Appendix: Data Sources and Methods

Supporting appendix for the Science & Data Byte: *Colorado Front Range Mountain Pine Beetle Outlook: Current Conditions, Future Potential Susceptibility and Capacity to Process Impacted Volume*

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Introduction

This appendix provides a detailed summary of the methods and data sources used to assess current ponderosa pine conditions and evaluate the potential spread of mountain pine beetle (MPB) outbreaks in Colorado's Front Range. It serves as supplementary documentation to the main Science & Data Byte.

This document is organized into sections that describe the following key components of the analysis:

- Characterizing current ponderosa pine conditions
- Assessing the extent of the current MPB outbreak
- Developing MPB spread scenarios
- Identifying structural thresholds associated with elevated MPB susceptibility
- Estimating susceptible acreage and live ponderosa pine volume across affected and potentially impacted areas

The methodologies outlined in this appendix incorporate data from multiple sources, including the USDA Forest Service (USFS) and Colorado State Forest Service (CSFS) Aerial Detection Survey, the USDA Forest Inventory and Analysis (FIA) program and FIA-linked TreeMap spatial data. *ArcGIS Pro* (Version 3.4.0; Esri Inc., 2024) and *R Statistical Software* (v4.2.3, R Core Team, 2023) were used to conduct the spatial and quantitative analyses described in this appendix.

Data Sources

USFS and CSFS Aerial Detection Survey

Annual aerial survey data from the USFS and CSFS are used to map visible insect and disease activity across Colorado. These survey data identify the mapped extent of observed damage or activity, the causal agent, host species and an estimated severity of infestation within each polygon. Because these data are based on aerial observation, they capture the location and extent of damage but do not characterize underlying forest structure. For this analysis, 2025 aerial survey data were used to identify mapped MPB activity and mortality in ponderosa pine forests within Colorado's Front Range (USDA Forest Service, 2026).

USDA Forest Inventory and Analysis (FIA) Program

The USDA Forest Inventory and Analysis (FIA) program provides a nationally consistent dataset for assessing forest conditions across the contiguous United States. FIA consists of a network of permanent field plots that are remeasured on a recurring basis using standardized protocols, allowing estimates of forest structure, species composition and volume to be generated across ownerships and jurisdictions. FIA plots exist at a density of roughly one plot per 6,000 acres. Resulting estimates are coarse in spatial resolution but are designed to support statistically robust population-level inferences (Bechtold & Patterson, 2005). FIA data products used in this analysis also reflect updated national volume and biomass estimation procedures (Westfall et al., 2023). For this analysis, FIA data were used both to summarize county-level ponderosa pine stand conditions and to support custom live ponderosa pine volume estimates linked to TreeMap pixels.

FIA TreeMap Raster Dataset

The FIA TreeMap 2022 CONUS raster dataset (Houtman et al., 2025) extends plot-based FIA information across forested landscapes by linking imputed FIA plots to 30 x 30 m raster pixels. Each pixel is assigned a plot identifier representing forest conditions that best match that location, allowing FIA-derived structural attributes to be summarized spatially across the landscape. TreeMap 2022 was developed using single-condition FIA plots that are 100% forested and physically located within CONUS boundaries, with source FIA data downloaded in February 2024 and LANDFIRE version 2.3.0 data accessed in June 2024 (Houtman et al., 2025). In this analysis, TreeMap was used to identify and summarize areas associated with stand conditions linked to elevated MPB susceptibility and to support estimates of susceptible acreage and live ponderosa pine volume.

Methods

Current Ponderosa Conditions

FIA data collected in field plots between 2014-2023, the most current publicly available dataset for Colorado as of April 2026, were used for this analysis. The FIESTA R package (Frescino et al., 2023) Green Book functions were used to query the FIA database and generate county-level estimates. The FIESTA package enables custom filtering of standard FIA variables and derived variables to produce estimates along with associated sample sizes and error. Because these summaries are based on plots located within each queried county, they provide county-specific approximations of conditions, with county-specific errors arising from fluctuations in sample size.

The FIESTA modGBratio function was used to estimate ponderosa-dominant acres, county-specific trees per acre and basal area per acre within the nine counties of interest. Data were first filtered to the ponderosa pine forest type and live ponderosa pine trees within those counties. Within ponderosa-dominant stands, trees per acre and basal area per acre were also summarized by diameter class for live ponderosa pine trees only, using approximately 6-inch diameter bins beginning at 1 inch DBH, defined as follows: Small (1.0–5.9” DBH), Medium (6.0–11.9” DBH), Large (12.0–17.9” DBH) and Very Large (18.0”+ DBH). Many of these estimates can also be generated using the FIA EVALIDator web tool (https://apps.fs.usda.gov/fia/evalidator/), a publicly available interface for querying FIA data without custom programming.

Because county size and plot availability vary across the Front Range, sample size and uncertainty also vary widely among counties. Some counties included more than 30 plots classified as ponderosa pine dominant, while others included only one. For counties represented by a single ponderosa-dominant plot, the reported estimate reflects the conditions of that plot expanded using standard FIA expansion factors, resulting in considerable uncertainty (see Table 1 in the main Science & Data Byte). Consequently, estimates for counties with very few plots should be interpreted with caution and treated as coarse approximations rather than as representative summaries of county-wide conditions. Estimates are intended to characterize average structural composition at the county level; actual conditions vary across the landscape.

Current Outbreak Extent

The 2025 USFS and CSFS Aerial Detection Survey dataset was used to identify areas of visible MPB activity and mortality in ponderosa pine forests within the nine Front Range counties included in this analysis. Aerial survey polygons were projected to NAD 1983 UTM Zone 13N, filtered to ponderosa pine as the host species and clipped to the analysis area.

Acreage for the current outbreak was summarized in two ways: as total polygon acreage and as severity-adjusted acreage. In addition to mapped polygon extent, the aerial survey includes an estimate of infestation severity reflecting the proportion of trees within each polygon identified as affected during survey flights. Severity-adjusted acreage was calculated to better approximate the portion of each mapped polygon currently affected by MPB. The mapped outbreak polygons covered 5,544 acres total, but severity-adjustment reduced the estimated currently affected area to 1,190 acres (see Table 2 in the main Science & Data Byte).

Development of MPB Spread Scenarios

Current outbreak polygons were used to develop 1 km and 2.5 km spread scenarios to estimate the acreage of ponderosa pine potentially affected if beetle activity expands outward from currently detected locations. Buffer distances were informed by the range of standard dispersal distances reported for bark beetle species in Colorado and Wyoming (Withrow et al., 2013), applied here as a conservative spread scenario range for MPB. Buffers of 1 km and 2.5 km were applied to the current outbreak polygons, and buffered features were dissolved to create two potential spread zones.

Current outbreak polygons and the 1 km and 2.5 km spread scenarios were converted to raster format to align with the 30 m FIA TreeMap raster for subsequent overlay and summarization. Rasterized current outbreak and spread scenarios were overlaid with county boundaries to determine the number of forested pixels associated with each scenario in each county. Because the buffered spread scenarios encompassed a mix of forest types, as well as non-forested land cover, FIA TreeMap data were used to restrict acreage estimates to forested areas represented in the TreeMap dataset. These forested acres served as the basis for subsequent summaries of susceptible acreage and live ponderosa pine volume.

TreeMap-Based Identification of MPB Susceptibility

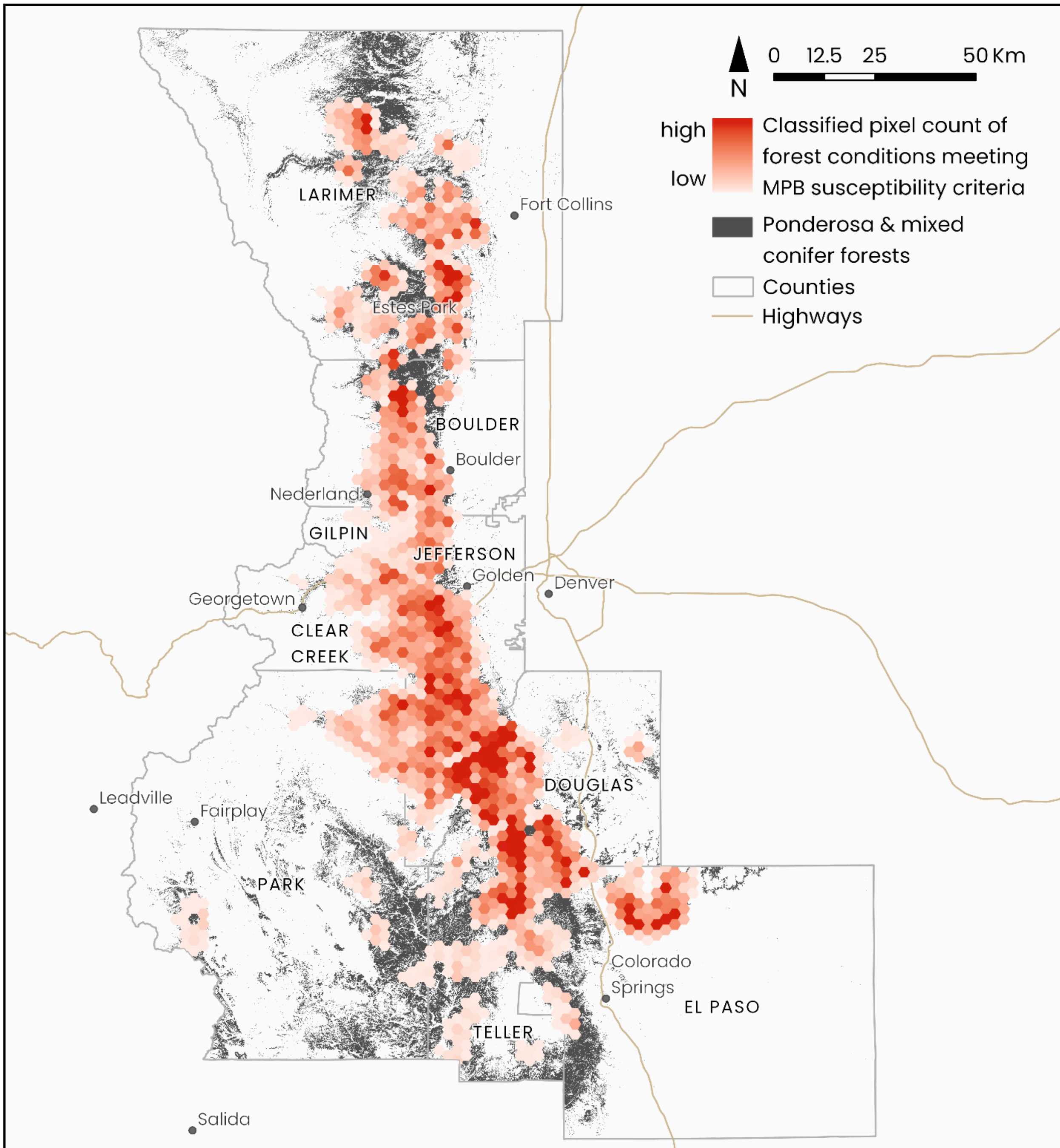
To evaluate forest susceptibility with the current outbreak area and spread scenarios, FIA TreeMap 2022 spatial data (Houtman et al., 2025) were used to identify pixels with stand conditions associated with elevated MPB susceptibility. Pixels within the analysis area were extracted and summarized by plot identifier to determine how many pixels in the area of interest were represented by each TreeMap plot, as well as identify specific plots for custom calculations of stand structural metrics.

Plot-level stand density index (SDI), quadratic mean diameter (QMD) and basal area were then derived using the *TreeMap2022_CONUS_Tree_Table.csv* file accompanying the TreeMap 2022 dataset (Houtman et al., 2025). This file includes species, status, diameter and other tree-level attributes for each tree record linked to a TreeMap plot. For this analysis, only species code, status code, diameter and the tree expansion factor were used. Records were filtered to retain live ponderosa pine trees and summarized to the plot level to calculate SDI and QMD. SDI was calculated as $\Sigma TPA_i(DIA_i/10)^{1.605}$ and converted to metric units by multiplying by 2.47105381. QMD was calculated as $\sqrt{(\ \Sigma(TPA_\mathrm{i}\ \times DIA_\mathrm{i}{}^2)\ /\ \Sigma TPA_\mathrm{i}\ )}$ and converted from inches to centimeters by multiplying by 2.54. Basal area was calculated as $\Sigma(TPA_i \times 0.005454 \times DIA_\mathrm{i}{}^2)$ and converted to m^2/ha by multiplying by 0.229568. Because the TreeMap tree table already contained the information needed for these calculations, FIA DataMart records were not required for this portion of the analysis.

Metric conversions were applied so that calculated values were directly comparable to the susceptibility thresholds reported by Negrón and Popp (2004). In their classification tree, stands with ponderosa pine SDI greater than 273.1 and QMD greater than 21.4 cm were associated with a predicted infestation probability of 73%. Further, stands with ponderosa pine SDI greater than 273.1, QMD less than or equal to 21.4 cm, and the total basal area greater than 29.2 m^2/ha were associated with a predicted infestation probability of 78%. Pixels meeting these thresholds do not necessarily represent stands classified as ponderosa pine-dominant forest type. Rather, they represent TreeMap pixels linked to FIA plots in which the live ponderosa pine component was sufficient to meet the SDI, QMD and basal area thresholds associated with elevated MPB susceptibility. Pixels meeting these thresholds therefore approximate areas at highest risk of infestation, though it should be noted that they represent imputed FIA plot conditions and may not capture the full range of structural variability present within the landscape.

Susceptible Pixel Map

To provide spatial context for the acreage and volume estimates presented in the Science & Data Byte, plot conditions meeting the Negrón and Popp (2004) criteria were mapped across the nine-county analysis area (Figure 1). Pixels that met the criteria were aggregated into hexagons based on pixel counts and were symbolized using the standard deviation symbology. On this scale, *high* indicates a higher number of pixels meeting the SDI, QMD and basal area thresholds described above; *low* indicates fewer such pixels meeting the thresholds within that hexagon. Ponderosa pine and mixed conifer forest cover are also shown to illustrate the broader extent of these forest types relative to the 2.5 km buffer zones from which the acreage and volume estimates were derived.



This is not a management priority map. Hexagons depict the number of 30x30 meter pixels (as assigned by TreeMap) with forest conditions that meet mountain pine beetle (MPB) susceptibility criteria (see text for details). Analysis was limited to stands containing ponderosa pine within 2.5 km of 2025 MPB outbreak in the 9 counties displayed. 1 hexagon = 5.85 km^2 = 1,444 acres.

Data Sources:
Aerial Detection Survey, USFS (https://tinyurl.com/5d7vmfr7); TreeMap, USFS (https://doi.org/10.2737/RDS-2025-0032); CO-WRA, CSFS (https://coloradoforestatlas.org)

Figure 1. Mountain pine beetle (MPB) susceptibility of ponderosa stands within the nine-county Front Range analysis area. Hexagons depict the count of 30 x 30 meter TreeMap pixels (Houtman et al., 2025) meeting Negrón and Popp (2004) MPB susceptibility thresholds within the 2.5 km spread scenario extent. Hexagon color reflects relative pixel count, ranging from low to high. Ponderosa pine and mixed conifer cover are shown in gray for reference (Colorado State Forest Service, 2023).

This map is not intended as a priority treatment map. It does not identify specific stands recommended for management action, nor does it imply that all areas with medium to high pixel density will experience MPB activity or areas with a low rating will not see beetle intensification. Rather, it is intended to illustrate the geographic extent from which acreage and volume estimates were derived, and to provide spatial context for where MPB activity could plausibly expand based on the current outbreak area and TreeMap-assigned stand structure.

Diameter Distribution of Live Ponderosa Pine Trees Within Identified Susceptible Plots

Because the Negrón and Popp (2004) criteria were applied at the plot level, the diameter distribution of live ponderosa pine trees within FIA-linked TreeMap plots identified as meeting the susceptibility thresholds was summarized to further describe the structure of these plots. Live ponderosa pine tree records from the TreeMap tree table were grouped into four diameter classes: Small (1.0–5.9” DBH), Medium (6.0–11.9” DBH), Large (12.0–17.9” DBH) and Very Large (18.0” + DBH). Percentages were weighted by the number of TreeMap pixels represented by each identified plot.

This diameter distribution summary was used to evaluate whether plots meeting the susceptibility thresholds were primarily composed of larger-diameter trees. **Across all identified plots, the weighted diameter distribution remained broad, with 31% of trees classified as small, 48% as medium, 16% as large and 4% as very large.** This indicates that the threshold-based screening did not strongly bias toward selecting plots with limited structural variability.

Differences between node 4 and node 6 help explain this pattern. Node 4, defined by high SDI and larger QMD, is more strongly associated with stands dominated by larger-diameter trees (Table 3). In contrast, node 6, defined by high SDI, smaller QMD and high basal area, captures stands with many small- to medium-diameter trees, including trees in the diameter range often considered susceptible to MPB attack.

Susceptibility node	Small (1.0–5.9”)	Medium (6.0–11.9”)	Large (12.0–17.9”)	Very large (18.0” +)
Node 4	25%	51%	19%	5%
Node 6	57%	37%	6%	0%

Table 3. Weighted diameter class distribution of live ponderosa pine trees within FIA-linked TreeMap plots meeting node 4 and node 6 stand susceptibility criteria from Negrón and Popp (2004).

Susceptible Acreage by Scenario

For each FIA TreeMap plot represented in the analysis area, the number of associated 30 m pixels was tallied and linked to the plot-level MPB susceptibility class derived from SDI, QMD and basal area thresholds. Pixel counts were then summed by county and susceptibility class to estimate the spatial extent of conditions meeting each class. Acreage was estimated by multiplying pixel counts by the area of each pixel (900 m^2) and converting to acres (1 acre = 4,046.86 m^2). Acreage estimates for the two susceptibility classes were summed to represent the total area with stand conditions associated with a 73% or greater predicted probability of MPB infestation, based on Negrón and Popp (2004).

Areas meeting susceptibility thresholds will not necessarily become infested. Acreage deductions were therefore applied to represent levels of infestation consistent with the severity estimation from the aerial survey. Severity deduction scenarios represented a range from light (6% of trees affected), moderate (20%), severe (40%) and very severe (75%) infestation levels. This represented a range from light (6% of individuals within a given area impacted), moderate (20% of individuals), severe (40% of individuals) and very severe (75% of individuals) infestation, reflecting a range of potential impacts as MPB spreads outward from current infestation centers. The resulting susceptible acreage estimates are summarized in Tables 4 and 5 by county and severity deduction scenario.

County	Light (6%)	Moderate (20%)	Severe (40%)	Very severe (75%)	No deduction
Boulder	238	795	1,590	2,981	3,975
Clear Creek	142	474	948	1,778	2,370
Douglas	542	1,806	3,613	6,774	9,031
El Paso	306	1,018	2,037	3,819	5,092
Gilpin	85	283	567	1,063	1,417
Jefferson	1,032	3,439	6,878	12,895	17,194
Larimer	344	1,147	2,294	4,300	5,734
Park	116	387	774	1,451	1,934
Teller	143	476	952	1,785	2,381
Total	2,948	9,825	19,651	36,846	49,127

Table 4. Estimated acreage of ponderosa pine stands meeting MPB susceptibility thresholds within the **1 km spread scenario,** by county, under severity deduction scenarios.

County	Light (6%)	Moderate (20%)	Severe (40%)	Very severe (75%)	No deduction
Boulder	708	2,359	4,718	8,846	11,795
Clear Creek	230	767	1,534	2,876	3,834
Douglas	1,287	4,289	8,579	16,085	21,447
El Paso	613	2,044	4,088	7,664	10,219
Gilpin	107	355	711	1,333	1,777
Jefferson	1,984	6,612	13,224	24,795	33,059
Larimer	1,126	3,752	7,504	14,069	18,759
Park	281	936	1,872	3,510	4,680
Teller	399	1,329	2,658	4,983	6,644
Total	6,733	22,443	44,886	84,161	112,215

Table 5. Estimated acreage of ponderosa pine stands meeting MPB susceptibility thresholds within the **2.5 km spread scenario,** by county, under severity deduction scenarios.

Live Ponderosa Pine Volume by Scenario

To estimate live ponderosa pine volume within the current outbreak and projected spread scenarios, TreeMap-linked plots classified as meeting the stand structure thresholds associated with elevated MPB susceptibility based on Negrón and Popp (2004) were identified. FIA DataMart Tree table records downloaded in February 2026 were then linked to these plots using the TreeMap plot identifier (TM_ID) and FIA plot control number (PLT_CN).

FIA tree records were filtered to retain live ponderosa pine trees at least 6 inches DBH and the FIA variable VOLTSGRS (gross total stem volume) was used as the per-tree volume measure. VOLTSGRS estimates the total volume of wood in the central stem from ground line to the tree tip (Burrill et al., 2025). Volume estimates therefore reflect total stem volume from ground to tip rather than merchantable volume, encompassing material that would be removed from the site, as well as material that would remain on-site. Merchantable volume estimates would be considerably lower but would not adequately capture the full scale of material potentially affected by MPB mortality.

For each unique TreeMap-linked plot, live ponderosa pine volume was calculated by summing VOLTSGRS × TPA_UNADJ across all retained tree records. This produced a plot-level estimate of live ponderosa pine stem volume in cubic feet per acre. Plot level volume per acre values were then scaled to total volume by multiplying by the acreage represented by each plot within a given county and scenario, based on the number of associated TreeMap pixels. Expanded plot-level totals were summed by county and scenario to estimate total live ponderosa pine volume within the mapped outbreak area and each projected spread zone.

Trees were filtered to 6 inches diameter and above based on personal observations in the field and the Munson and Anhold Risk Rating technique (Chojnacky et al., 2000) that uses six inches as the lowest diameter threshold for moderate MPB infestation in stands on ponderosa pine. The 6-inch threshold was selected to ensure comprehensive inclusion of potentially susceptible trees and to reflect field observations of the current outbreak.

For Wyoming trees from inventory year 2000, VOLTSGRS were not available for live trees. These records were associated with periodic FIA data, for which NSVB-derived variables such as VOLTSGRS may not be populated. For those plots, FIA-calculated tree-level VOLTSGRS values were provided by John Shaw, USDA Forest Service FIA, via personal communication in April 2026.

The resulting live ponderosa pine volume estimates are summarized in Tables 6 and 7 by county and severity-deduction scenario.

County	Light (6%)	Moderate (20%)	Severe (40%)	Very severe (75%)	No deduction
Boulder	4,655	15,516	31,033	58,187	77,582
Clear Creek	2,341	7,802	15,604	29,258	39,010
Douglas	11,278	37,593	75,186	140,974	187,965
El Paso	6,590	21,966	43,932	82,373	109,831
Gilpin	1,476	4,918	9,837	18,444	24,592
Jefferson	19,724	65,747	131,493	246,550	328,733
Larimer	7,884	26,279	52,558	98,546	131,394
Park	1,837	6,122	12,244	22,957	30,609
Teller	2,174	7,245	14,490	27,170	36,226
Total	57,957	193,188	386,377	724,457	965,942

Table 6. Estimated live ponderosa pine volume (CCF) within stands meeting MPB susceptibility thresholds in the **1 km spread scenario**, by county, under severity deduction scenarios.

County	Light (6%)	Moderate (20%)	Severe (40%)	Very severe (75%)	No deduction
Boulder	13,941	46,471	92,943	174,268	232,357
Clear Creek	3,803	12,676	25,352	47,534	63,379
Douglas	26,107	87,022	174,045	326,334	435,112
El Paso	12,460	41,532	83,064	155,746	207,661
Gilpin	1,844	6,147	12,294	23,051	30,735
Jefferson	39,232	130,772	261,544	490,394	653,859
Larimer	23,935	79,785	159,569	299,192	398,923
Park	4,447	14,823	29,645	55,585	74,113
Teller	6,102	20,340	40,681	76,277	101,702
Total	131,870	439,568	879,136	1,648,381	2,197,841

Table 7. Estimated live ponderosa pine volume (CCF) within stands meeting MPB susceptibility thresholds in the **2.5 km spread scenario**, by county, under severity deduction scenarios.

Literature Cited

Bechtold, W. A., & Patterson, P. L. (2005). The enhanced Forest Inventory and Analysis program - national sampling design and estimation procedures. USDA Forest Service. https://doi.org/10.2737/SRS-GTR-80

Burrill, E. A., DiTommaso, A. M., Turner, J. A., Pugh, S. A., Christensen, G., Kralicek, K. M., Perry, C. J., Lepine, L. C., Walker, D. M., & Conkling, B. L. (2025). The Forest Inventory and Analysis Database, FIADB User Guides, Volume: Database Description (version 9.4), Nationwide Forest Inventory. U.S. Department of Agriculture, Forest Service. https://research.fs.usda.gov/understory/forest-inventory-and-analysis-database-user-guide-nfi

Chojnacky, D.C., Bentz, B.J., & Logan, J.A. 2000. Mountain pine beetle attack in ponderosa pine: Comparing methods for rating susceptibility. Res. Pap. RMRS-RP-26. Ogden UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station 10 p.

Colorado State Forest Service (2023). Colorado Wildfire Risk Assessment (CO-WRA). https://coloradoforestatlas.org/customers/colorado/manuals/CO-WRA_2022_Final_Report_20230724.pdf

Esri Inc (2024). *ArcGIS Pro* (Version 3.4.0). https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

Frescino, T. S., Moisen, G. G., Patterson, P. L., Toney, C., & White, G. W. (2023). 'FIESTA': A forest inventory estimation and analysis R package. Ecography, 2023(7), e06428. https://doi.org/10.1111/ecog.06428

Houtman, Rachel M.; Leatherman, Lila S. T.; Zimmer, Scott N.; Housman, Ian W.; Shrestha, Abhinav; Shaw, John D.; Riley, Karin L. 2025. TreeMap 2022 CONUS: A tree-level model of the forests of the conterminous United States circa 2022. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2025-0032

Negrón, J. F., & Popp, J. B. (2004). Probability of ponderosa pine infestation by mountain pine beetle in the Colorado Front Range. *Forest Ecology and Management, 191*(1–3), 17–27. https://doi.org/10.1016/j.foreco.2003.10.026

R Core Team (2023). *R: A language and environment for statistical computing* (v4.2.3). R Foundation for Statistical Computing. https://www.R-project.org/

USDA Forest Service, Forest Health Protection and its partners. (2026, January 27). Aerial detection survey: 2025. U.S. Department of Agriculture. https://www.fs.usda.gov/r02/natural-resources/forest-health/aerial-detection-survey

Westfall, J. A., Coulston, J. W., Gray, A. N., Shaw, J. D., Radtke, P. J., Walker, D. M., Weiskittel, A. R., MacFarlane, D. W., Affleck, D. L. R., Zhao, D., Temesgen, H., Poudel, K. P., Frank, J. M., Prisley, S. P., Wang, Y., Meador, A. J. S., Auty, D., & Domke, G. M. (2023). A national-scale tree volume, biomass, and carbon modeling system for the United States. USDA Forest Service. https://doi.org/10.2737/WO-GTR-104

Withrow, R. J., Lundquist, J. E., & Negrón, J. F. (2013). Spatial dispersal of Douglas-fir beetle populations in Colorado and Wyoming. ISRN Forestry, 2013, Article 542380, 1–10. https://doi.org/10.1155/2013/542380