TNC WOOD INNOVATION PROJECT SIMULATION METHODS

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CONTENTS

1 INTRODUCTION

We developed a set of forest growth, management, and disturbance scenarios for Washington state to analyze carbon storage in the standing forest and quantify harvest volume by species and log size class. Harvest volumes were used to conduct a life-cycle analysis of the wood products. Scenarios were defined by three major factors: management strategy (no action, business as usual, extended rotations, intensive shortened rotations, and extended rotations with increased thinning), wildfire (with and without wildfire), and climate change (with and without growth model adjustments for climate change). In total, 20 scenarios were developed for Washington state. Forest Inventory and Analysis plots were used to represent initial forest conditions. The Forest Vegetation Simulator was used simulate growth, treatments, and fire.

2 DATA

2.1 FOREST INVENTORY AND ANALYSIS PLOT DATABASE

Forest Inventory and Analysis (FIA) plots were used to represent forest conditions circa 2020 (Burrell et al. 2018). FIA plots are remeasured every 10 years. Plots representing current conditions were measured between 2010 and 2019. We used 6003 plots to represent 22 million acres of forestland in Washington.

FIA plots include attributes useful for prescribing silvicultural treatments, developing management scenarios, and summarizing results. These include county, owner class (National Forest, National Park, State, Private and Tribal), and forest type. Additionally, attributes for localizing growth and yield with the Forest Vegetation Simulator (FVS) include variant, habitat type, site index, maximum stand density index, slope, aspect, and elevation. The FIA Database includes FVS-ready tables to simulate either Plots or Conditions (one or more sub-Plots within a Plot). We simulated Plots in this analysis.

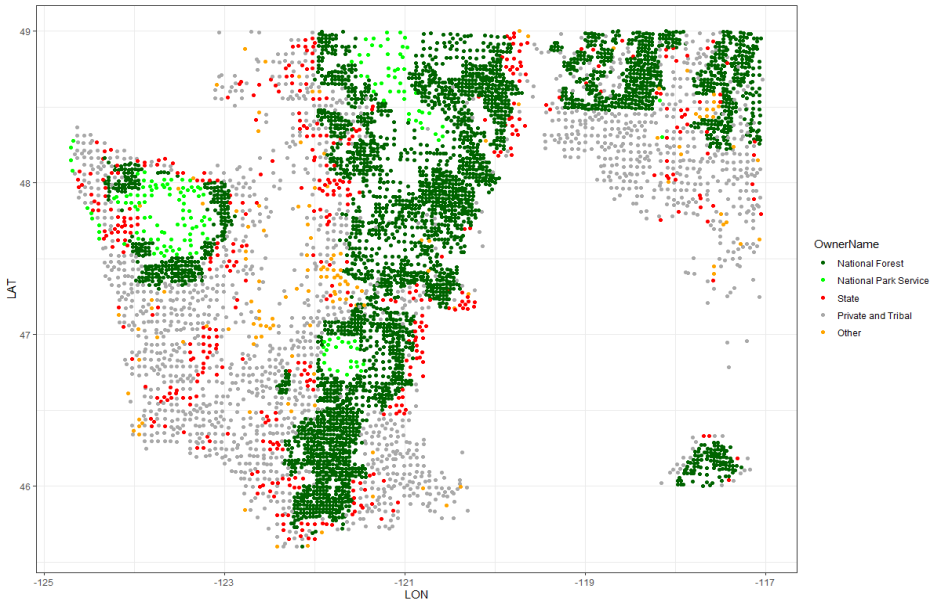

Figure 1.FIA Plots in Washington state by owner class.

2.2 Historical Fire Data

Remeasured FIA Plots were used to estimate wildfire acres by county. We used the county estimate to calculate the proportional burned acres for each county-owner (by owner acres). The mean annual burned estimate was approximately 115,000 acres in Eastern Washington compared to 3,000 acres in Western Washington. We recognize that the 10-year remeasurement period for FIA is too short to accurately characterize fire regimes with long return intervals, in particular in Western Washington (though numerous large fires did occur in Eastern Washington during the remeasurement period). The FIA analysis was used to guide the burn target acres for each scenario. The adjustments made to the historical averages to set targets for each scenario are described in section 3.6.

2.3 Historical Timber Harvest Data

We used mill-delivered log volumes by county and owner to guide harvest rates (Bureau of Business and Economic Research 2021). This volume is reported for excise tax purposes to the Washington State Department of Revenue. We calculated the average annual harvest rate for each county-owner from 2002 to 2020. The adjustments made to the historical averages to set targets for each scenario are described in section 3.6.

3 Methods

3.1 Missing FVS Site Values

Although most FIA Plots were attributed with values to localize FVS simulations, some values were missing. FVS default values can be a cause of unrealistic growth. We were careful to fill in any missing values (in particular site index and maximum stand density index) with appropriate estimates using Plots from the same variant and forest type.

3.2 Silvicultural Prescriptions

Representative silvicultural prescriptions for final harvest, pre-commercial thin, commercial thin, and regeneration treatments were determined through two complementary investigations. Personal interviews were conducted with professional foresters at the Washington State Department of Natural Resources and USDA Forest Service. An analysis of Forest Service draft Environmental Assessments (for example, Mt Baker-Snoqualmie National Forest 2021) and reported activity layers (USDA Forest Service 2021) informed residual thinning levels and annual treatment acres, respectively.

Guided by the investigation, sets of treatments were defined by county and owner. Prescriptions were used during the growth modeling step to develop a comprehensive database of feasible pathways for each Plot. During the scenario development step of the analysis, additional constraints (such as minimum final harvest age) were applied.

Each treatment set initially consisted of a final harvest, commercial thin, and, optionally, a pre-commercial thin. A second commercial thin was added to increase the range of treatment options. This treatment approximately halved the residual stand density of the original commercial thin. In the Private and Tribal, Douglas-fir forest type in Western Washington, a second final harvest treatment was added

to represent intensively managed, 'maximum productivity' forest management. This treatment used the same residual target value as the original final harvest treatment but increased the planted trees per acre. Plots were also simulated with a 5% increase in site index and basal area increment to represent increased productivity due to activities such as site preparation, fertilization, herbicides, and improved genetics.

All treatments were specified using basal area per acre (BAA), percent BAA, or trees per acre (TPA) to define the residual forest condition seedlings per acre representing planted and/or natural regeneration. For natural regeneration, the basal area proportion by species of the pre-treatment stand was used to determine which species were planted. Most treatments were implemented from below (removing the smallest trees first) by diameter at breast height (DBH); a small number of treatments were applied proportionally (removing trees across the diameter distribution). Example treatment definitions are provided for one forest type in Western and Eastern Washington in Table 1 and Table 2, respectively.

Table 1. Example treatment definitions for the Douglas-fir forest type in Western Washington.

Douglas-fir forest type in Western Washington			
Private and Tribal owner class			
Treatment Type	**Age Range**	**Residual Value**	**Regeneration (TPA)**
Final harvest	30+	3 TPA	435 Douglas-fir
Final harvest 'Max Productivity'	30+	3 TPA	538 Douglas-fir
Pre-commercial thin	7-21	250 TPA	
Commercial thin	30+	150 TPA	50 other species
Heavy commercial thin	30+	75 TPA	50 other species
State owner class			
Treatment Type	**Age Range**	**Residual Value**	**Regeneration (TPA)**
Final harvest	30+		350 Douglas-fir
Pre-commercial thin	7-21	300 TPA	
Commercial thin	30+	50% of BAA	50 other species
Heavy thin	30+	30% of BAA	50 other species
National Forest owner class			
Treatment Type	**Age Range**	**Residual Value**	**Regeneration (TPA)**
Final harvest	40+	15 TPA	100 Douglas-fir; 350 other species
Pre-commercial thin	7-21	200 TPA	
Commercial thin	30+	100 TPA	50 other species
Heavy commercial thin	30+	50 TPA	50 other species

Table 2. Example treatment definitions for the Ponderosa pine forest type in Eastern Washington.

Ponderosa Pine forest type in Eastern Washington			
Private and Tribal owner class			
Treatment Type	**Age Range**	**Residual Value**	**Regeneration (TPA)**
Final harvest	40+	3 TPA	150 Ponderosa pine; 30 other species
Pre-commercial thin	7-21	80 TPA	
Commercial thin	30+	45 BAA	50 other species
Heavy commercial thin	30+	30 BAA	50 other species
State owner class			
Treatment Type	**Age Range**	**Residual Value**	**Regeneration (TPA)**
Final harvest	40+	12 TPA	120 Ponderosa pine; 30 other species
Pre-commercial thin	7-21		
Commercial thin	30+	50% of BAA	50 other species
Heavy commercial thin	30+	30% of BAA	50 other species
National Forest owner class			
Treatment Type	**Age Range**	**Residual Value**	**Regeneration (TPA)**
Final harvest	40+	25 BAA	150 Ponderosa pine; 30 other species
Pre-commercial thin	7-21	130 TPA	
Commercial thin	30+	65 BAA	50 other species
Heavy commercial thin	30+	40 BAA	50 other species

3.3 FIRE

We used the Forest Vegetation Simulator Fire and Fuels Extension (FFE) to simulate moderate and severe wildfire events for each Plot (Rebain 2010). FFE allows several variables to be adjusted that effect the intensity of the simulated fire and resulting mortality. Table 3 lists the values we used to simulate each fire type. When simulated wildfire resulted in stand replacing levels of mortality, regeneration was simulated based on the final harvest treatment(s) definition for the Plot.

Table 3. Parameters used to simulate moderate and severe fires in the Forest Vegetation Simulator Fire and Fuels Extension. See Rebain (2010).

FFE Variable	Moderate Fire	Severe Fire
Wind speed (miles per hour) at 20 feet above the vegetation	10	20
Temperature	FVS Variant / Temperature: PN 60, WC 60, EC 65, IE 65, BM 65	FVS Variant / Temperature: PN 75, WC 75, EC 85, IE 90, BM 90
Moisture Level	Dry	Very dry
Fire Season	After greenup	After greenup

3.4 Climate Change

To consider the effects of climate change, we adjusted FVS growth to reduce site productivity and carrying capacity. For this analysis, we assume 1) climate change will result in slower growing, more widely spaced stands in all forest types; and 2) mortality will generally target the least competitive trees in the stand. FVS has recently been modified to allow this behavior by changing site index and maximum stand density index values during a simulation (Dixon 2002). We also modified predicted basal area increment and mortality rates. We use a linear model to simulate increasingly severe impacts of climate change by specifying an initial and final value for each FVS adjustment.

We explored three sets of FVS adjustments representing light, moderate, and severe climate change impacts. We evaluated the effects of our adjustments on a subset of Plots. We selected Plots with a Douglas-fir forest type from each FVS variant. These Plots were identified as the 100th, 75th, 50th, and 25th percentile Plots from a distribution of basal area per acre for all Plots in the variant. Results were consistent with our expectations, with increasing climate change severity resulting in decreased TPA, BAA, and board feet per acre at each point in time. See Appendix 1. We selected FVS adjustments representing moderate climate change impacts for this analysis. The values are listed in Table 4.

Table 4. FVS adjustments used for the climate change scenarios. See Van Dyck and Smith-Mateja (2021).

FVS Keyword	Adjustment Description	Initial Value	Final Value
SETSITE	Percent change in site index	-2	-15
SETSITE	Maximum SDI (proportion of initial value)	.98	.85
BAIMULT	Multiplier on predicted basal area increment	.98	.85
FIXMORT	Proportion of tree records that will be killed (applied 50% smallest to largest and 50% across the diameter distribution)	.01	.02

3.5 Growth and Yield Simulations

For each set of growth assumptions (with and without climate change adjustments), we used the treatment and fire definitions to simulate a comprehensive set of management and disturbance pathways for each Plot. We used the Forest and Vegetation Simulator to project 6 time periods with a 15-year time step (representing 95 years). Plots were located in the Pacific Northwest Coast (PN), West Cascades (WC), East Cascades (EC), Inland Empire (IE), and Blue Mountains (BM) variants.

We used a branching logic to simulate pathways. For each Plot, in the first time period, we simulated each treatment that met minimum requirements (minimum Plot age, cut board foot volume for a final harvest and commercial thins, and cut TPA for a pre-commercial thin). In subsequent time periods we evaluated each treatment against inventories grown from successful treatments in the previous time period. We required at least 30 years after commercial and pre-commercial thins before another treatment was possible. After a fire was simulated, we required at least 45 years until another fire could be simulated. An example of the set of pathways developed for one Plot is shown in Figure 2. We maintained parent-child relationships to reconstruct complete pathways. The simulated data was stored in a database for use during scenario development and summarization. In total, we simulation nearly 10.6 million growth, management, and disturbance pathways across 6003 plots under two sets of growth assumptions.

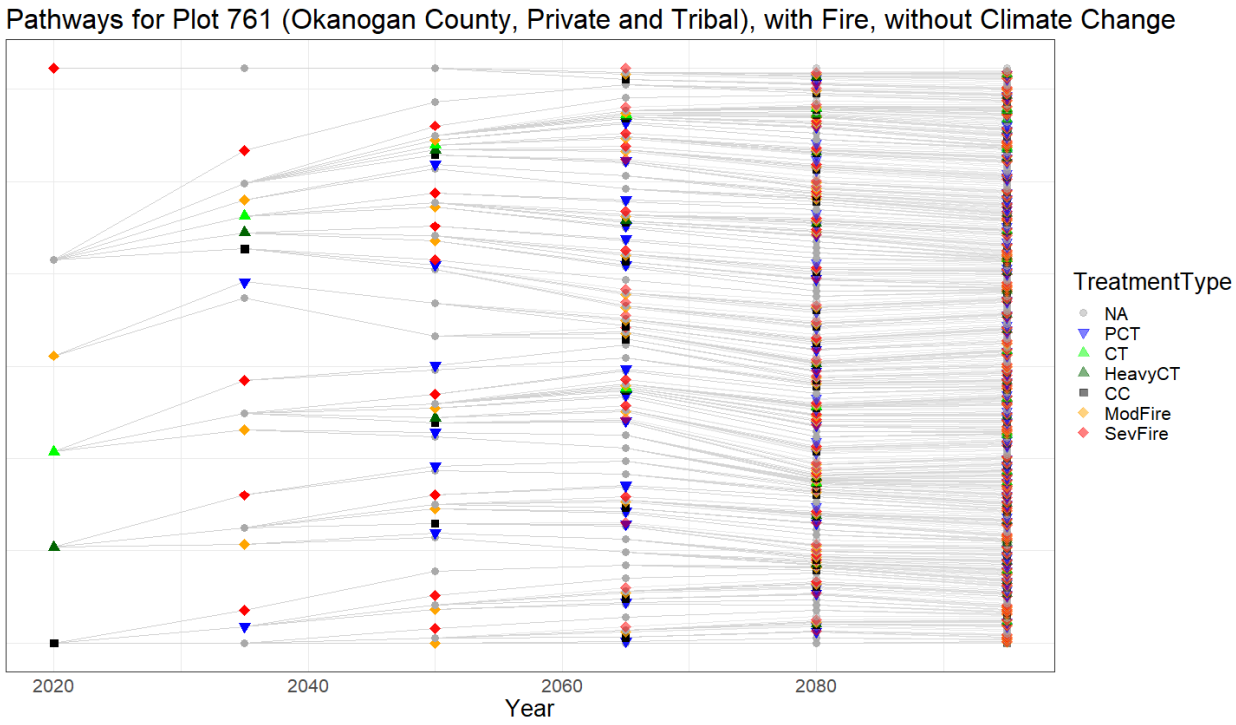

Figure 2. Set of pathways generated for example Plot 761.

3.6 Statewide Scenarios

We developed 20 statewide scenarios by querying the simulated data and assigning proportions of Plot acres to treatments in each time period. Scenarios were a combination of management, fire, and climate change scenarios. The management scenarios were business as usual, extended rotations,

shortened rotations, and extended rotations with increased thinning. The five management scenarios were simulated with each combination of fire scenario (with and without fire) and climate change scenario (with and without climate change).

Although we used 15-year time intervals for growth modeling, we used an annual time step to match targets. Each year we prioritized targets in the following order: pre-commercial thin acres, final harvest cut volume, moderate fire burned acres, severe fire burned acres, and commercial thin cut volume. Remaining acres were assigned to no action. We restricted treatment options in later time periods based on the sequence of treatments that occurred in earlier time periods. The final sequence of treatments was used to identify the number of acres assigned to each pathway. Results were stored in a database to summarize scenario outputs.

To ensure similar harvest volumes across all scenarios, we set volume targets at 90 percent of the historical average for Private and Tribal and State owner classes. For fire scenarios without climate change, we used the historical average burned acres for Eastern Washington as the annual target for acres to burn. In Western Washington we increased the historical average by a factor of 10. For fire scenarios with climate change, we further increased annual targets by a factor of 1.5.

Management differed between scenarios (business as usual, extended rotations, shortened rotations, and extended rotations with increased thinning) by the target final harvest age and the proportion of harvest volume from commercial thins. Table 5 and Table 6 list the target final harvest age and proportion of harvest volume from commercial thins, respectively, by management scenario and owner class. All management scenarios set a target age of 30 for commercial thins.

Table 5. Target final harvest age by management scenario.

Management Scenario	Private and Tribal	State	National Forest
Business as usual	45	60	75
Extended rotations	75	75	75
Shortened rotations	30	30	75
Extended rotations with increased thinning	75	75	75

Table 6. Proportion of harvest volume from commercial thinnings by management scenario.

Management Scenario	Private and Tribal	State	National Forest
Business as usual	.1	.3	.8
Extended rotations	.1	.3	.8
Shortened rotations	0	0	.8
Extended rotations with increased thinning	.2	.3	.8

3.7 Summary Calculations

3.7.1 Carbon

We calculated carbon in the forest using the Component Ratio Method (Woodall et al. 2011). This method calculates stem biomass using national-scale estimators from Jenkins et al. (2003) and by multiplying stem volume (from FVS) by species specific gravity (Ross 2021). The ratio of these two estimates is used to scale biomass component predictions for bark, branch, foliage, and roots (Jenkins et

al. 2003). We used biomass estimates from the FVS Fire and Fuels Extension for snags and downed woody debris (Rebain 2010). Biomass was multiplied by .5 to calculate carbon.

3.7.2 Log Volume

We grouped similar species together and applied a taper equation by Kozak et al. (1969) to buck cut trees into logs. We used a maximum log length of 32 feet, a one-foot stump, and reported the volume between a four- and six-inch diameter separately (as a bolt that may or may not be merchantable). Using the large and small end diameter of each log, we calculated cubic foot log volume using the equation for the frustum of a cone. We then calculated the proportion of total tree volume in each log and multiplied this value by the FVS cubic foot volume to determine the final log volumes. Log volumes were summarized by species and small end diameter class.

4 SCENARIO RESULTS

The 20 scenarios were designed to produce a similar amount of harvest volume each time period. Table 7 lists the average, minimum, and maximum annual harvest volumes. The fire scenarios burned nearly identical numbers of acres (within 200 acres annually). Fire scenarios without climate change burned close to 146,840 acres annually. With climate change, 220,220 acres were burned. Under each fire scenario, burned acres were evenly split between moderate and severe fires.

Table 7. Average, minimum, and maximum harvest volume (billion board feet) for each scenario.

No Fire, No Climate Change			
Management Scenario	**Average Cut BBF**	**Min Cut BBF**	**Max Cut BBF**
No Action	0	0	0
Business As Usual	2.77	2.68	2.80
Extended Rotations	2.78	2.68	2.81
Shortened Rotations	2.79	2.78	2.81
Extended Rotations + Increased Thinning	2.75	2.59	2.79
With Fire, No Climate Change			
Management Scenario	**Average Cut BBF**	**Min Cut BBF**	**Max Cut BBF**
No Action	0	0	0
Business As Usual	2.75	2.67	2.79
Extended Rotations	2.75	2.68	2.79
Shortened Rotations	2.77	2.75	2.80
Extended Rotations + Increased Thinning	2.73	2.58	2.78
No Fire, With Climate Change			
Management Scenario	**Average Cut BBF**	**Min Cut BBF**	**Max Cut BBF**
No Action	0	0	0
Business As Usual	2.72	2.65	2.75
Extended Rotations	2.72	2.65	2.76
Shortened Rotations	2.73	2.69	2.77
Extended Rotations + Increased Thinning	2.70	2.59	2.74
With Fire, With Climate Change			
Management Scenario	**Average Cut BBF**	**Min Cut BBF**	**Max Cut BBF**
No Action	0	0	0
Business As Usual	2.67	2.63	2.74
Extended Rotations	2.67	2.64	2.75
Shortened Rotations	2.69	2.63	2.76
Extended Rotations + Increased Thinning	2.64	2.58	2.68

The scenarios achieved similar harvest volumes by targeting different Plots and harvesting a different number of acres. Figure 3 shows the average age of the Plots treated with a final harvest. Statewide, the average final harvest age for shortened rotations, business as usual, and extended rotations (with and without increased thinning), respectively, was roughly 47, 62, and 80 years old. Figure 4 shows the annual final harvest (CC) acres for each scenario. The business as usual scenarios treated roughly 70,000 to 80,000 acres with a final harvest each year. The extended rotation scenarios treated fewer acres (targeting older, higher volume Plots), while the shortened rotation scenarios treated more acres (targeting younger, lower volume Plots).

The effects of management, fire, and climate scenarios on forest carbon are illustrated in Figure 5. Forest carbon totaled approximately 1.5 billion tons in 2020. At the end of the simulation, forest carbon ranged from 3 billion tons (no action, no fire, no climate change) to 1.75 billion tons (active management scenarios with fire and climate change).

The simulations suggest that between management, fire, and climate change, modifications to growth to represent climate change had the largest effect on forest carbon. Comparing like management and fire scenarios (such as no action without fire), climate change reduced forest carbon by approximately 500 million tons by the end of the simulation. Without climate change (for like management scenarios), fire reduced forest carbon by 250 million tons by 2095. With climate change (for like management scenarios), fire reduced forest carbon by roughly 310 million tons by 2095. Management, except for no action versus active management, had a much smaller effect on forest carbon. Between active management scenarios (with like fire and climate change scenarios), forest carbon in 2095 differed by about 50 million tons.

Finally, management strategy effected the size of trees and logs harvested. The percentage of cut log volume by small end diameter size class is shown in Figure 7 (4 to 8 inches), Figure 8 (8 to 12 inches), Figure 9 (12 to 16 inches), Figure 10 (16 to 20 inches) and Figure 10 (greater than 20 inches). Half of all log volume under business as usual was in the 4 to 8 inch size class, with a significant amount of volume in the 8 to 12 inch size class. As expected, extended rotations (with and without increased thinning) increased the proportion of volume from the three largest size classes (12 to 16 inches, 16 to 20 inches, and greater than 20 inches). Shortened rotations increased the proportion of log volume in the smallest size class (4 to 8 inches).

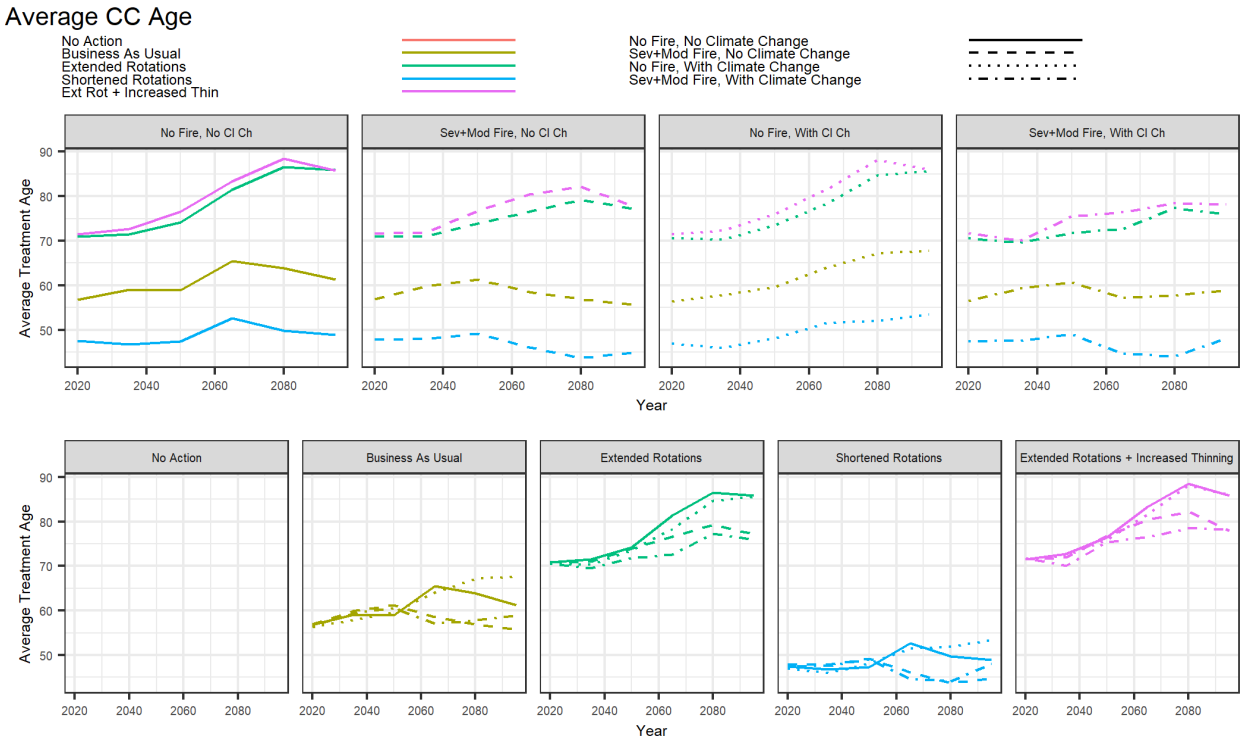

Figure 3. Average final harvest age (CC) for each scenario.

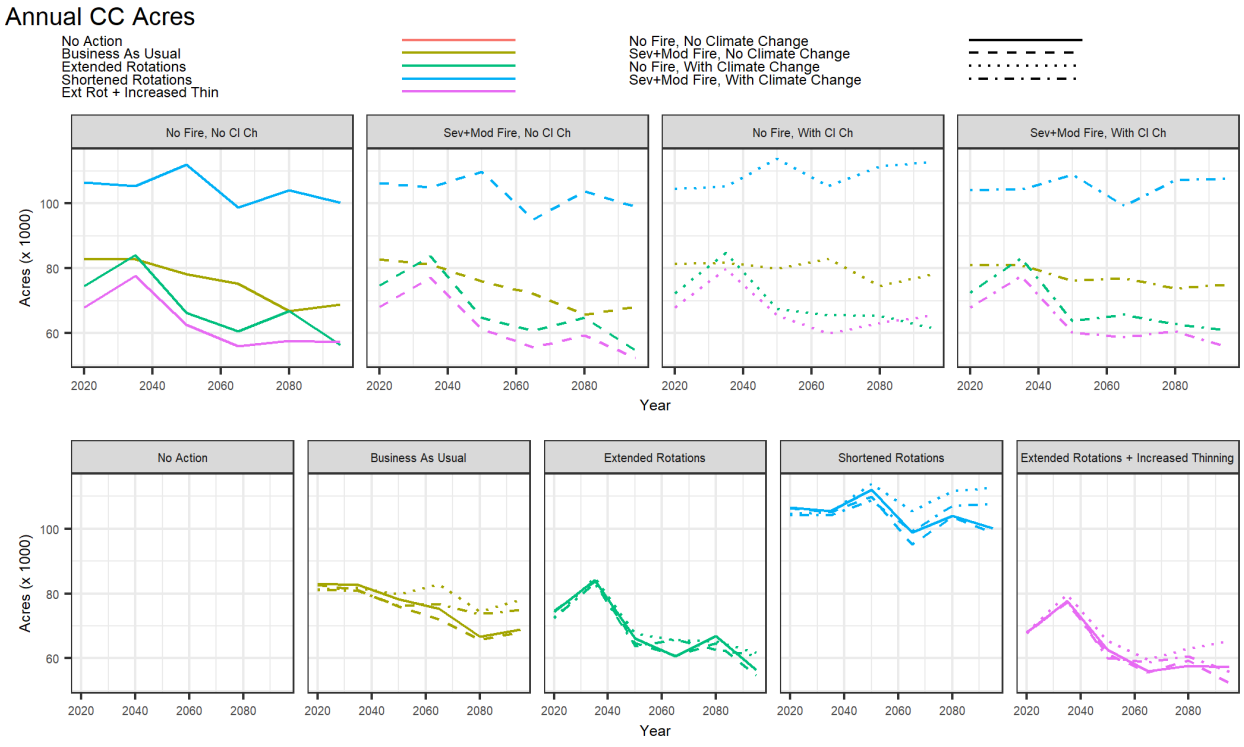

Figure 4. Annual acres treated with a final harvest (CC) for each scenario.

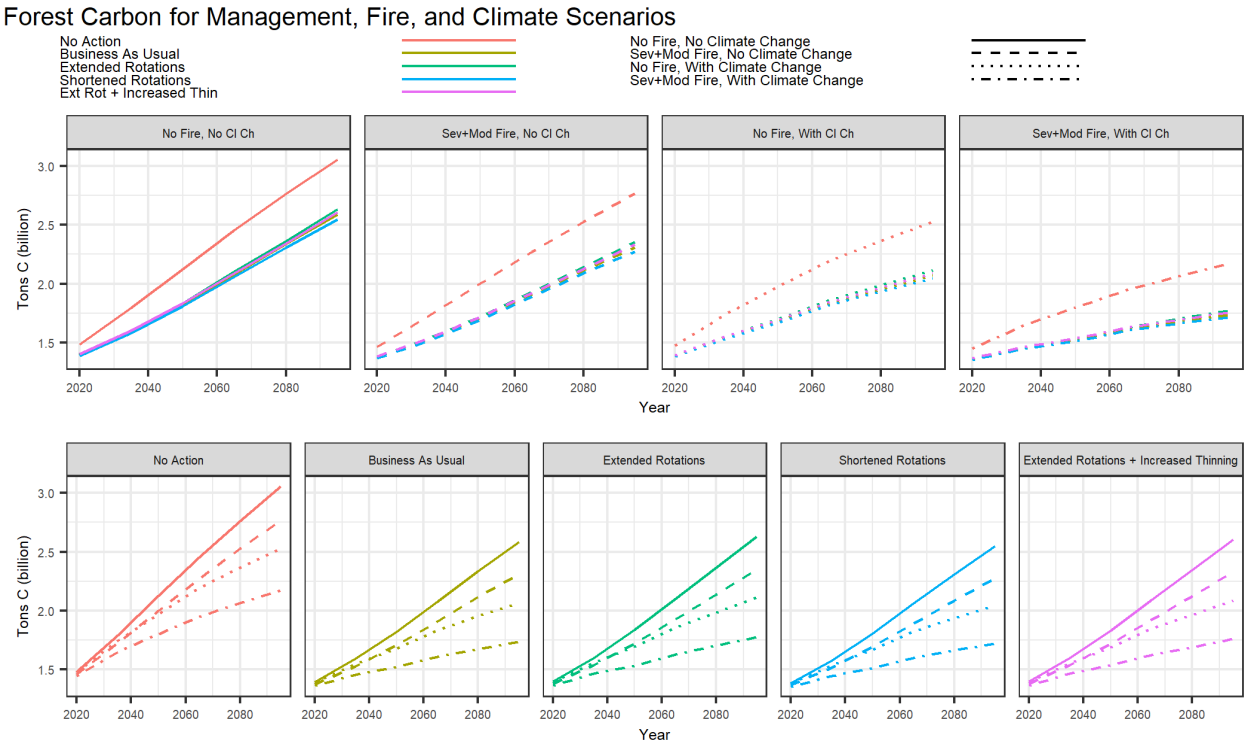

Figure 5. Forest carbon by scenario.

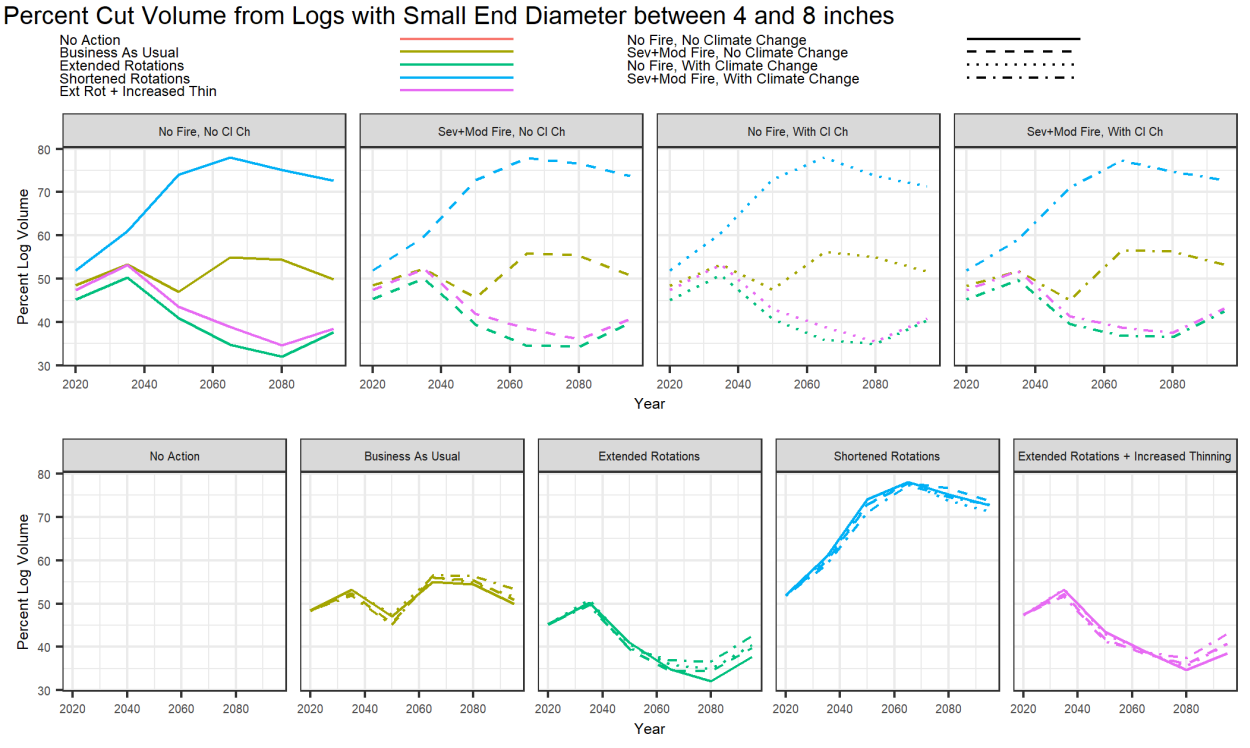

Figure 6. Percent of volume from logs with a small end diameter between 4 and 8 inches.

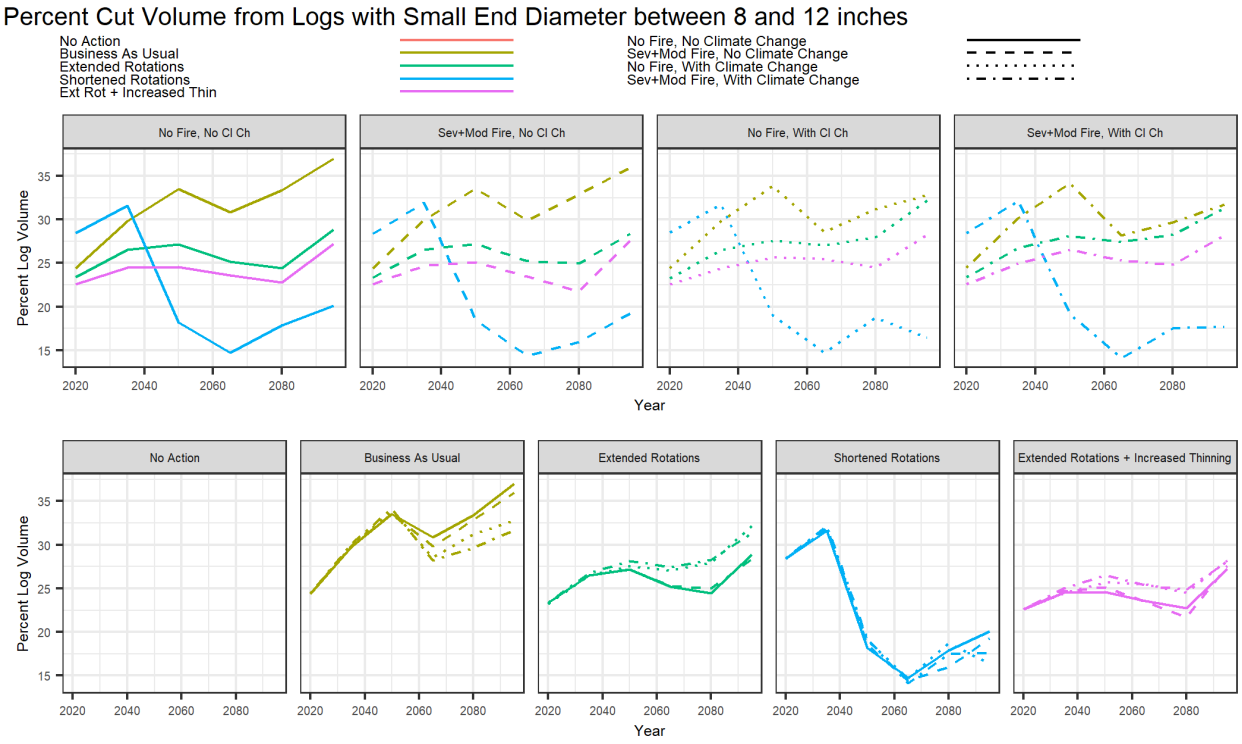

Figure 7. Percent of volume from logs with a small end diameter between 8 and 12 inches.

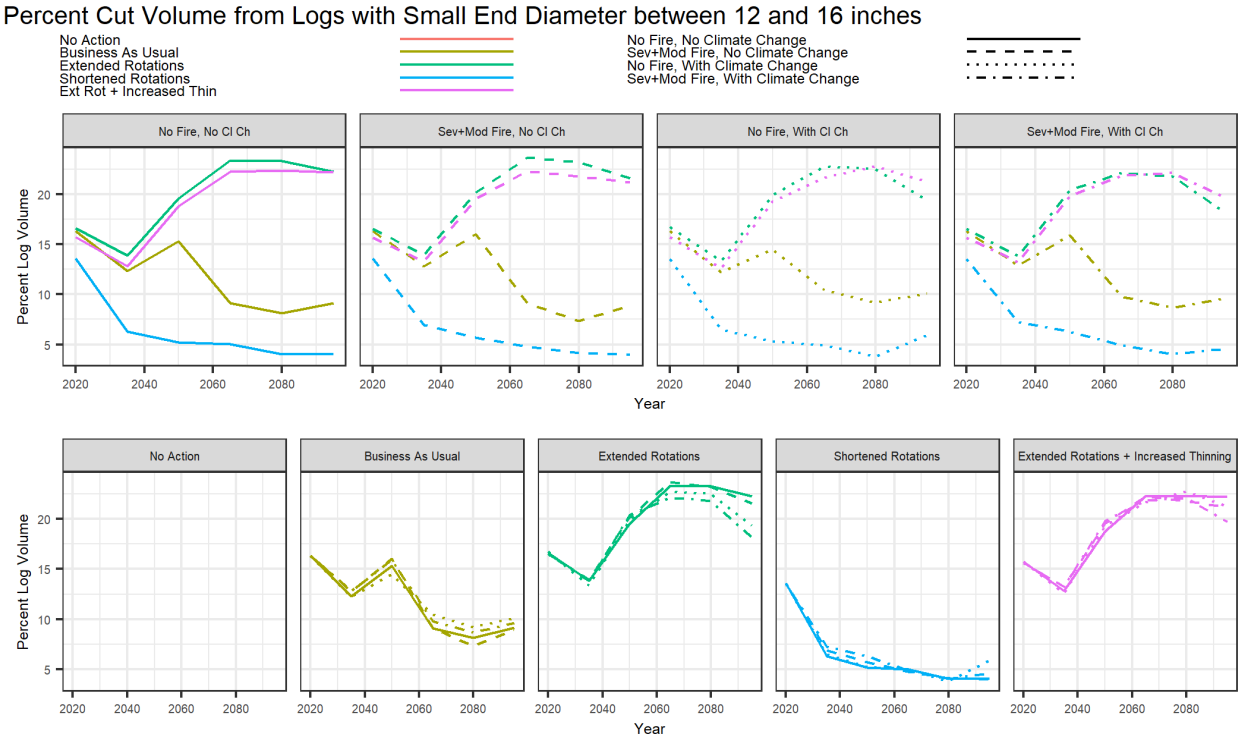

Figure 8. Percent of volume from logs with a small end diameter between 12 and 16 inches.

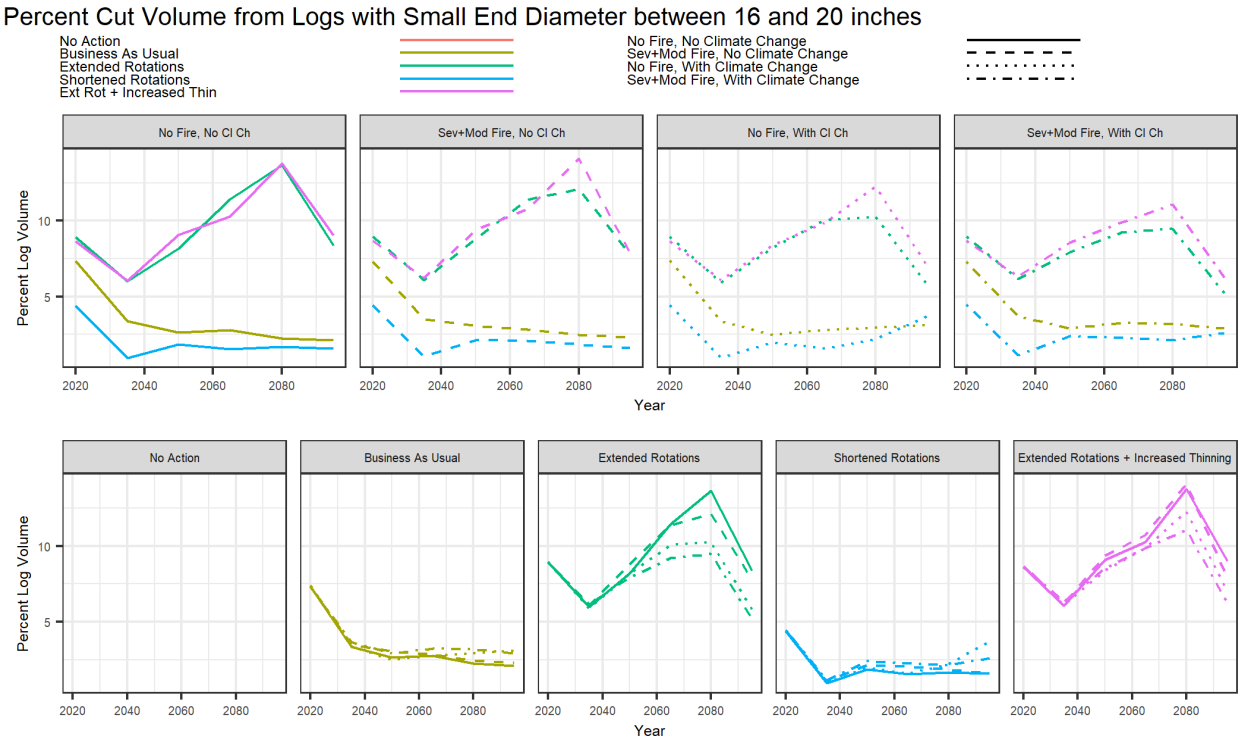

Figure 9. Percent of volume from logs with a small end diameter between 16 and 20 inches.

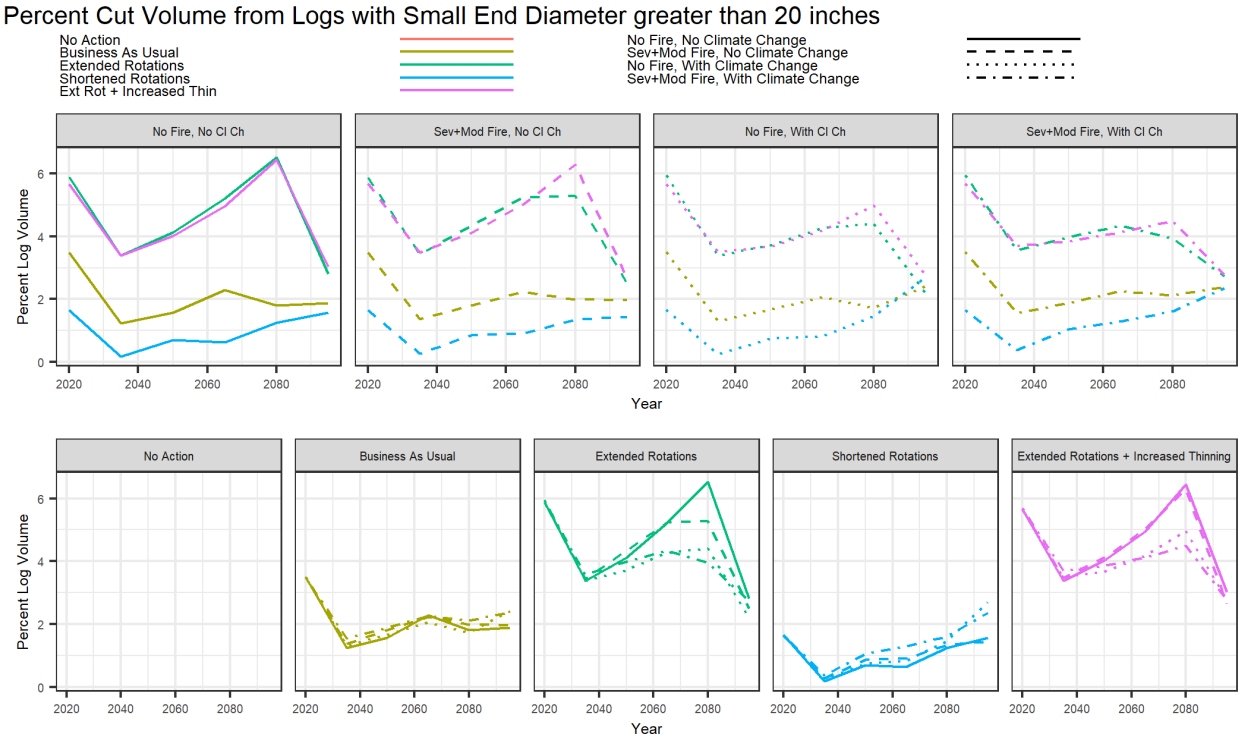

Figure 10. Percent of volume from logs with a small end diameter greater than 24 inches.

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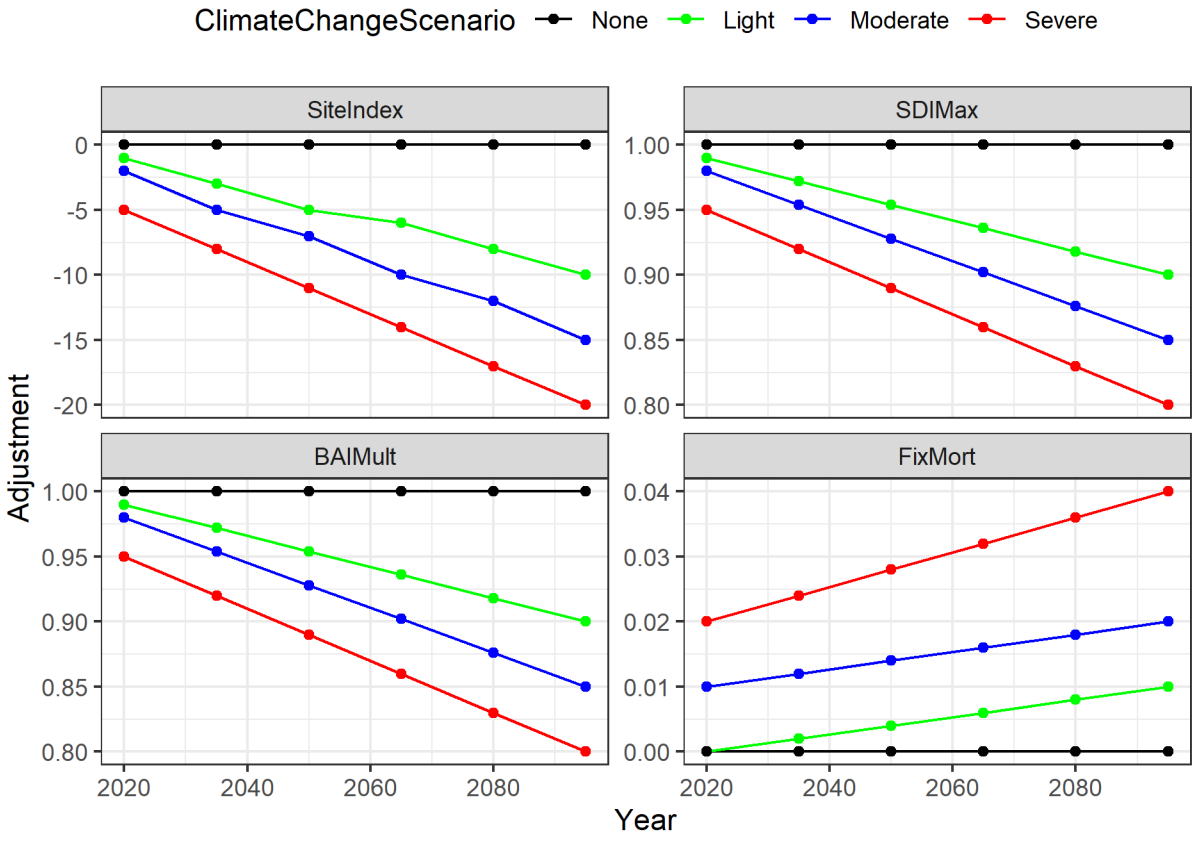
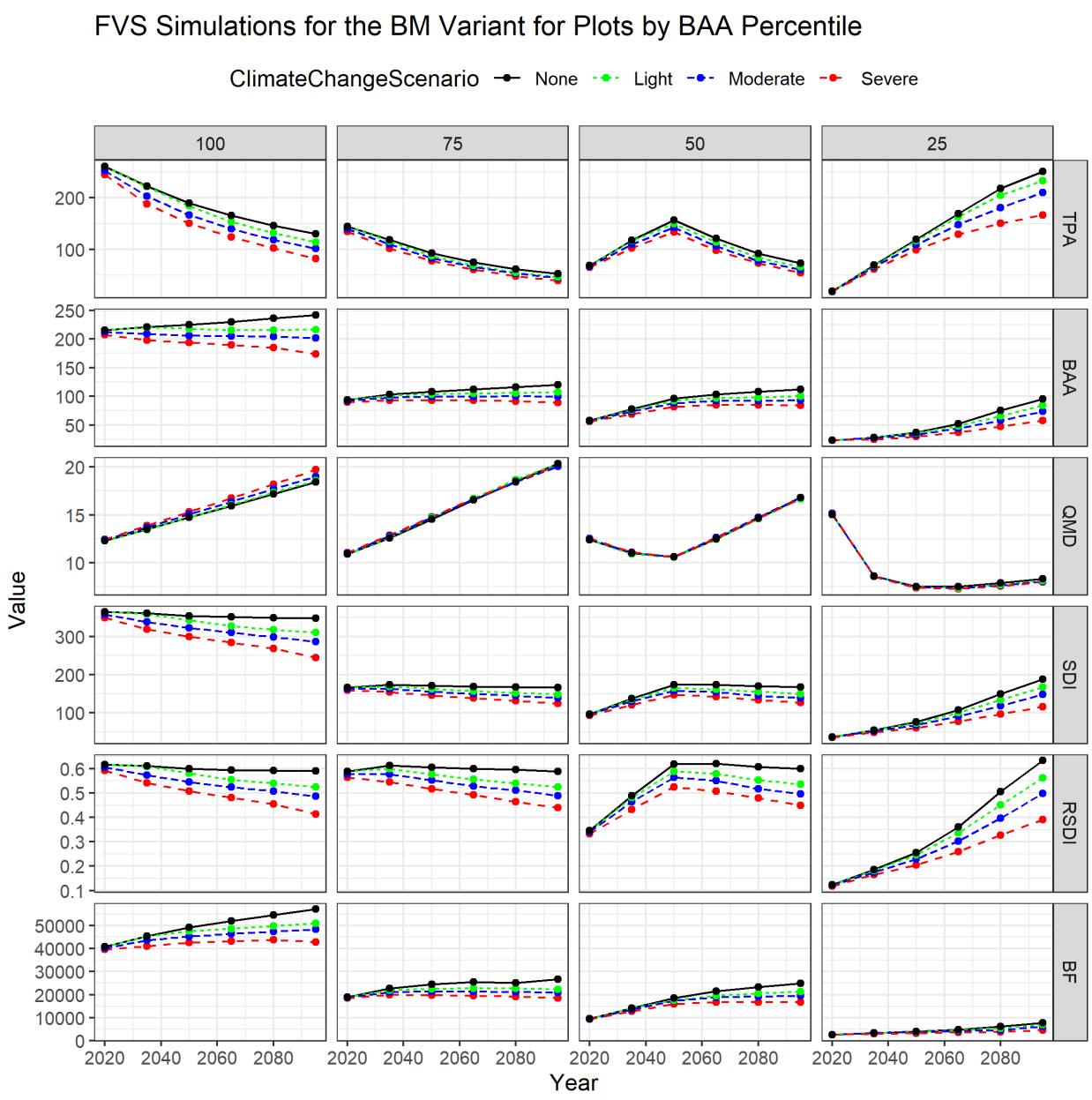
6 APPENDIX 1: CLIMATE CHANGE ANALYSIS

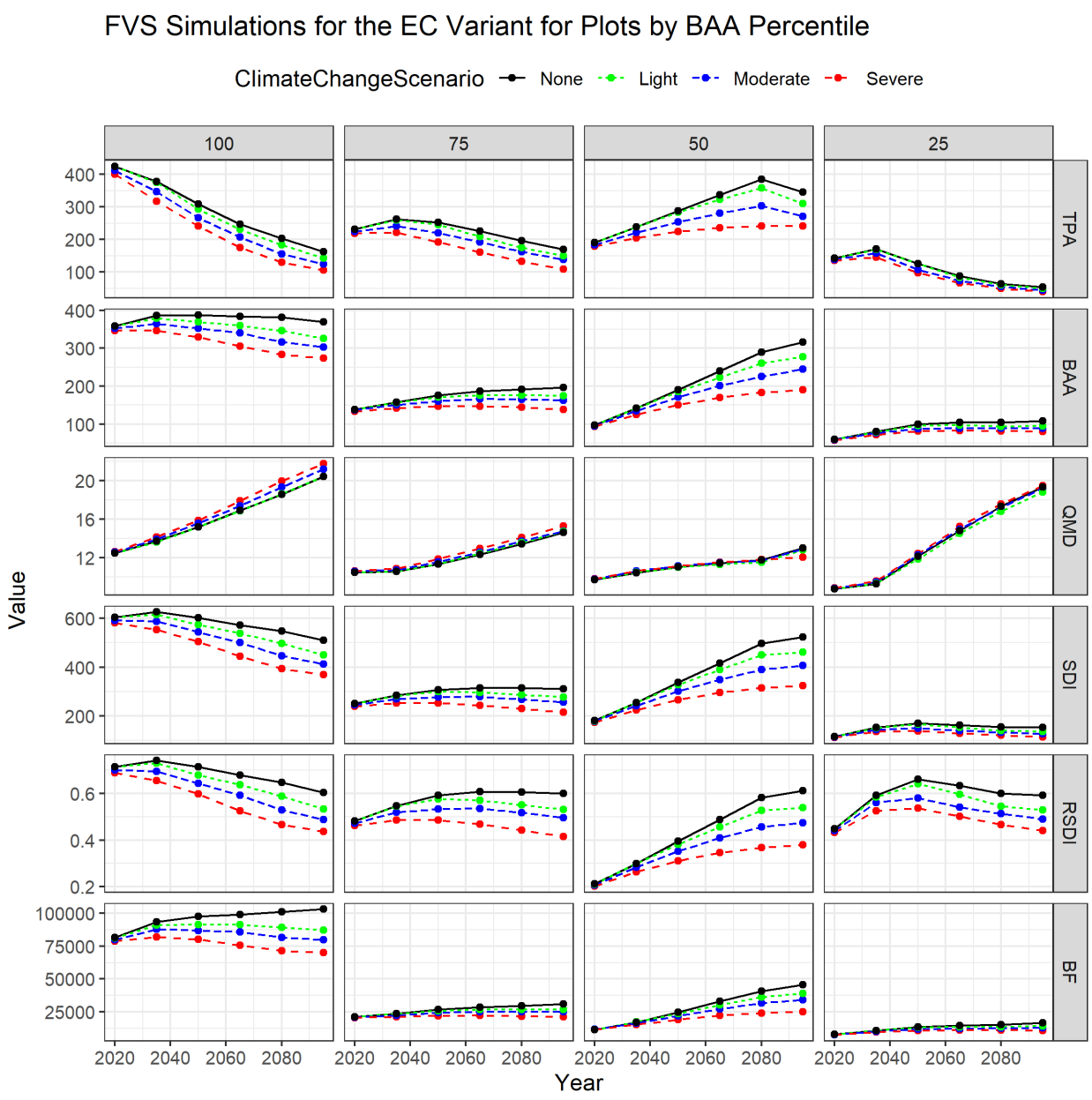
In the following chart and table, Site Index values refer to percent change, SDIMax and BAIMult (basal area increment multiplier) refer to multipliers on the initial values, and FixMort (fixed mortality) is an additional amount of mortality calculated by multiplying the value times the trees per acre for each tree record.

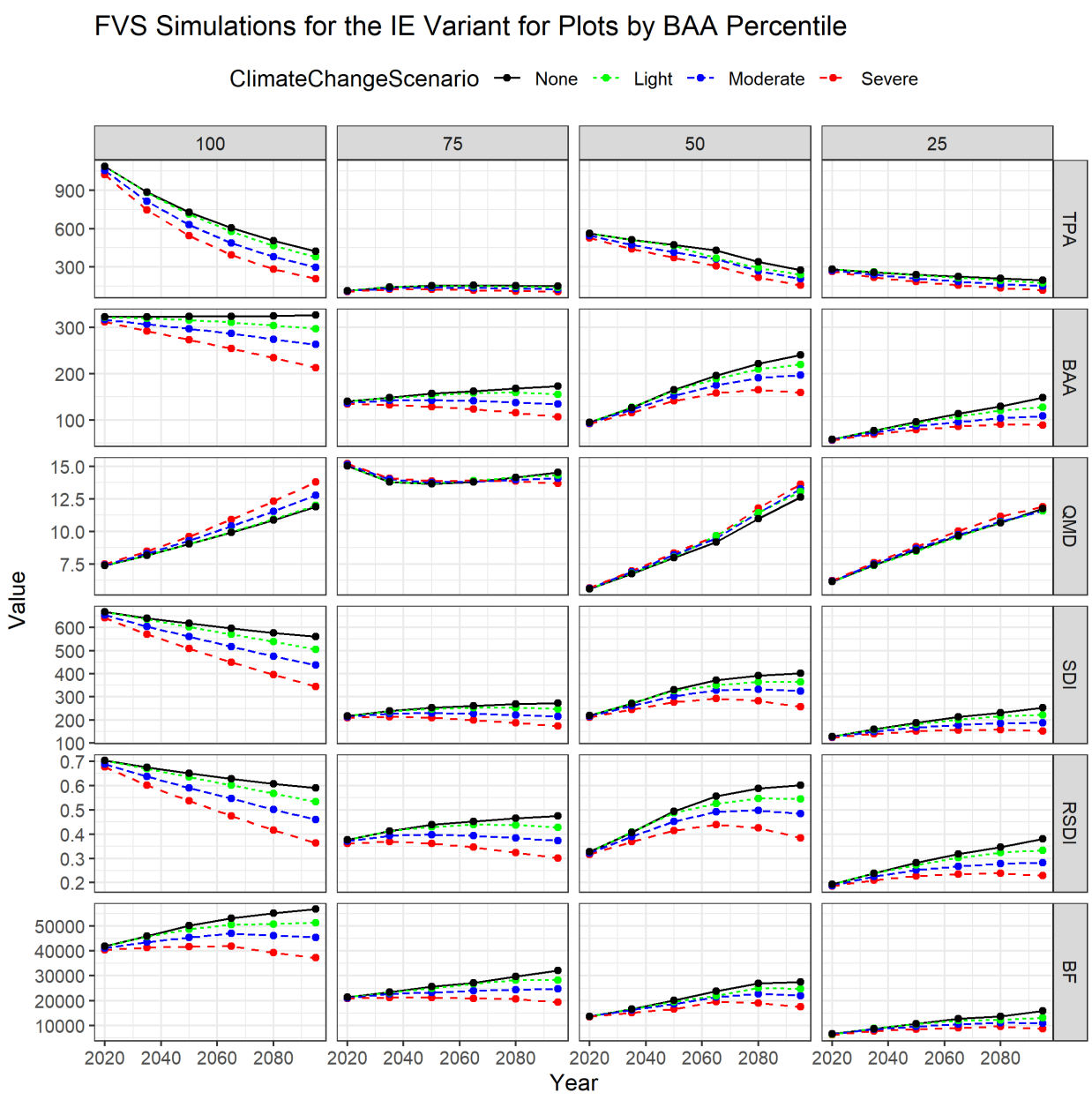


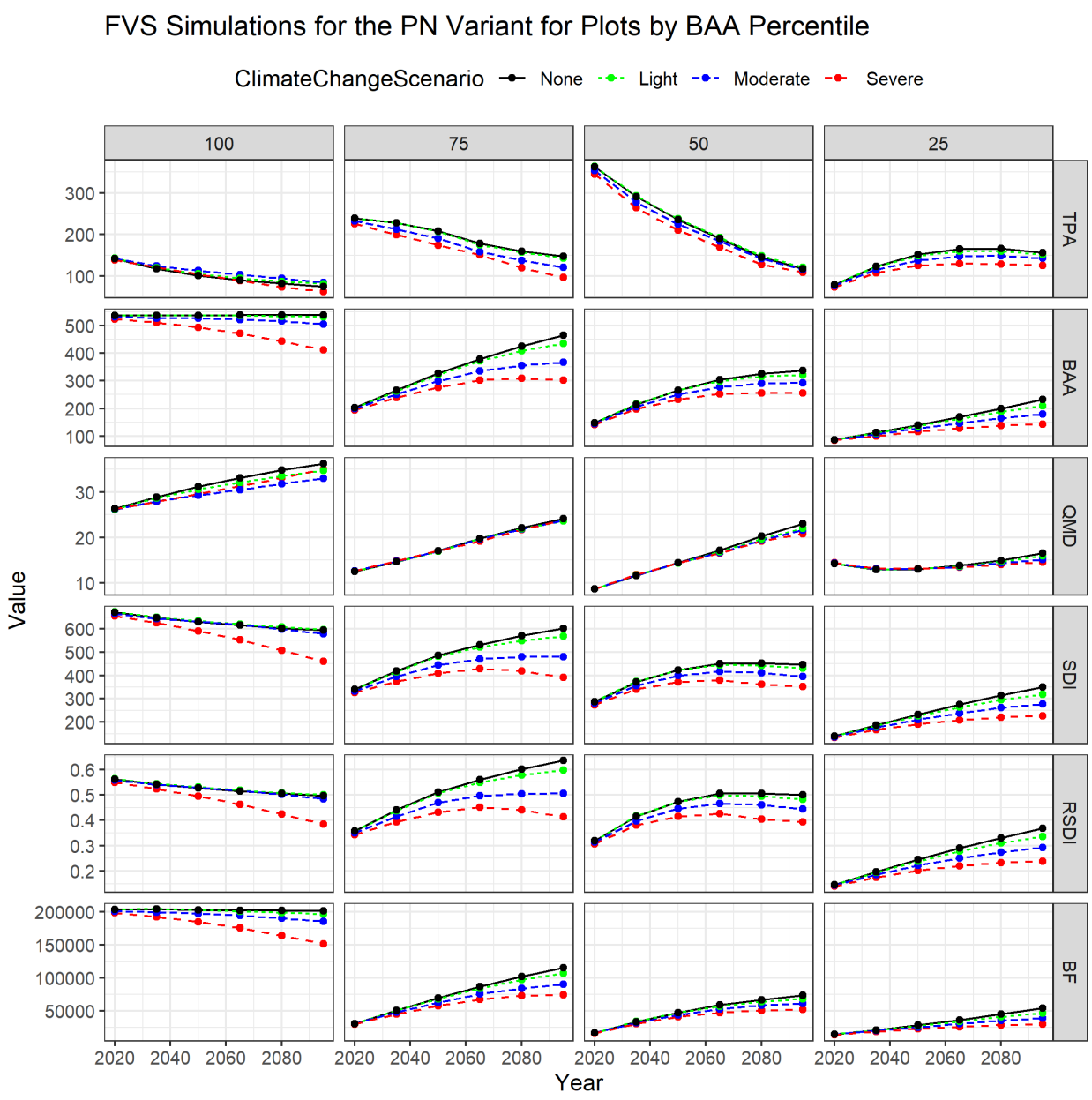
CLIMATE CHANGE SCENARIO	YEAR	SITEINDEX	SDIMAX	FIXMORT	BAIMULT
LIGHT	2020	-1	0.99	0	0.99
LIGHT	2035	-3	0.972	0.002	0.972
LIGHT	2050	-5	0.954	0.004	0.954
LIGHT	2065	-6	0.936	0.006	0.936
LIGHT	2080	-8	0.918	0.008	0.918
LIGHT	2095	-10	0.9	0.01	0.9
MODERATE	2020	-2	0.98	0.01	0.98
MODERATE	2035	-5	0.954	0.012	0.954
MODERATE	2050	-7	0.928	0.014	0.928
MODERATE	2065	-10	0.902	0.016	0.902

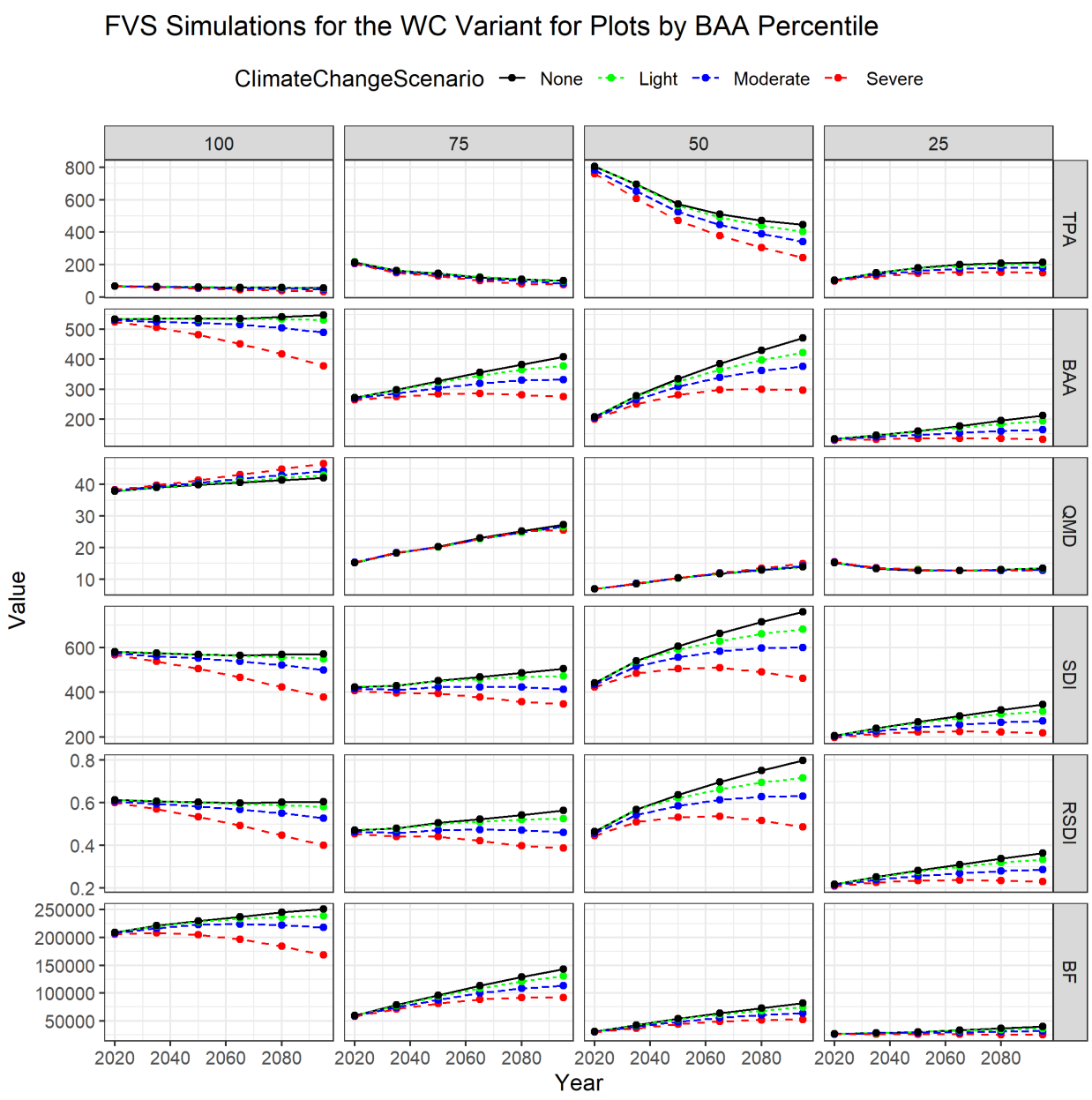
MODERATE	2080	-12	0.876	0.018	0.876
MODERATE	2095	-15	0.85	0.02	0.85
SEVERE	2020	-5	0.95	0.02	0.95
SEVERE	2035	-8	0.92	0.024	0.92
SEVERE	2050	-11	0.89	0.028	0.89
SEVERE	2065	-14	0.86	0.032	0.86
SEVERE	2080	-17	0.83	0.036	0.83
SEVERE	2095	-20	0.8	0.04	0.8
NONE	2020	0	1	0	1
NONE	2035	0	1	0	1
NONE	2050	0	1	0	1
NONE	2065	0	1	0	1
NONE	2080	0	1	0	1
NONE	2095	0	1	0	1

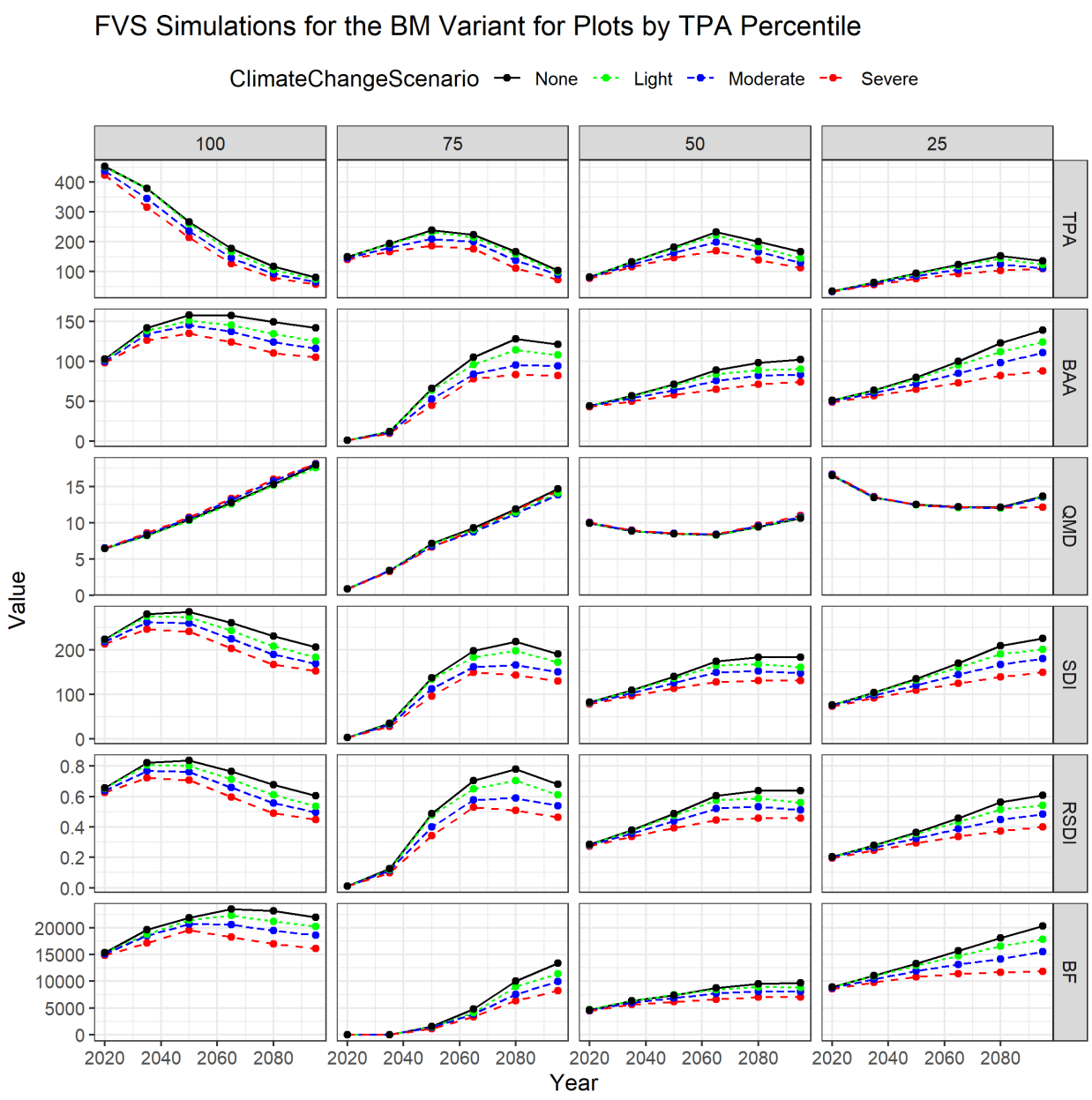

FVS Simulations for the BM Variant for Plots by BAA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080

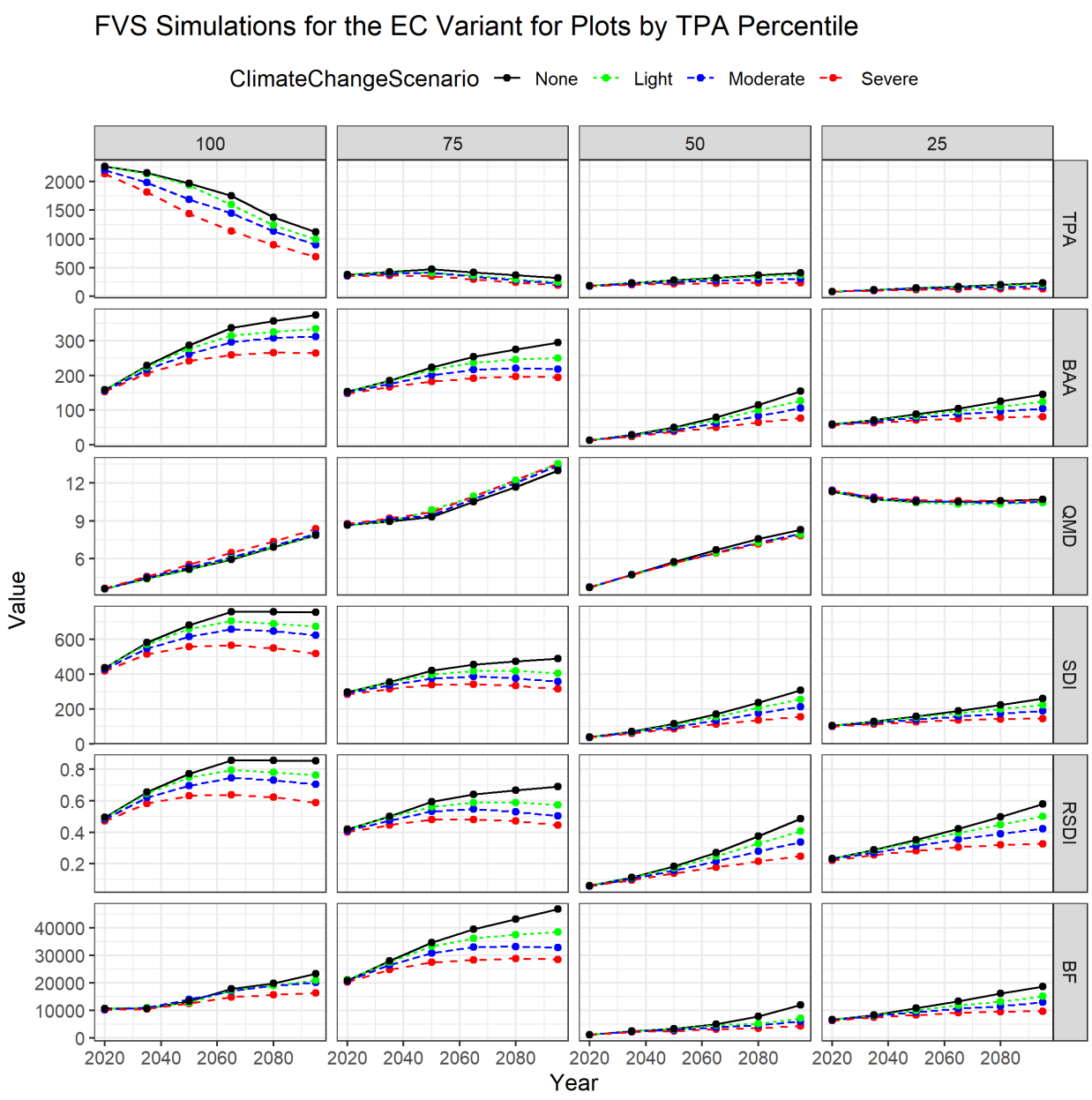

FVS Simulations for the EC Variant for Plots by BAA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080

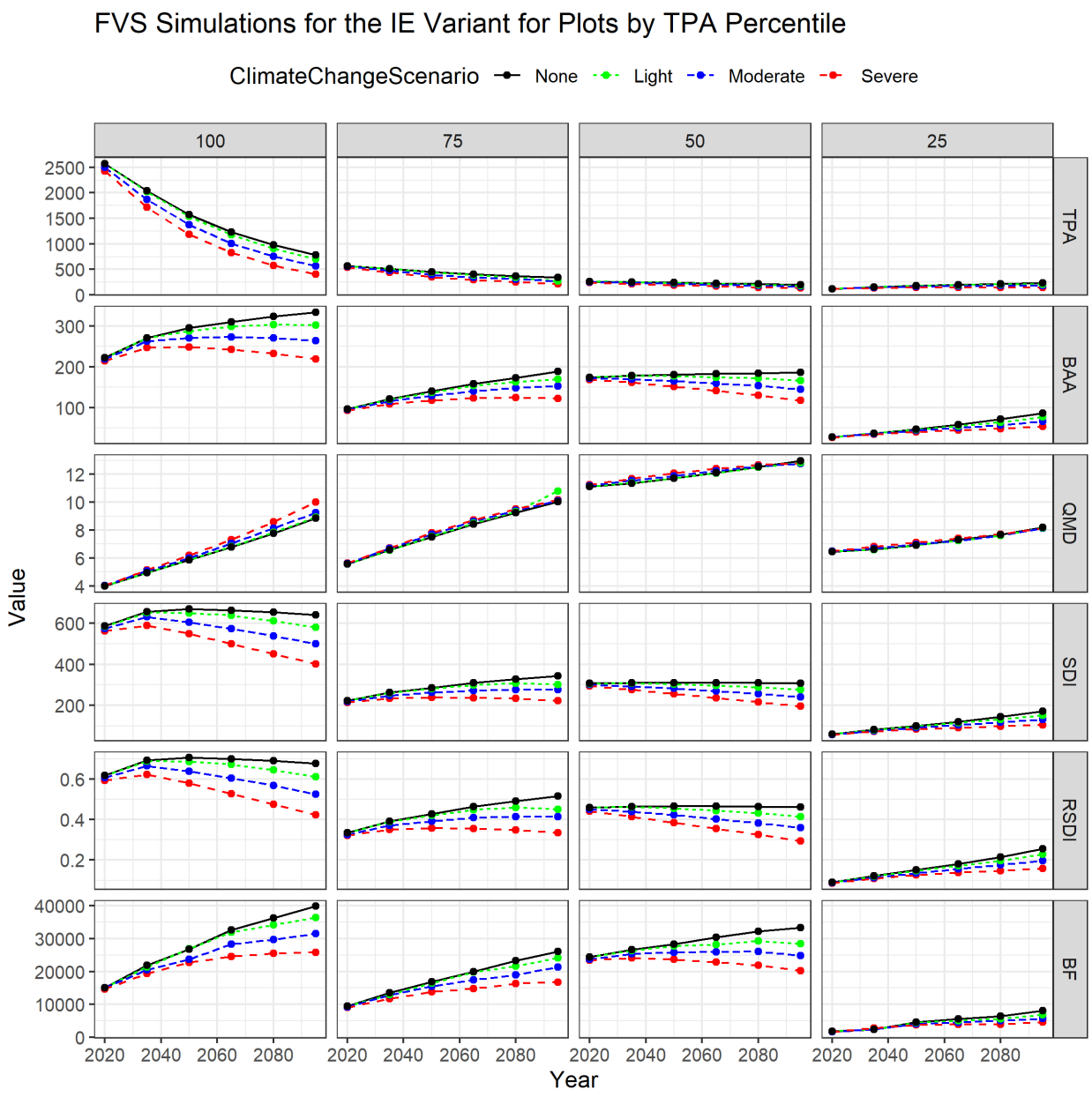

FVS Simulations for the IE Variant for Plots by BAA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080

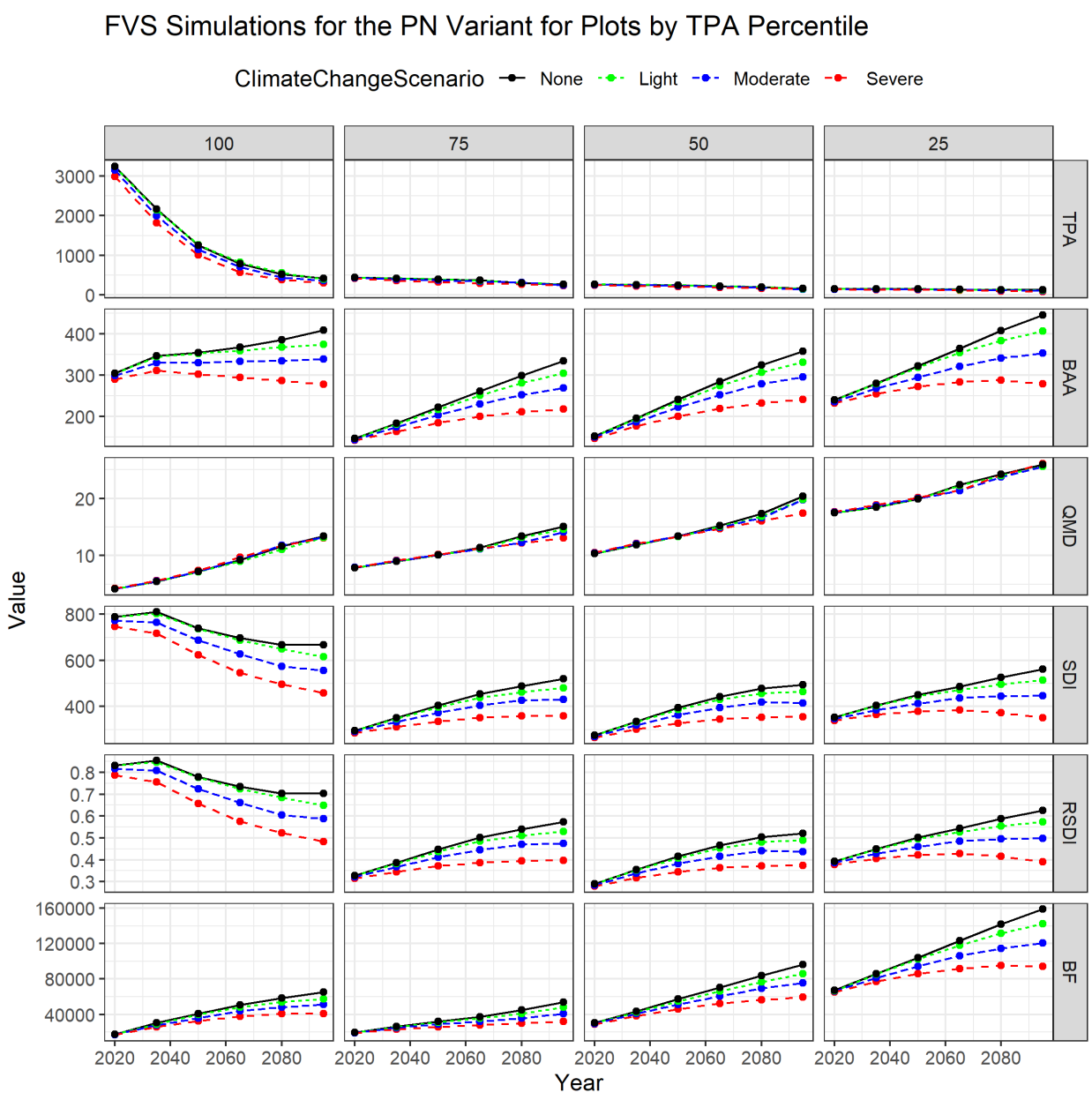

FVS Simulations for the PN Variant for Plots by BAA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080

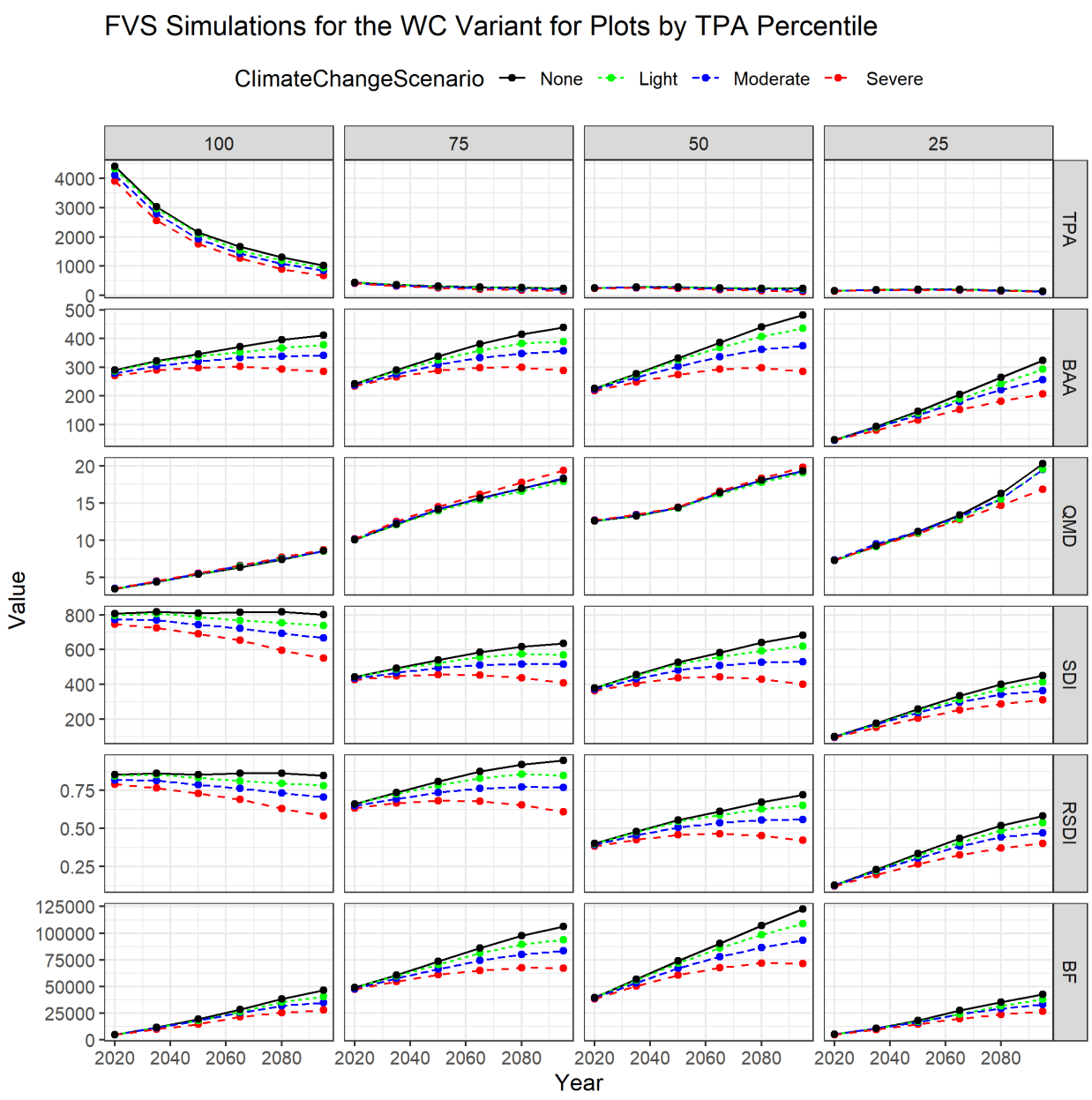

FVS Simulations for the WC Variant for Plots by BAA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080


FVS Simulations for the BM Variant for Plots by TPA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080


FVS Simulations for the EC Variant for Plots by TPA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080


FVS Simulations for the IE Variant for Plots by TPA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080


FVS Simulations for the PN Variant for Plots by TPA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
3000
2000
1000
0
400
300
200
20
10
800
600
400
0.8
0.7
0.6
0.5
0.4
0.3
160000
120000
80000
40000
2020
2040
2060
2080


FVS Simulations for the WC Variant for Plots by TPA Percentile
ClimateChangeScenario
None
Light
Moderate
Severe
100
75
50
25
TPA
BAA
QMD
SDI
RSDI
BF
Value
Year
2020
2040
2060
2080