Modeling Stream Food Web Response to Riparian Prescriptions in the Olympic Experimental State Forest:

Summary Report

Revised

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Introduction

Within the Olympic Experimental State Forest (OESF) on the western Olympic Peninsula of Washington state, a multi-agency collaborative study is underway to examine innovative approaches to managing forests. The Type 3 Watershed Experiment, hereafter referred to as the T3, led by the University of Washington's Olympic Natural Resources Center and Washington Department of Natural Resources (WADNR) with collaboration from the National Marine Fisheries Service, Washington State University-Vancouver, Oregon State University, Forest Service Pacific Northwest Research Station, and University of California-Davis, and implemented by WADNR, includes eight experimental silvicultural prescriptions in upland forests (Bormann et al., 2022), paired with five experimental prescriptions in the riparian zone (Martens et al., 2021). These prescriptions were developed based on social, economic, and ecological concepts with a goal of balancing community and environmental wellbeing. The riparian component of the project is collecting and examining evidence of the effectiveness of these approaches using a BACI (before after control impact) monitoring design to better understand how these ecosystems, which support stream-rearing salmonids, sculpin, and amphibian populations, respond to these different experimental logging prescriptions.

Populations of fish in streams and rivers are tied to a complex and interconnected series of interactions related to both biotic (e.g., predation and competition) and abiotic (e.g., hydrologic and thermal regimes) factors. When there are changes to the aquatic ecosystem or the adjacent riparian forest, such as those prescribed in the T3 experiment, the effects on the stream food web can be complex, indirect, and non-linear (Scheffer et al., 2009; Wootton, 1994). Measuring the impact of these prescriptions on stream ecosystems, including the fish that reside in them, can be nuanced. The magnitude and the duration of ecological responses can make detecting a response to the prescriptions a labor intensive and logistically intense undertaking. Modeling is one tool that can be used to evaluate outcomes of the prescriptions prior to implementation. This approach can be used to identity hypotheses about prescription responses that may be challenging to conceptualize using field observations alone due to multiple biotic and abiotic interactions and feedbacks in stream and riparian ecosystems.

Food web models, such as the Aquatic Trophic Productivity (ATP) model have been shown to be a useful approach for evaluating these complex responses to stream and riparian management (Bellmore et al., 2017; Whitney et al., 2020). The ATP model is a dynamic food web simulation model wherein the capacity of stream ecosystems to sustain fish is tied to the flow of organic matter between different components of a simplified stream-riparian food web (Bellmore et al., 2017; Whitney et al., 2019). This model mechanistically links the dynamics of the food web and the resultant performance of different web members to the physical and hydraulic conditions of the stream and the structure and composition of the adjacent riparian zone (Figure 1). The modeling framework assumes that the general dynamics of stream food webs can be simulated if the dynamics of these environmental factors are known. Following this assumption, the model has been used to explore how environmental changes or changes to the structure of the food web itself (e.g., nutrient or food augmentation), might impact the overall dynamics of the system and the performance of specific web members (Bellmore et al. 2017; Benjamin et al. 2020; Whitney et al. 2020).

Here we apply the ATP model to the five prescriptions within the riparian component of the T3 experiment to assess the potential impacts of current and alternative forest management strategies on stream food webs (Figure 2). The prescriptions include: no action (control), no-entry OESF buffers (30m riparian buffers (OESF standard management operation), hereafter referred to as fixed-width buffers), variable-width buffers dependent on stream size and conditions (referred to as variable-width buffers), active habitat restoration including light thinning with gaps and instream wood placement (referred to as active habitat restoration), and alder rotations under heavily thinned conifers (referred to as alder rotations). The objective of this work was to simulate how changes in environmental conditions associated with the prescriptions influence algal, aquatic insect, and fish productivity at a generalized stream site within the T3 study area over both the short term (5-10 years) and long term (50 years). Thereby, the simulations provide a tool for comparing prescription responses under the same environmental conditions. Beyond informing prescriptions within the OESF, this effort has broader-scale implications as to how other locations in the Pacific Northwest may respond to similar riparian prescriptions.

Methods

Aquatic Trophic Productivity Model

The food web used in the ATP model has aquatic organisms compartmentalized into “trophic groups” that share similar predators and prey. There are aquatic invertebrates that consume periphyton and terrestrial detritus and fishes that consume aquatic and terrestrial invertebrates. Specifically, the model tracks the biomass of periphyton, terrestrial detritus (leaf litter), aquatic invertebrates (grazers and shredders/collectors), and juvenile fish. Grazers in the model select for periphyton and shredders/collectors select for detritus. The dynamics of these interactions and the biomass of these trophic groups are governed by a series of mass balance equations that represent processes that increase the biomass of a group, such as periphyton growth or food consumption, and processes that decrease the biomass, such as predation and mortality. See the User Manual for the ATP model for a detailed description (Whitney et al., 2019). For examples how the model has been applied, see Bellmore et al., 2017; Benjamin et al., 2020; Whitney et al., 2020.

The dynamics of these food web members are tied to the physical, chemical, and hydraulic conditions of the river or stream and the composition and structure of the riparian vegetation. For example, the amount of light available to support periphyton is affected by the turbidity and the depth of the water as well as sunlight and the amount of stream shading. The growth of periphyton is further affected by nutrient availability, water velocity, and water temperature. In addition to mediating the bioenergetics of food web members, water temperature also affects the decay rates of organic matter. Stream discharge and the width and depth of the channel affect velocity and shear stress, which in turn affect the retention of organic matter within the reach. Feedback loops in the model allow for interactions between food web members (e.g., grazer consumption of periphyton) and the site conditions. The model structure can be explored in online interface accompanying the User Manual (https://exchange.iseesystems.com/public/ryan-bellmore/atp).

The ATP model was built in Stella Architect version 3.3 (Isee Systems, Lebanon, New Hampshire, www.iseesystems.com). It was run to simulate 60 years of biomass dynamics for each of the food web members (10 years prior to any riparian prescriptions and 50 years post prescription). The model outputs include daily values of biomass in grams of ash-free dry mass (AFDM) per square meter. AFDM is used to allow for comparison among trophic levels.

Specific to the T3 project application, an annotated interface can be found on the Isee Exchange (https://exchange.iseesystems.com/public/whitney/oesf-t3-atp-model). This interface can be used without requiring access to the Stella Architect software. Accompanying this report is also a copy of the Stella model file including the data import spreadsheets for the generalized site and each of the prescriptions. Making changes to the model beyond the interface will require access to the licensed software but the file is included for archiving purposes.

Generalized site model

There are a number of environmental parameters in the ATP model that can be input to parameterize the model for a given reach of interest, such as gradient, channel hydraulics, and riparian vegetation composition. Here we parameterized the model for a generalized site in the T3 study area using data available from riparian monitoring at T3 experimental reaches as well as data available from other data collection efforts in the area (Table 1). Thus, the generalized site model does not reflect the conditions at any one site in the OESF prescription watersheds but rather represents the average of conditions seen across the prescription watersheds. For temporally dynamic environmental parameters (e.g., water temperature, discharge, and turbidity (Figure A.1.), the model uses the same daily or monthly inputs for each year of the simulation, with the exception of conditions that were modified in response to the riparian prescriptions (see below). Therefore, the model results do not reflect changes in climatic conditions over the 60-year model simulation but instead allows for a comparison of the potential food web responses across prescriptions, when other conditions are held constant.

That said, we ran a sensitivity analysis in which we varied the environmental parameters for our “generalized site” to represent the range of pre-implementation conditions seen throughout T3 watersheds (Appendix B). Parameters included in the sensitivity analysis were: stream shading, water temperature, nutrient concentration (phosphorus and nitrogen), riparian vegetation composition, substrate size, stream gradient, and stream discharge. For example, stream temperature was varied using individual temperature regimes for 13 monitored sites in water year 2021 that were selected as representative of streams considered for the prescriptions. Stream shading was varied across three temporally dynamic regimes: an average, minimum, and maximum regimes based on shading values recorded at T3 sites. To visualize the uncertainty, we plotted 100 simulations with randomly selected combinations of environmental parameters (Latin hypercube sampling of point values of parameters, such as gradient, and regimes of temporally dynamic parameters, such as water temperature or stream discharge). The results of this analysis provide a range of potential outcomes to riparian prescriptions, which reflect variation in site conditions observed in OESF.

Prescription responses

Following the parameterization of the model for a generalized site, the model was run to simulate each of the four treatment prescriptions (the control scenario being the same as the baseline conditions of the generalize site model). To simulate the prescriptions, environmental parameters hypothesized to be affected by the prescriptions were systematically modified in the model. Parameters that we modified were selected in collaboration with T3 riparian project partners at a workshop in October 2022. After an overview of both the T3 experiment and the ATP model, workshop participants discussed model parameters and identified those inputs that were expected to change in response to the prescriptions. The following model parameters were included in the discussion of the potential prescription responses:

- Vegetation cover: Change in the proportion of stream covered by vegetation (i.e., overhanging vegetation, which mediates leaf litter contributions and light flux).
- Deciduous veg cover: Change in the proportion of riparian vegetation that is deciduous.
- Stream shading: Change in the proportion of incoming solar radiation that is blocked by vegetation and topographic features.
- Water temperature: Percent change in water temperature.
- Nitrogen (DIN): Percent change in stream nitrogen concentration.
- Phosphorous: Percent change in stream phosphorus concentration.
- Turbidity: Percent change in water clarity.
- Water depth: Percent change in the average water depth of the channel.
- Channel width: Percent change in the channel wetted width.
- Substrate size: Percent change in the size of benthic substrata.
- Channel retention: Percent change in the capacity of reach to physically retain material.

Participants were asked to generate hypothetical parameter responses to the T3 prescriptions. There were two components to the response trajectories: the magnitude of the change in the parameter and the duration of the response. For example, group members hypothesized that stream shading would change in response to the alder rotation prescription: a sharp decline of up to 20% change in stream shading with the initial action followed by a gradual re-shading of the stream as the remaining vegetation filled in over the next 10-15 years. These response trajectories, combined with literature sources on the types of responses seen with similar prescriptions, were coded into the model to simulate each of the four prescriptions (Figure 3). Among groups, there were different hypothesized response trajectories, predominately in the magnitude or duration of the changes but in some cases in the direction of the change. These different hypotheses were incorporated into a sensitivity analysis where we looked at the change in fish biomass across the hypothesized response trajectories. We included hypotheses from different groups and simulated earlier or later peaks in the parameter change as well as a larger or smaller response level for the three environmental conditions to which the model was found to be most sensitive. We plotted 100 of the simulations (selected via Latin hypercube sampling of the various response trajectories) for each prescription. We selected the three environmental conditions to include in the above sensitivity using a parameter homogenization experiment. We looked at the change in fish biomass when the hypothesized change of individual parameters was reset to 0 across the four prescriptions (excluding the control). We ranked the parameters by those whose change had the largest impact on the fish biomass.

Results

Generalized site model

The generalized site model was first run under the no prescription or control scenario. The modeled biomass of food web members equilibrated within 5 years (model “burn-in” period) and remained stabilized for the remainder of the simulation. Under these ambient conditions, the average annual biomass of juvenile fish was 0.95 g AFDM/m^2. The biomass of the stocks of grazers and the shredders/collectors averaged 0.54 and 0.22 g AFDM/m^2 respectively and at the base of the food web, periphyton biomass averaged 1.49 g AFDM/m^2 and deciduous detritus averaged 3.81 g AFDM/m^2. These numbers represent the capacity of the modeled reach to support the food web members but may not match the levels observed at an individual site due the environmental conditions at a specific site or factors outside of the model, such as fish movement out of the reach.

The results of the sensitivity analysis show that the range of environmental conditions seen at the different study reaches may result in higher or lower biomass levels across food web members (Figure 4). Some combinations of environmental parameters result in a higher capacity of the modeled reach to support juvenile fish and other food web members. For instance, in simulations with lower alder cover, there is less deciduous leaf litter entering the stream, which supports a smaller population of shredders and collectors, and in turn fish. Whereas, simulations with higher alder cover and lower stream shading supported higher fish biomass. Similarly, when phosphorus is the limiting nutrient, higher phosphorus concentrations support increased periphyton, grazer, and fish populations.

The range of values generated by the sensitivity analysis illustrate how variation in environmental conditions shown to occur across sites in the OESF might influence the productivity of the stream food web. It is important to note, however, that some randomly selected combinations of environmental conditions in the sensitivity analysis may not be representative of an actual T3 site, and could result in unrealistic outputs (e.g., high densities of fish or zero invertebrate biomass; Figure 4).

Prescription response

In the short term (0-10 years post implementation), the fish biomass increased in response to each of the proposed prescriptions but the magnitude and shape of the response differed among prescriptions (Figure 5). The percent change in fish biomass ranged from +5 to +20% compared to the control. Initially, there was a slight lag in the response to the active habitat restoration scenario compared to the others, but this prescription had the greatest modeled increase in fish biomass 10-years post implementation (20.1%), followed by the variable-width buffers (7.6%), fixed-width buffers (5.7%), and alder rotation (5.4%) prescriptions.

Mid-term (10-40 years), the response of fish to prescriptions was more variable (Figure 5). For the fixed- and variable-width buffer prescriptions, fish biomass returned to control conditions because many of the environmental conditions (Figure 3) returned to background conditions. The effect of the alder rotation prescription on fish biomass was also declining at 20 years post implementation due to the increase in stream shading with vegetation regrowth; however, at 30 years after the initial prescription implementation, the disturbance associated with the anticipated second entry to harvest alder resulted in a second increase in fish biomass and overall stream productivity. Under the active habitat restoration prescription, the increased fish biomass response was sustained until approximately 40 years post implementation, when the response declines due to hypothesized decay of the instream wood installment.

At the end of the simulation (year 50), the average fish biomass returned to the no prescription scenario values for most prescriptions and declined to slightly below (-3%) the control prescription values in the active habitat restoration prescription. When the response to each of the prescriptions is averaged across the 50 years post implementation, the percent change in fish biomass ranges from 2.0% to 18.0% (Table 2). The ranking of the prescription responses changed by the end of the simulation. The greatest overall increase in fish biomass across the 50 years was seen with the active restoration prescription (18.0%), followed by the alder rotation (3.4%), variable width buffers (2.2%), and fixed width buffer (1.7%) prescriptions. Averaged across the duration of the simulations, all food web members responded positively, albeit a small response in some cases, to the fixed-width buffers, variable-width buffers, and the active habitat restoration. For the alder rotations, the response from the grazers was a slight decline (-3.4%) below controls values but a stronger positive response in the shredder community (13.4%).

When variability due to site conditions is incorporated into the modeled prescription response, the magnitude of the food web response changes, however under most conditions, the shape of the response remains consistent as seen in the Figure 6 with the percent change in fish biomass. Under the alder rotation prescription, we see that there are some conditions under which there is a different inflection point in the fish biomass response. The percent change for fish biomass remains positive longer when there is high pre-existing alder cover, whereas when the randomly selected site conditions include low initial alder cover, the fish biomass drops below control values around year 15 post implementation (the low alder cover contributes to lower deciduous detrital inputs and a smaller shredder invertebrate biomass).

We found that these modeled outcomes were most sensitive to three environmental conditions: (1) proportion of deciduous vegetation cover, (2), the proportion of the stream shaded, and (3) water temperature (determined from variable homogenization experiment, see Methods). In contrast, for the response trajectories modeled, the fish biomass was less sensitive to changes in channel width and depth, and changes to nitrogen and phosphorus concentrations. Figure 7 shows how variation in the trajectories of the three environmental conditions to which the model was most sensitive influences the shape and magnitude of modeled fish biomass responses to the prescriptions. The scale of the changes in fish biomass in response to different hypotheses of environmental responses to the prescriptions (Figure 7) is much smaller relative to the percent change associated with different environmental conditions (Figure 6).

Discussion

In the model simulations, the stream food web shows a net positive response in fish biomass across the prescriptions relative to the control. The largest response was observed in the first 5-10 years following the implementation of the prescriptions, with active habitat restoration prescription prompting the greatest response followed by variable-width buffers, fixed-width buffers, and the alder rotations prescription respectively. Longer term, the fish biomass response decreased as environmental conditions returned to pre-prescription levels. This happened within 20 years for the fixed and variable width buffers. The active habitat restoration response was sustained longer, in part due to the effect of the large woody debris on channel conditions (Figure 3: retention and substrate size response trajectories). The response to the alder rotation prescription was driven by the change in vegetation cover and composition and had a longer lasting effect due to an anticipated second-entry alder harvest 30 years after the initial prescription (a second entry is dependent on an economically viable of an alder harvest within the prescription area). The modeled differences across prescriptions could help generate hypotheses about which prescriptions may provide the largest benefits to the stream community while also balancing community and economic needs.

While the model produces absolute values of food web member biomass, the greater utility of these simulations is found in looking at the results relative to one another. There are certainly site conditions that are not incorporated into the model that could increase or decrease biomass values. Discussions with T3 project partners have raised questions for example about the role of amphibians in food webs at T3 sites, dissolved organic carbon dynamics, and changes to understory vegetation, such as salal and blueberries; dynamics which are not included in the ATP model. Still, we can compare changes over time and across prescriptions with the ATP model framework. Further, the similarity in the shape of the prescription responses across varying environmental conditions highlights the applicability of using a generalized site response to compare prescription responses. Even under different site conditions, the model results can be used to examine the size and shape of one prescription response relative to another.

The magnitude and duration of the response to each of the prescriptions is a function of which parameters were modified with each prescription and the estimates of how long these parameters would be affected. For example, in Figure 3, we see that stream shading in response to timber harvest with fixed-width buffers was hypothesized to decrease and then to return to the reference light value within approximately 10 years due to vegetation growth and canopy closure. The modeled food web is sensitive to changes in light availability and thus, variation in how long the decrease in stream shading would persist has the potential to affect the overall prescription response. Additionally, under the active habitat restoration response, there was discussion of how long the large woody debris installment would remain in place. One hypothesis captured in Figure 3 is that if the wood moves downstream around year 40, the substrate size would increase, returning to baseline levels with the movement of the wood, and the change in organic matter retention for the reach would gradually return to control levels. In turn, these changes can lead to a decrease in fish biomass that actually drops below the no prescription scenario (Figure 5). Understanding how these inputs contribute to the modeled results can further aid in the interpretation of the stream food web response to actions in the riparian zone.

The results suggest this modeling approach may be particularly useful in comparing prescription responses. The percent change in fish biomass modeled within the first 5-10 years post implementation (5-20%) is of a size that could make field detection difficult. Monitoring data from this initial monitoring period could be used to evaluate the hypothesized response trajectories using the tools on the ATP model interface. The model results, however, and the modeled small positive responses and subsequent decline over time have been observed in other experimental studies (Kaylor & Warren, 2018; Swartz & Warren, 2023). When we look at how the modeled fish biomass could vary in response to the different hypotheses of parameter change versus site conditions, we see that in addition to understanding how conditions will change with the prescriptions, the conditions found at the site mediate the response and may result in a minimal or null response (Johnson et al., 2023; Roon et al., 2022). For example, in the Trask River Watershed, it is hypothesized that the co-limitation of nutrients at headwater sites limited the response to increased light and dissolved inorganic nitrogen associated with riparian manipulations (Johnson et al., 2023). The ATP model, however, provides a tool for modeling these changes and identifying the environmental conditions that lead to the modeled food web response.

Figures

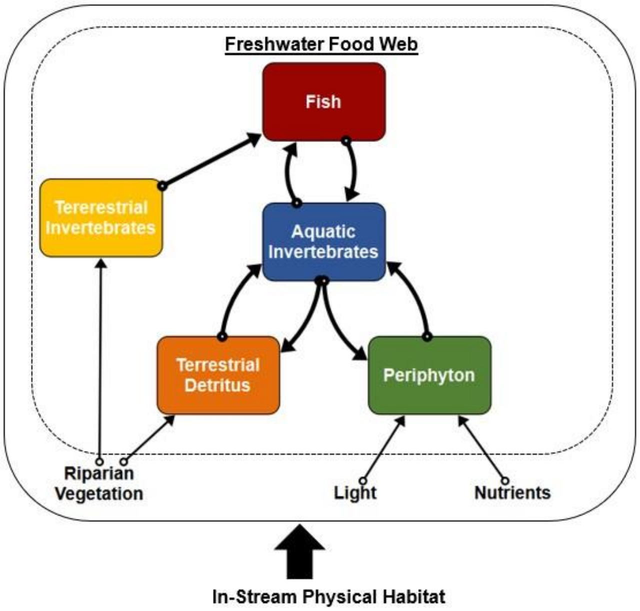

Figure 1. The Aquatic Trophic Productivity model includes biomass stocks of periphyton, terrestrial detritus, aquatic and terrestrial invertebrates, and fish that are linked together via a series of consumer-resource interactions. The food web is fueled by inputs of light, nutrients, and terrestrial organic matter (taken from Whitney et al. 2019).

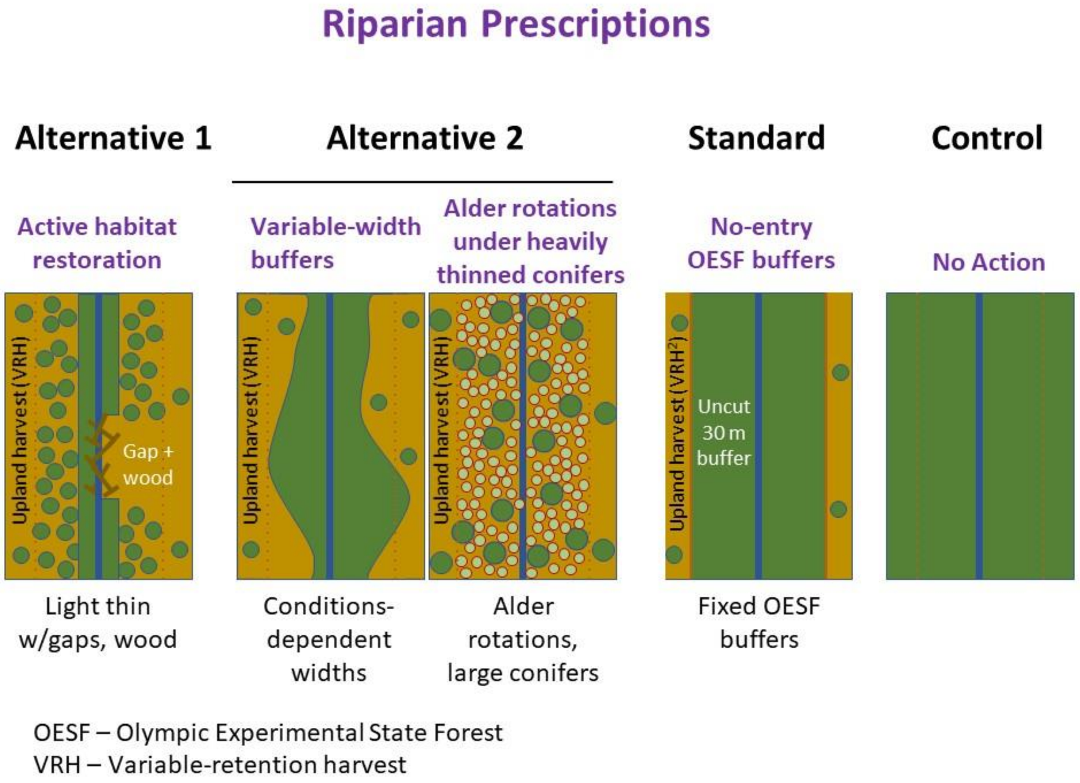

Figure 2. Proposed riparian prescription in the Olympic Experimental State Forest in Washington State (Martens et al., 2021).

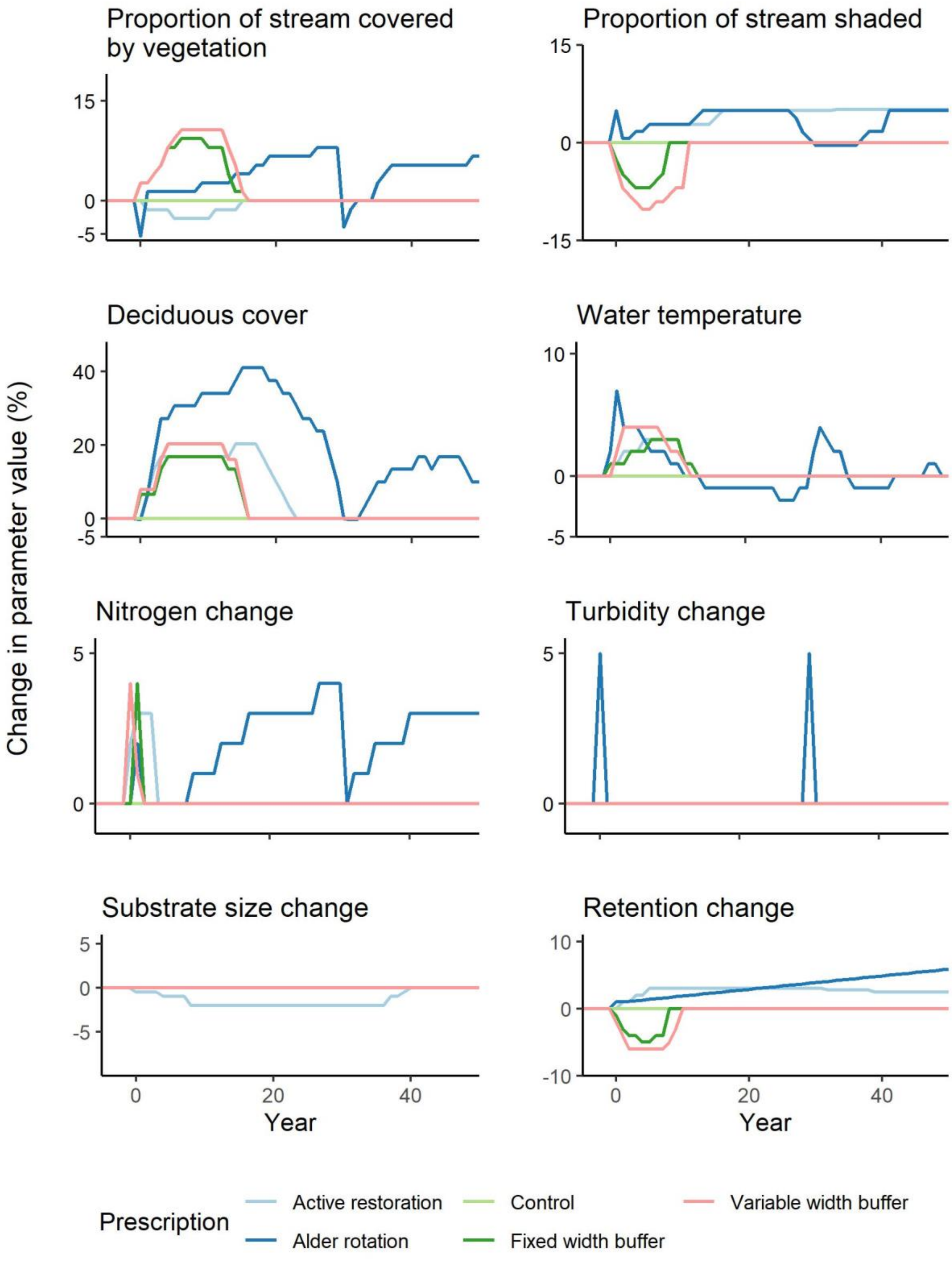

Figure 3. Hypothesized response trajectories for model parameters by riparian prescription.

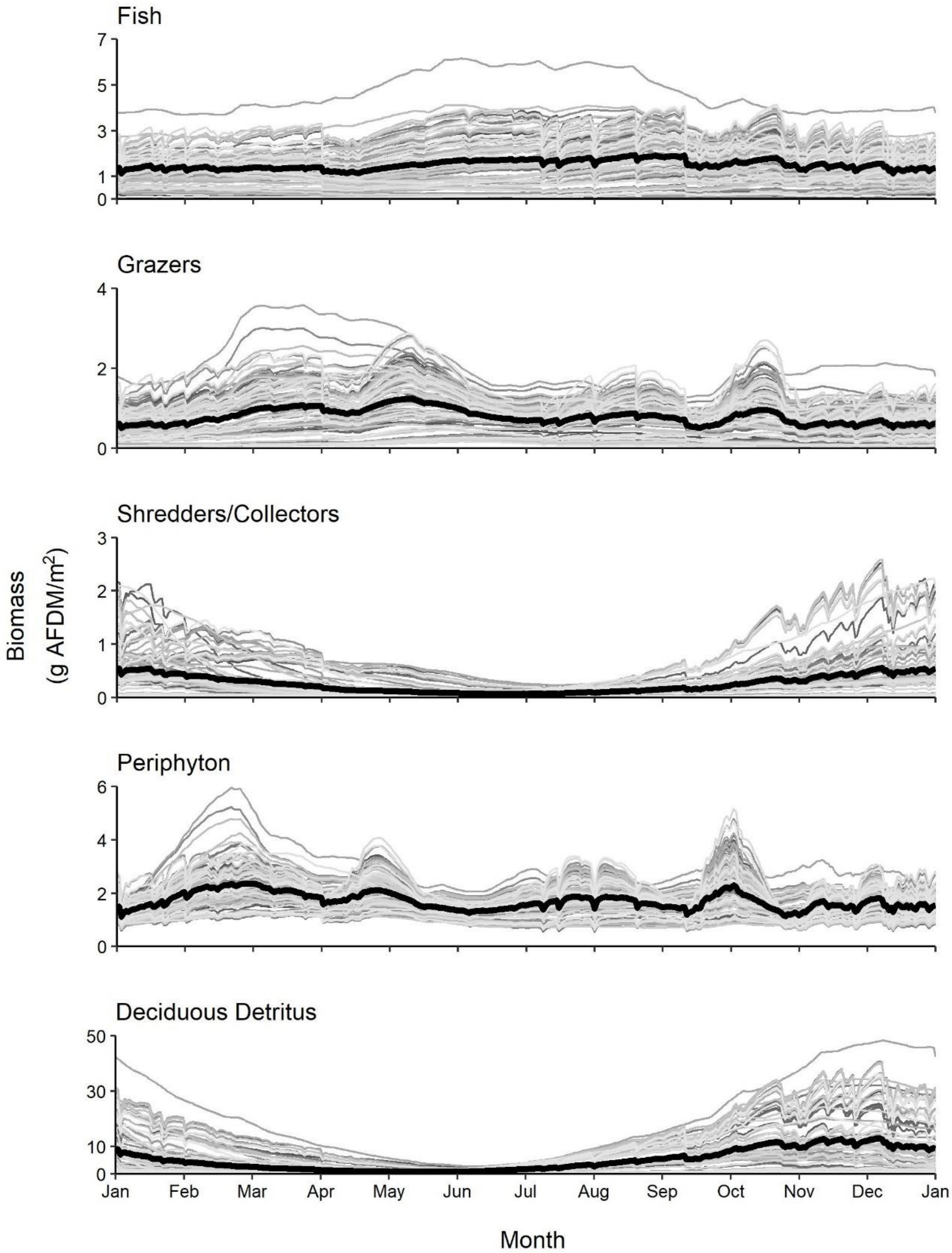

Figure 4. Food web member biomass variation under the control or no action prescription from a 100-simulation sensitivity analysis that captures variation in environmental conditions seen across T3 study reaches. Each gray line represents the biomass dynamics during one year of a model run with a different combination of environmental conditions. The average value across runs is shown in the bold, black line.

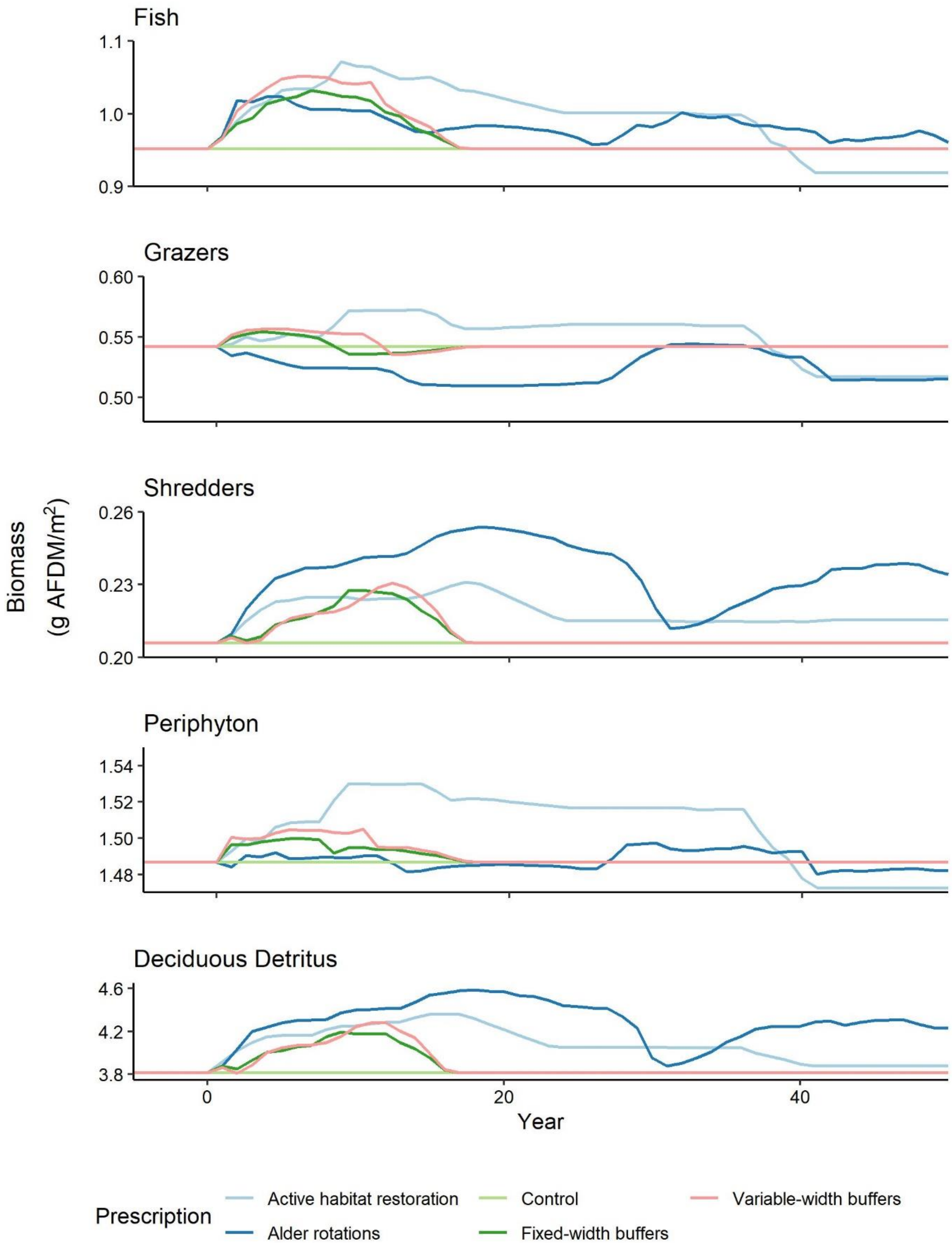

Figure 5. Biomass dynamics of food web members under each of the riparian prescriptions.

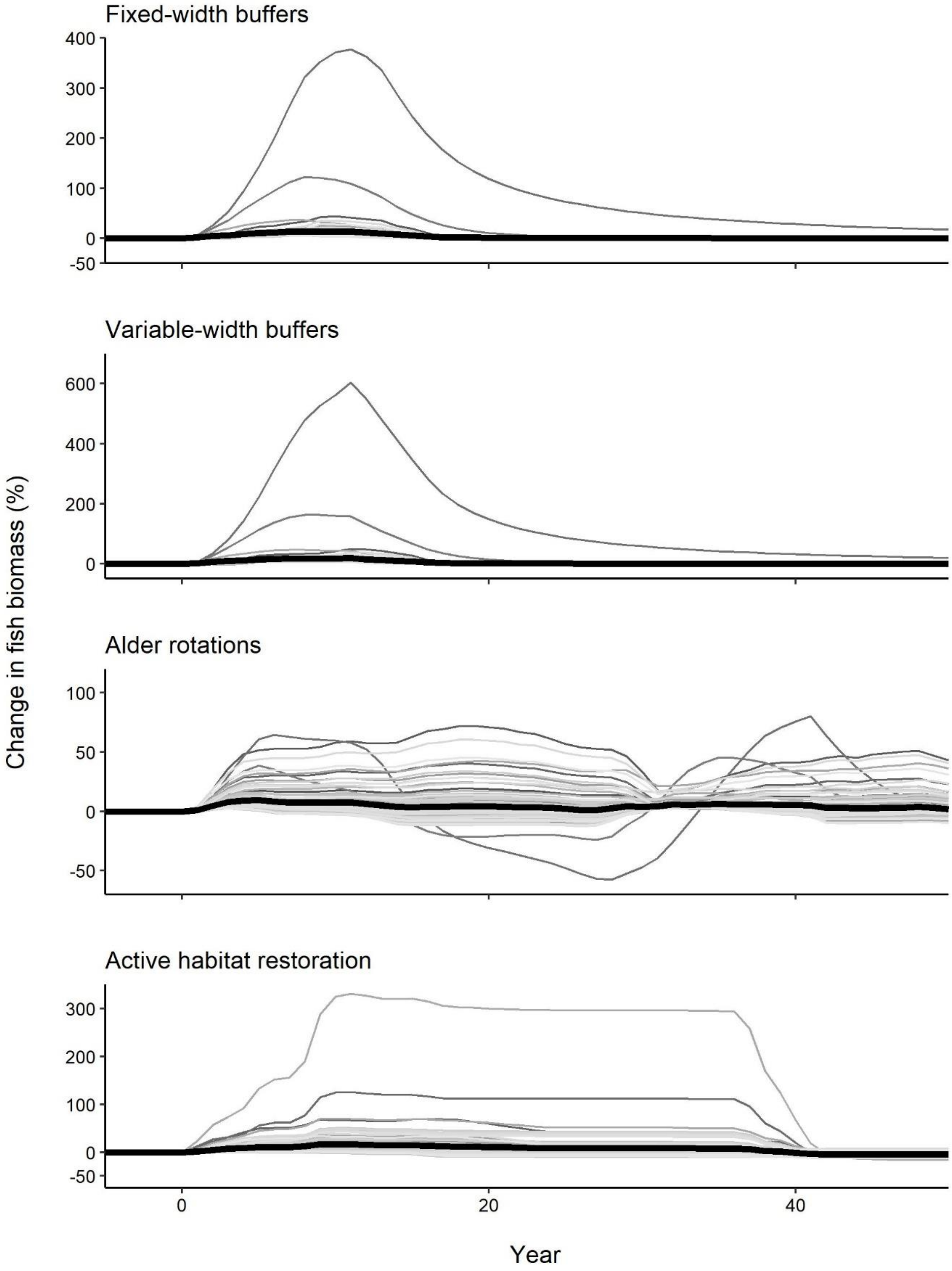

Figure 6. Effects of site variation on the modeled fish biomass response to each prescription. Each gray line represents the fish biomass dynamics of a model run with a different combination of environmental conditions. The average value across the 100 model runs is shown in the black, bold line.

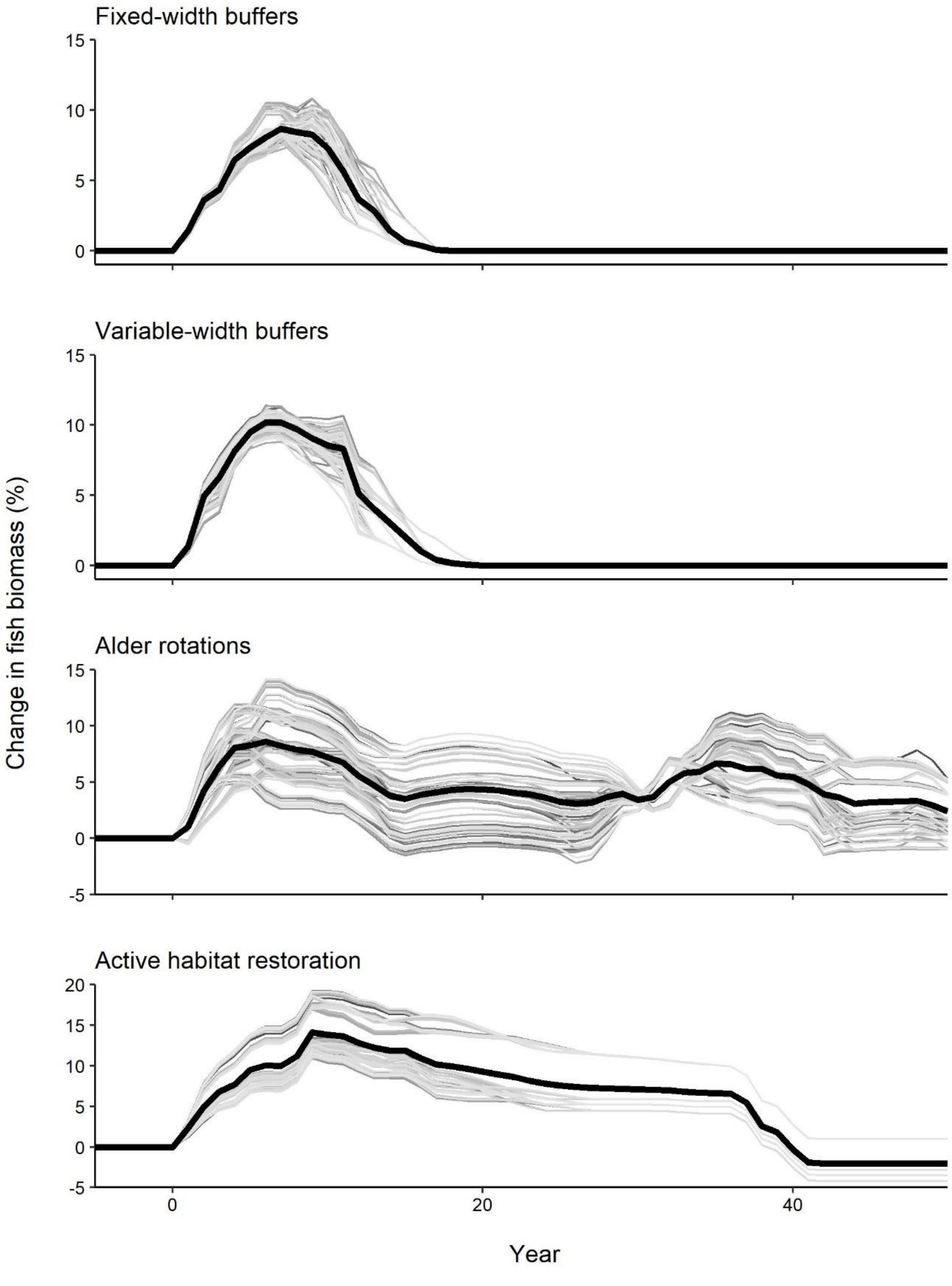

Figure 7. Effects of parameter response trajectory variation on the modeled fish biomass response to each prescription. Each gray line represents the fish biomass dynamics of a model run with a different combination of response trajectories. The average value across the 100 model runs is shown in the black, bold line.

Table 1. Values and sources of environmental parameters for the generalized T3 site

Parameter:	**Initial Value**	**Source**
Reach length	1000 m	
Channel slope	0.055 m/m	Average value, T3 data summary
Discharge	Figure A.1	Site 584, WADNR, Jeff Keck
One-dimensional rating curve relating discharge and wetted width	0.4 m	Site 584, WDNR, Jeff Keck, average wetted width
One-dimensional rating curve relating discharge and water depth	0.24 m	Site 584, WADNR, Jeff Keck, average water depth
Cumulative substrate size distribution	0.064 m	T3 data summary, Median substrate size (D50) of distribution
Water temperature	Figure A.1	Average daily water temperature across 13 streams from OESF Riparian Status and Trends Monitoring (Devine et al., 2022). Streams IDs: 694, 718, 724, 730, 744, 760, 763, 767, 769, 773, 776, 790, 804. Sites selected were in the vicinity of the T3 watershed and similar in size to T3 sites.
Soluble reactive phosphorus concentration	Figure A.1	Average monthly values from Twin Creek at Upper Hoh Road Bridge (SiteID 20E100, Washington Department of Ecology, 2023)
Dissolved inorganic nitrogen concentration	Figure A.1	Average monthly values from Twin Creek at Upper Hoh Road Bridge (SiteID 20E100, Washington State Department of Ecology, 2023)
Nephelometric turbidity	Figure A.1	Average monthly values summarized across multiple sites (Quileute Natural Resources, 2023; U.S. Geological Survey (USGS), 2023a, 2023b)

Sunlight (Photosynthetically active radiation)	Figure A.1	Forks, WA RAWs station (Western Regional Climate Center, 2022). Aligned with water year 2021
Proportion of the stream shaded	Figure A.1	Average fall value, T3 data summary, with season pattern assumed (Whitney et al., 2020)
Proportion of stream covered by vegetation	0.4	Calculated, assuming 1 m overhang per bank and average width
Proportion of riparian vegetation that is deciduous	0.366	Average value across T3 sites based on basal area within 5m of bank
Proportion of riparian vegetation that is coniferous	0.634	1-Proportion of riparian vegetation that is deciduous
Leaf litter input per square meter of deciduous vegetation	Figure A.1	Kiffney & Richardson, 2010; Richardson et al., 2009; Six et al., 2022. Assumes 5% ash content of litter samples (Conners & Naiman, 1984; Muto et al., 2009)
Leaf litter input per square meter of coniferous vegetation	Figure A.1	Kiffney & Richardson, 2010; Richardson et al., 2009; Six et al., 2022. Assumes 5% ash content of litter samples (Conners & Naiman, 1984; Muto et al., 2009)
Terrestrial invertebrate input per square meter of vegetation	10 g AFDM/m^2/year	Bellmore et al., 2013. Normal distribution around time of peak input

AFDM= ash-free dry mass

Table 2. Average percent change in food web member biomass across treatments from 0 to 10 years and 0 to 50 years post implementation

0 to 10 years

Percent change from control	Fixed-width buffers	Variable-width buffers	Alder rotations	Active habitat restoration
Fish	5.7	7.6	5.4	20.1
Grazers	1.0	2.1	-2.3	13.6
Shredders	4.6	4.0	11.3	7.6
Periphyton	0.6	1.0	0.2	5.8

0 to 50 years

Percent change from control	Fixed-width buffers	Variable-width buffers	Alder rotations	Active habitat restoration
Fish	1.7	2.2	3.4	18.0
Grazers	0.1	0.4	-3.4	13.2
Shredders	1.8	1.9	14.3	6.7
Periphyton	0.2	0.3	0.1	5.7

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Appendix A: Temporally dynamic environmental inputs (see Table 1 in main text for data sources)

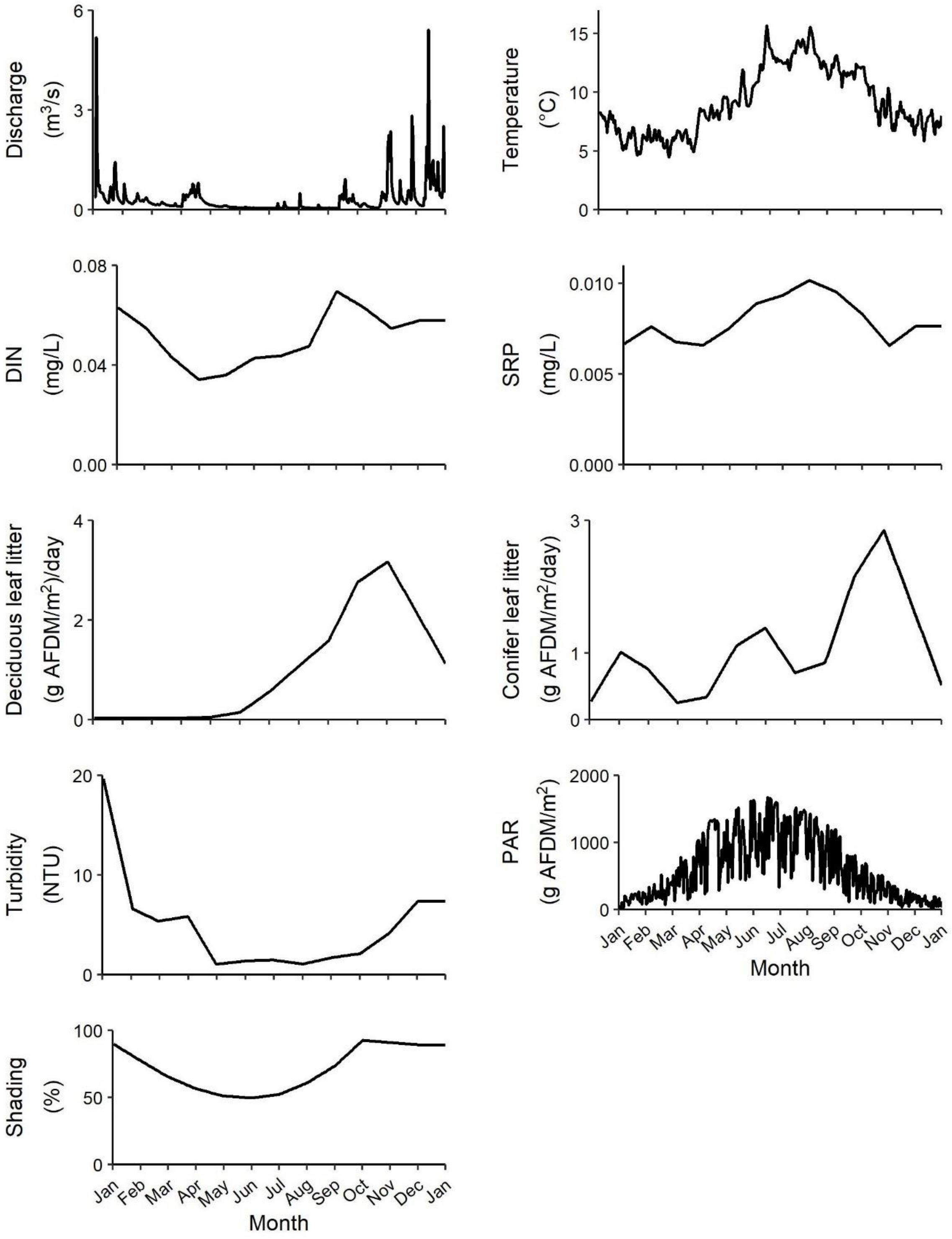

Figure A. 1. Temporally dynamic inputs of discharge; water temperature; DIN (dissolved inorganic nitrogen); SRP (soluble reactive phosphorus); turbidity (NTU=nephelometric turbidity unit); PAR (photosynthetically active radiation); shading (percentage of the reach shaded).

Appendix B: Description of values used in the sensitivity analysis in which environmental parameters were varies across the range of pre-implementation conditions.

Variable	Description of values used in the sensitivity analysis
Channel slope	Twenty values were included: The channel slope from each of the 20 T3 reach monitoring sites.
Dissolved Inorganic Nitrogen	Three annual patterns of DIN from Twin Creek at the Upper Hoh Road Bridge were included: Monthly average values, the average minus 10%, and the average plus 10%.
Proportion of the riparian vegetation that is deciduous	Three values were included: The average percent cover of alders by basal area within 5 m of the stream (36.6%) based on data from 20 T3 reach monitoring sites, 5%, and 95% cover.
Proportion of the stream shaded	Three values were included based on the average fall percent shading across the 20 T3 reach monitoring and the seasonal pattern from other ATP model applications (Central Washington, Whitney et al. 2020).
Soluble Reactive Phosphorus	Three annual patterns of SRP from Twin Creek at the Upper Hoh Road Bridge were included: Monthly average values, the average minus 10%, and the average plus 10%.
Stream discharge	Three annual patterns were included: The average weekly discharge across water years (2015-2020) and a high and low bound around water year 2019 (the year used for the generalized T3 site model).
Substrate size	Three values were included: An average substrate size distribution with a D50 of 0.064m, a minimum substrate size distribution of 0.032m, and a maximum substrate size distribution 0.128m based on data collected at the 20 T3 reach monitoring sites.
Turbidity	Eight annual patterns of turbidity were included from monthly average values taken from locations sampled year-round by the Quileute Natural Resources or USGS. Sites included Dowans Creek, Ponds Creek, East Fork Dicket River, Bear Creek, Bogachiel, Elk Creek, Sol Duc, a pond on the Quileute Reservation, and an averaged value across sites. Sites were selected to represent different seasonal trends observed in available data and not necessarily physical proximity to T3 monitored sites.
Water temperature	Eleven annual patterns of water temperature were included. Daily average values from water year 2021 for were used for sites selected from the OESF Riparian Status and Trends Monitoring (sites 694, 718, 724, 730, 744, 760, 763, 767, 769, 804, and an averaged value across sites). Warren Devine selected sites similar in size to those in T3 and in the vicinity of the T3 watershed. Average daily water temperatures ranged from 4.5 to 15.7° C with an annual average of 9.2°C.