% to 100% of beetles are univoltine)
    - If ***h*** > 412, ***u*** = 100 (100% of beetles are univoltine) Note: data are from Hansen et al. 2011 and are interpolated linearly between values provided for 1%, 25%, 50%, and 100% univoltinism.

Predation model component

1. Predation by woodpeckers is not directly climate linked, but had to be included in order to accurately model the relative success rates of univoltine and semivoltine beetles.
2. Predation is significant for larvae, and negligible for adults, so only larval predation is considered.
3. Univoltine larvae have two advantages against woodpeckers:
    - less time in the larval stage and
    - no time as larvae during winter, when woodpeckers have few other food sources, and may subsist on a diet that is as much as 99% beetle larvae.
4. Let ***P*** = survival from predation.
    - Let us assume that the time as larvae is two months for univoltine beetles and 10 months for semivoltine.
    - Let us further assume that predation on beetles is doubled during the 8 additional months.
    - This yields a relative factor of 9 – that is, semivoltine beetles have only one ninth the survival percentage of univoltine.
    - Thus ***P***(semivoltine) = ***P***(univoltine)/9
    - Average woodpecker predation has been stated as 32%, (survival 68%).
    - This would yield survival of 68/9 = 7.55% for semivoltine beetles.
    - The relative predation rates of univoltine versus semivoltine beetles are more robust within this model than overall rates, due to the wide range reported in the literature. This is a source of model uncertainty that is not directly climate-linked.

Fall rapid cooling model component

1. Survival rates relating to cold (fall cooling and winter cold) are statistically indistinguishable for larvae and adults.
2. Let ***f*** (fall survival) represent % survival from rapid cooling with the following rules based on Miller and Werner 1987
    - Based on their data, at the beginning of the 21-day cooling period, all beetles were hardy to at least -12°C, and there was a range from there down to ~ -22°C for the hardiest.
    - By the end of the 21-day period, the range for cold-hardiness was from ~ -22°C to ~ -42°C. Most were clustered between -29°C and -37°C, with an average of -33°C.
    - All beetles gained at least 10 degrees of cold-hardiness over the time period, and all beetles were hardy to at least -12°C at the start, so at roughly 0.5 degrees cooling per day, a ramp from -12°C to - 22.5°C, all survive.
    - Given that some beetles were hardy to -42°C at the end of the time period, and some were hardy to -22°C at the start, we can assume a ramp from -21°C to -42°C, one degree decrease per day, below which survival is zero.
    - Between these two lines, survival is between 0% and 100%. We assume that mortality is determined by the greatest deviation below the upper bounding curve. For example, if that deviation is halfway between the upper and lower curves, mortality would be 50%.
    - Miller and Werner found almost no insulating value from snow at root height in October and November.
    - Given the above, ***f*** is defined as:
    - ***f*** = 100 if the minimum temperature value for each day (***t***) never falls below the line "a" defined by $f(x) = -x/2 - 12$ for x in 0, 1, ..., 20
    - ***f*** = 0 if the value ever falls below the line defined "b" by $f(x) = -x - 22$ for x in 0, 1, ..., 20
    - For all other cases, ***f*** = the maximum value of 100% -[-(a-t)/(b-a)] for all 21 values of ***t.***

Winter extreme cold model component

1. Let w (winter survival) represent % survival from extreme cold temperature based on the following rules (based on data from Miller and Werner 1987 and supported by Frye et al. 1974) where ***tmin*** = minimum winter temperature
    - Without snow (or with minimal snow)
        - ***w*** = 0% when ***tmin*** < -40°C
        - ***w*** = 100% when ***tmin*** > -20°C
        - ***w*** = (200 + 5****tmin***)% [a linear ramp from -20°C to -40°C such that survival is 50% at -30°C]
    - With insulating snowpack, assuming insulation of 10°C, the model above shifted by 10°C
        - ***w*** = 0% when ***tmin*** < -50°C
        - ***w*** = 100% when ***tmin*** > -30°C
        - ***w*** = (250 + 5****tmin***)% [a linear ramp from -30°C to -50°C such that survival is 50% at -40°C]

Combining all factors

1. Equation based on time ***t,*** where ***t*** is the current year (the one we are modeling), ***t*-**1 is the prior year, etc.
2. X(t) is dependent on univoltinism, fall conditions, and winter conditions in years ***t*-**2 and ***t*-**1.
3. Beetles that are semivoltine in year ***t*-**2 can affect year t by surviving cold conditions for fall (***t*-**2), winter (***t*-**2), fall (***t*-**1), winter (***t*-**1), predation (***t*-**2) and predation (***t*-**1) (and then breeding in year t).
4. Beetles that are semivoltine in year ***t*-**1 do not contribute to populations in year ***t.***

5. Beetles that are univoltine in year ***t***-1 contribute to population in year t by surviving cold conditions for fall (***t***-1) and winter (***t***-1), and predation (***t***-1), and then breeding in year ***t.***
6. Beetles that are univoltine in year ***t***-2 contribute to population in year ***t*** in two ways, either by surviving all the same things as the semivoltine beetles from that cohort and then breeding in year ***t*** (having also bred the previous year), or by contributing to the population in year ***t***-1 by surviving cold conditions for fall (***t***-2), winter (***t***-2), and predation (***t***-2) (and then breeding in year ***t***-1). Their contribution to the ***t***-1 population would become multiplicative with the ***t***-1 component of the overall equation.

Combining all of the above:

$$X(t) = [(1-u)t-2 * P/9 * ft-2 * ft-1 * wt-2 * wt-1] + ([ut-2 * P * ft-2 * wt-2] * [ut-1 * P * ft-1 * wt-1]) + [[(u)t-2 * P * ft-2 * ft-1 * wt-2 * wt-1]$$

Historical calibration

Sample outputs of the above model for historical time periods were assessed in order to validate and calibrate the model and set thresholds for climate protection categories. This step involved gathering data from historical reports on locations, severity, and acreage of outbreaks.

Setting a single-value threshold for climatic conditions in relation to beetles is too sharp-edged, particularly given regional differences. Some regions accumulate risk via a larger number of moderate-protection years, while other regions have some years in which climate affords no protection at all from beetle population growth, followed by years in which beetles are “frozen out.” Thus, calibration required examining patterns not only across summer, fall, and winter – as already included in the model – but also across multiple years.

Linking climate to outbreaks necessitated accounting for an innate time lapse between climate factors, beetle population surges, and observed damage to spruce trees. Dead needles observed in Summer X means damage in Summer X-1. That suggests univoltinism in either Summer X-1 or X-2. Likewise, observed beetle damage would correlate with high fall and winter beetle survival in the years 2-3 years prior to the noted damage.

For example, a minor outbreak in the Fairbanks area observed (based on dead needles) in 2018 would have actually occurred in 2017. This outbreak would, based on beetle ecology as described above, be linked with univoltine numbers for the summers of 2015 and 2016, coldest temperatures of the winters of 2014/15 and 2015/16, and the rate of autumnal cooling for 2014 and 2015.

Key calibration locations were selected based on geographic diversity, availability of data, and notable increases or decreases, percentage-wise, in beetle killed trees. Thus, we looked not only at areas with large outbreaks, but also at locations such as Delta Junction, which went from no noted activity in one year, to 3372 acres the following year, then back down to 90 acres the next year.

Model calibration was aided by the fact that different climatic limitations on beetle population growth have been of primary importance in different regions. In Interior Alaska, e.g. Delta and Fairbanks, summers are generally warm enough for univoltine maturation every year, but beetles are moderated by rapid fall cooling and cold winter conditions. Conversely, in southcentral Alaska, a shift toward warmer summers, allowing semivoltine populations to become univoltine, plays a larger role.

This is borne out by the data. In Talkeetna, a shift from non-univoltine to univoltine summers starting in 2013 helped to trigger the outbreak that started damaging trees in summer 2014 and was thus first observed in 2015. A small outbreak in the Fairbanks area appears to have been partially triggered by just a single year that lacked limiting cold conditions. In King Salmon an uptick in observed damage in 2017 and 2018 (which occurred in summers 2016 and 2017) can be linked to a combination of lack of rapid cooling in the fall of 2014 and a warm univoltine summer in 2016.

In the Matanuska-Susitna Valley, the ongoing outbreak is harder to use for calibration given that Daymet (historical) data ends at 2017. The outbreak started to be observed in 2015, increased dramatically in 2016, and increased (but more moderately) in 2017 and 2018. This pattern represents a “slower” outbreak scenario.

The Kenai outbreak, although ultimately devastating, appears to have been triggered by an even longer sequential number of years below a relatively modest threshold for climate-related risk protection. The outbreak was observed from 1987 onward, peaking in 1996. A clearer view of the actual Kenai outbreak was afforded by creating and examining all the Daymet outputs for 1982-1996. Decreases in modeled climate-linked protection from outbreaks in these years correspond very well with actual beetle increases. However, model output values for that time period and region are moderate rather than extreme. The fact that the outbreak itself was extreme can be attributed to the combination of a long time period of moderate climate factors and several other well-documented factors relating to forest composition, age, health, and management.

The same is true for other regions; outbreaks may not occur in regions that have little or no beetle-protection from climate. There are many ecological reasons for this, as already described. For example, the trees may be primarily a non-vulnerable species such as black spruce, cedar, etc;, or the forest may be very young (early succession hardwoods, or spruce with few larger, older, susceptible trees).

After extensive iterations and model testing, outputs were calibrated as follows:

1. **We defined a time period with little to no climate protection as being one during which half or more of the years have model outputs above 0.24. For the 30-year time periods used in the model this means 15 or more years above this threshold.**

2. **We defined a time period with moderate climate protection as being one which does not meet the above criteria, but in which 75% or more of the years (23 out of 30 years) have model outputs above 0.04.**

3. **We defined a time period with high climate protection as being one which meets neither of the above criteria.**

About the beetle maps

Modeled climate protection levels are based on conditions during more than half the years in a given time period. **Results are shown for forested areas only.**

🟩 **HIGH protection** = climate conditions are likely to protect forests and prevent major outbreaks even if other risk factors exist.

🟨 **MINIMAL protection** = climate conditions may provide some protection, but other risk factors can make outbreaks likely.

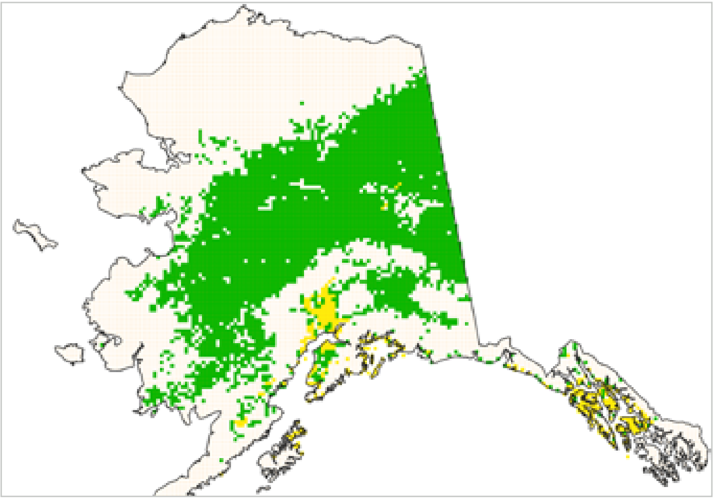
🟥 **NO protection** = beetle populations are unlikely to be effectively limited by climate.

⬜ **Not modeled or no data**

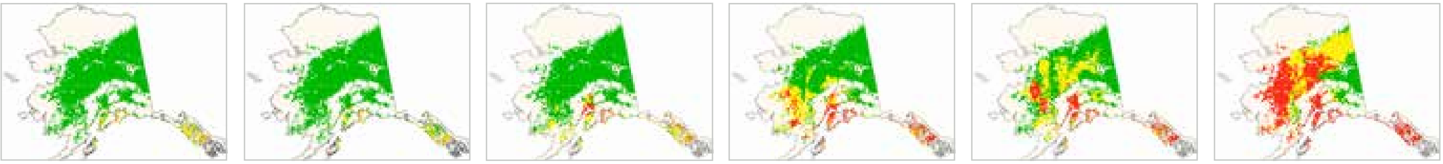
RCP 4.5 is a moderate scenario in which emissions peak around 2040 and then decline.

RCP 8.5 is the highest baseline emissions scenario in which emissions continue to rise throughout the 21st century.

Historical climate protection, 1988–2017, Daymet



Projected climate protection from beetles, 2010–2099. Four models, two RCPs, medium snowpack



2010–2039
NCAR-CCSM4, RCP 4.5

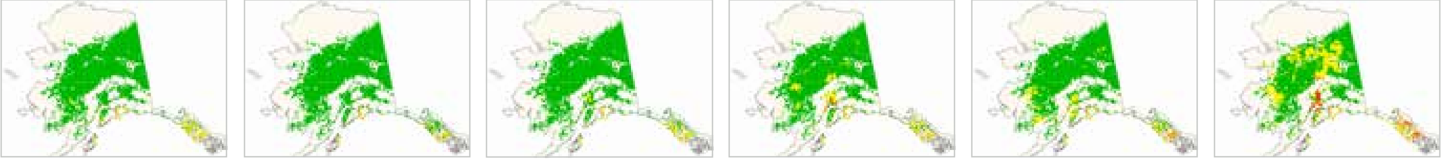
2010–2039
NCAR-CCSM4, RCP 8.5

2040–2069
NCAR-CCSM4, RCP 4.5

2040–2069
NCAR-CCSM4, RCP 8.5

2070–2099
NCAR-CCSM4, RCP 4.5

2070–2099
NCAR-CCSM4, RCP 8.5



2010–2039
GFDL ESM2M, RCP 4.5

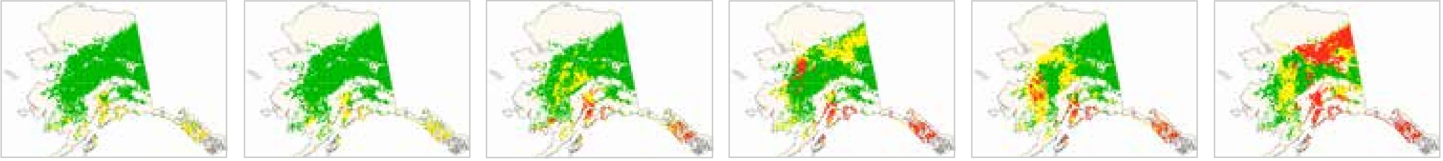
2010–2039
GFDL ESM2M, RCP 8.5

2040–2069
GFDL ESM2M, RCP 4.5

2040–2069
GFDL ESM2M, RCP 8.5

2070–2099
GFDL ESM2M, RCP 4.5

2070–2099
GFDL ESM2M, RCP 8.5



2010–2039
HadGEM2 ES, RCP 4.5

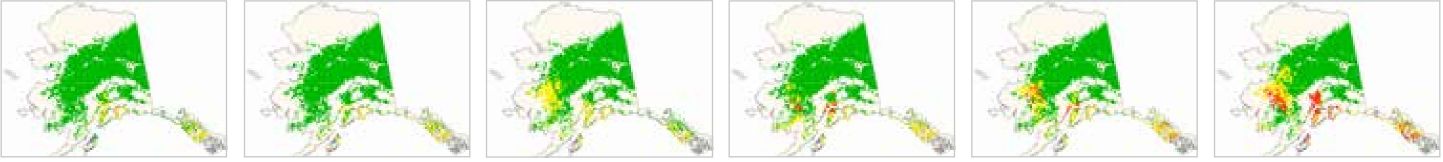
2010–2039
HadGEM2 ES, RCP 8.5

2040–2069
HadGEM2 ES, RCP 4.5

2040–2069
HadGEM2 ES, RCP 8.5

2070–2099
HadGEM2 ES, RCP 4.5

2070–2099
HadGEM2 ES, RCP 8.5



2010–2039
MRI CGCM3, RCP 4.5

2010–2039
MRI CGCM3, RCP 8.5

2040–2069
MRI CGCM3, RCP 4.5

2040–2069
MRI CGCM3, RCP 8.5

2070–2099
MRI CGCM3, RCP 4.5

2070–2099
MRI CGCM3, RCP 8.5

Sources

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