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Toward efficient riparian restoration: integrating economic, physical, and biological models

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Abstract

This paper integrates economic, biological, and physical models to explore the efficient combination and spatial allocation of conservation efforts to protect water quality and increase salmonid populations in the Grande Ronde basin, Oregon. We focus on the effects of shade on water temperatures and the subsequent impacts on endangered juvenile salmonid populations. The integrated modeling system consists of a physical model that links riparian conditions and hydrological characteristics to water temperature; a biological model that links water temperature and riparian conditions to salmonid abundance, and an economic model that incorporates both physical and biological models to estimate minimum cost allocations of conservation efforts.

Our findings indicate that conservation alternatives such as passive and active riparian restoration, the width of riparian restoration zones, and the types of vegetation used in restoration activities should be selected based on the spatial distribution of riparian characteristics in the basin. The relative effectiveness of passive and active restoration plays an important role in determining the efficient allocations of conservation efforts. The time frame considered in the restoration efforts and the magnitude of desired temperature reductions also affect the efficient combinations of restoration activities. If the objective of conservation efforts is to maximize fish populations, then fishery benefits should be directly targeted. Targeting other criterion such as water temperatures would result in different allocations of conservation efforts, and therefore are not generally efficient.

Keywords: Conservation targeting; Spatially explicit models; Water temperature; Watersheds

1. Introduction

Salmonid populations have declined in many stream systems in the Pacific Northwest. The number of salmon returning to the Columbia River prior to European settlement has been estimated to be between 10 and 16 million. The present annual return is only about 1 million fish, and a majority of the return is artificially propagated and released from hatcheries (Northwest Power Planning Council, 2000). To date, six salmonid species have been listed as threatened or endangered in Oregon under provisions of the Endangered Species Act (ESA). The causes for the decline in salmon populations are complex, but degradation in fish habitat, deterioration in water quality, and excessive ocean and freshwater harvest have been suggested as some of the main causes (Lichatowich, 1999). High water temperature in salmonid rearing and spawning habitat areas is one of the primary reasons for

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impaired water quality. The US Environmental Protection Agency (2003) states that 'water temperatures significantly affect the distribution, health, and survival of native salmonids in the Pacific Northwest.'

In the last three decades, substantial public resources have been allocated to improve salmonid habitat, but many wild salmonid species continue to decline. This has led many to question the cost effectiveness of conservation expenditures (Lackey, 2002). When making allocation decisions concerning public funds, conservation managers must consider the heterogeneous nature of stream and riparian conditions as well as multiple impacts of restoration activities, including cumulative and threshold effects. Cumulative effects refer to situations where impacts of upstream practices accumulate downstream, potentially affecting water quality. Threshold effects refer to the nonlinear relationship between the level of conservation effort and the biological impact. For example, it is known that salmonids cannot survive when water temperatures are above some (lethal) level. This implies that unless water temperatures are reduced below such lethal levels, conservation efforts will produce no benefit in terms of increased fish production. Such threshold effects have important implications for the allocation of conservation efforts (e.g. Wu and Boggess, 1999; Wu et al., 2000, 2003). Furthermore, these effects are not uniform across the basin due to the heterogeneous nature of stream morphology and riparian conditions. Fish response to restoration activities also depends on the life stage. Public attitudes and preferences and land ownership patterns are other important factors that conservation managers must take into account.

The overall purpose of this paper is to explore the efficient combination and spatial allocation of conservation efforts to protect water quality and increase salmonid populations in the Grande Ronde basin, Oregon. This study has two specific goals. Resource managers currently must make decisions on conservation alternatives such as passive and active vegetation restoration, the width of riparian restoration zones, and the location where conservation efforts are implemented within a basin characterized by heterogeneous riparian conditions. The first goal of this paper is to gain insights on the choice of these conservation alternatives. The second goal is to examine the allocation of conservation efforts to maximize juvenile salmonid populations in the basin. We conduct this analysis by comparing the allocation of restoration efforts to attain a physical criterion or goal (reducing water temperatures) and a biological criterion (increasing fish populations) at minimum costs, respectively, and show that the two result in different allocations of conservation efforts.

To attain these goals, we develop a modeling system that integrates economics, hydrology, and biology to simulate policy alternatives. The modeling system consists of (1) a physical model that links physical and riparian characteristics to water temperature; (2) a biological model that links water temperature and riparian conditions to salmonid abundance, and (3) an economic model that incorporates both physical and biological models to estimate minimum cost allocations of conservation efforts. The modeling system incorporates cumulative and threshold effects as well as the spatial heterogeneity of stream and riparian conditions.

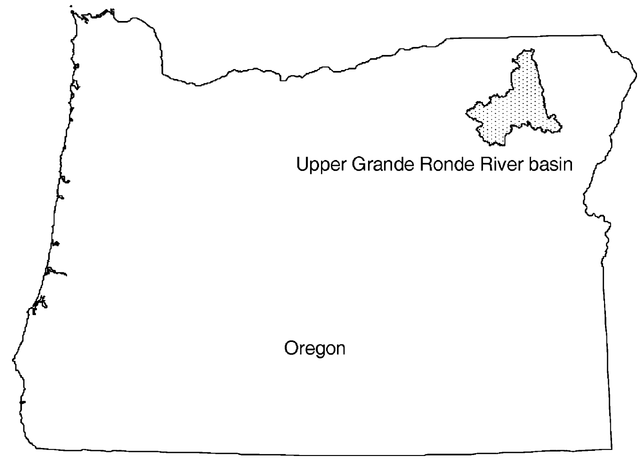

Fig. 1. Location of the Upper Grande Ronde River Basin.

In this modeling exercise, we focus on the effects of riparian restoration efforts on water temperatures by means of shading and the subsequent effects of the change in water temperature on juvenile salmonid populations. Riparian restoration efforts such as passive and active restoration influence water temperatures in various ways. For example, it is known that riparian restoration efforts lead to a decrease in the width to depth ratio of the stream thereby contributing to a decrease in water temperatures.[1]

The empirical focus of this study is the Grande Ronde River basin, a tributary of the Snake River, located in northeastern Oregon (Fig. 1). The study area is the upper portion of the basin, which includes approximately 7100 km^2 of drainage area and 320 km of the mainstem and six tributary systems. Most segments of the upper basin violate the maximum water temperature standard, and are subject to Total Maximum Daily Load (TMDL) regulations (ODEQ, 2000). The Grande Ronde river is a typical Northwest stream; the area is an important spawning and rearing habitat for spring/summer chinook salmon (Oncorhynchus tshawytscha) and steelhead trout (O. mykiss), species listed as 'threatened' under the Endangered Species Act, but high summer and early fall water temperatures frequently exceed sub-lethal levels for salmonid species

[1] Restoration efforts may also increase the frequency of the presence of coldwater patches, which also decrease water temperatures. However, such cold water patch effects are not considered in this study because of lack of data. Likewise, juvenile salmonid populations are affected by riparian restoration efforts in many ways. For example, riparian restoration would improve habitat conditions by increasing nutritional inputs, making large wood debris available, and stabilizing stream banks. These relations are also difficult to incorporate due to lack of data and are not considered in this study. These exclusions will likely result in underestimation of restoration benefits.

(ODEQ, 2000). Drake (1999) found that seasonal maximum temperatures and related variables explained the distribution and abundance of trout in the Upper Grande Ronde River basin. Ebersole (2001) also found that maximum water temperature is one of the significant variables for chinook salmon and rainbow trout densities in the Grande Ronde River basin.

This paper is structured as follows: Section 2 reviews literature. Sections 3 and 4 present the procedures and results of the simulation analyses, respectively. Conclusions are offered in Section 5.

2. Literature review

A large number of studies have examined the relationships between riparian conditions and water temperatures (e.g. Brown, 1970; Bohle, 1994; Beschta, 1997; Boyd and Sturdevant, 1997; Moore and Miner, 1997; Johnson and Jones, 2000). These studies show that shading provided by riparian vegetation plays an important role in determining water temperatures in Pacific Northwest streams. The interaction between riparian conditions, water temperature and fish abundance has also been examined extensively (e.g. Platts and Nelson, 1989; Li et al., 1994; Baigun et al., 2000; Ebersole, 2001; and Welsh et al., 2001). Salmonid biomass/density/existence is negatively correlated with water temperatures above 15 °C (Li et al., 1994; Drake, 1999; Baigun et al., 2000; Ebersole, 2001; and Welsh et al., 2001). Riparian characteristics such as stream canopy (Platts and Nelson, 1989) and bank stability (Li et al., 1994) are also found to be correlated with salmonid abundance.

There are few economic studies related to water temperatures that combine these biological and hydrological relationships. However, these relationships have been examined as an extension of hydrological and biological studies (e.g. Theurer et al., 1985; Bartholow, 1991; Chen et al., 1998a; Chen et al., 1998b; Hickey and Diaz, 1999). Theurer et al. (1985) integrated ecological and biological effects to examine the impact of different riparian vegetation and discharge scenarios on water temperatures and salmonid abundance in the Tucannon River, Washington. They considered four scenarios involving different riparian vegetation and stream morphology conditions and found that estimated juvenile fish production would more than double when the climax vegetation is restored. They also conducted a cost-benefit analysis and argued that the benefit (an increase in the return of adult salmonid species) from the climax vegetation would far exceed the costs. Bartholow (1991) evaluated the effectiveness of alternatives to reduce summer maximum water temperatures for a 30 km stretch of the Cache la Poudre River, Colorado. The alternatives included increasing discharge, doubling riparian shading, and halving stream width; an increase in discharge was determined to be the most effective in reducing water temperatures.

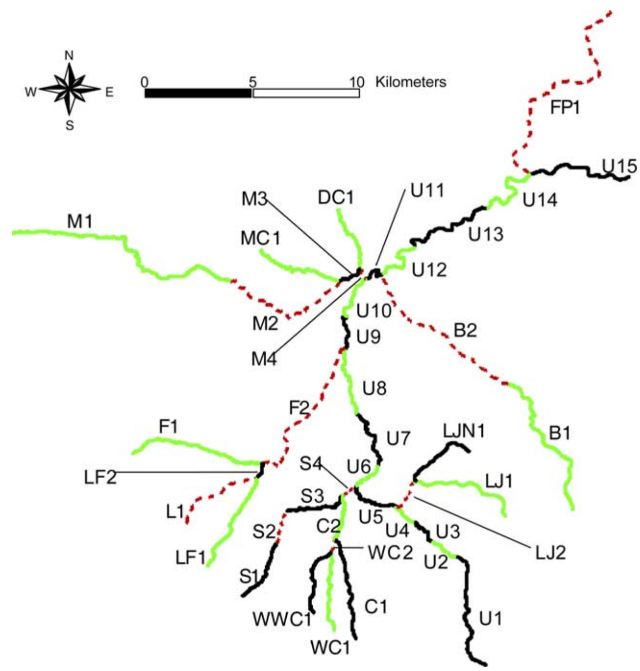

Fig. 2. The Upper Grande Ronde River basin and reaches.

These studies are similar to this study in that they evaluate policy alternatives associated with riparian vegetation. However, these previous studies only compared selected conservation scenarios and did not evaluate the most efficient spatial distributions for restoration activities. In addition, these studies only examined restoration alternatives on the mainstem, abstracting from effects in the tributaries. The research presented here thus provides additional insights into the issue by addressing the spatial distribution of restoration efforts.

3. Procedures

This section explains the methodology employed in developing a simulation model that integrates economics, hydrology, and biology and that reflects the physical and economic conditions in the Upper Grande Ronde River basin.

3.1. Distribution of geographic coverage

For this analysis, the study basin is divided into 41 reaches (Fig. 2).[2] The division is based on stream orders, geomorphologic characteristics and land ownership patterns. For example, each stream is divided into reaches at each confluence, which frequently match the borders of land ownership patterns (public and private). Reaches 7 and 8 in the UGR mainstem (U7 and U8 in Fig. 2) are distinguished from other reaches on the basis of alluvial characteristics.

[2] The names of each reach in Fig. 2 are shown in Table 1.

Table 1
Riparian vegetation/land use types in each reach

Reach	Fig. 2 notation	Length (m)	Agriculture (AG) (%)	Emergent vegetation (EM) (%)	Scrub-Shrub (SS) (%)	Herbaceous uplands (HU) (%)	Forest (Height, m)					Others
							6–12 m (%)	−18 m (%)	−24 m (%)	−30 m (%)	30 m (%)	
UGR mainstem 1	U1	10,580	0	3	2	0	0	0	18	74	0	3
UGR mainstem 2	U2	2413	0	0	36	8	0	0	17	9	0	30
UGR mainstem 3	U3	2692	0	0	3	17	0	0	27	49	0	4
UGR mainstem 4	U4	3527	0	7	4	29	0	0	0	56	0	3
UGR mainstem 5	U5	5386	49	26	1	8	0	0	0	15	0	0
UGR mainstem 6	U6	3519	31	50	2	4	0	1	1	1	0	10
UGR mainstem 7	U7	5932	0	2	24	17	2	0	1	40	0	14
UGR mainstem 8	U8	6436	0	0	35	4	0	0	0	53	2	6
UGR mainstem 9	U9	3341	0	1	28	9	6	0	3	19	0	35
UGR mainstem 10	U10	4354	18	2	22	5	0	2	2	8	0	42
UGR mainstem 11	U11	2436	0	0	9	18	0	0	0	25	0	48
UGR mainstem 12	U12	5034	0	0	13	17	0	0	0	14	0	56
UGR mainstem 13	U13	8659	13	9	4	10	0	0	0	17	0	47
UGR mainstem 14	U14	7149	2	1	17	10	0	1	1	12	0	56
UGR mainstem 15	U15	9018	0	0	2	6	0	6	0	13	0	73
Limber Jim Cr. Source	LJ1	9482	0	5	3	4	0	0	23	65	0	0
Limber Jim Cr. Mouth	LJ2	3814	0	1	4	79	4	0	6	6	0	0
Limber Jim N.Fk. Cr.	LJN1	6547	0	0	2	6	0	0	11	79	0	2
Sheep Cr. 1	S1	6402	0	3	1	36	0	0	5	55	0	0
Sheep Cr. 2	S2	4102	77	8	2	1	0	4	7	1	0	0
Sheep Cr. 3	S3	8561	61	35	2	1	0	0	0	1	0	1
Sheep Cr. 4	S4	2442	2	97	0	0	0	0	0	0	0	1
Chicken Cr. Source	C1	9784	0	1	1	18	0	1	6	72	0	1
Chicken Cr. Mouth	C2	5610	42	50	1	7	0	0	0	0	0	1
West Chicken Cr. Source	WC1	7399	0	0	0	13	0	0	11	76	0	0
West Chicken Cr. Mouth	WC2	1507	0	0	0	82	0	0	14	4	0	0
W.West Chicken Cr.	WWC1	6576	0	0	0	11	0	0	9	81	0	0
Fly. Cr. Source	F1	13,343	24	13	2	37	0	0	15	8	0	0
Fly. Cr. Mouth	F2	14,760	2	10	21	10	2	0	3	51	0	0
Little Fly Cr. Source	LF1	9698	18	1	2	17	1	0	27	29	0	4
Little Fly Cr. Mouth	LF2	1743	67	17	0	7	0	0	9	0	0	0
Lookout Cr.	L1	7924	4	2	0	9	0	0	36	49	0	0
Meadow Cr. 1	M1	22,484	0	14	1	24	0	2	27	31	0	0
Meadow Cr. 2	M2	13,010	6	1	29	33	2	0	3	23	0	3
Meadow Cr. 3	M3	2313	26	6	25	5	0	0	3	34	0	0
Meadow Cr. 4	M4	1205	0	0	42	1	0	0	0	47	0	10
McCoy Cr.	MC1	7962	28	3	17	28	4	7	2	10	0	1
Dark Canyon Cr.	DC1	6237	0	0	39	3	0	0	1	55	2	1
Beaver Cr. Source	B1	14,870	0	1	19	16	0	0	7	45	0	10
Beaver Cr. Mouth	B2	15,535	1	2	10	12	0	0	1	72	0	1
Five Point Cr.	FP1	22,133	1	0	10	22	0	3	0	63	0	0

Note: Others include developed land such as roads. Source: ODEQ (2000).

The mainstem of the Upper Grande Ronde (UGR) River flows northward starting in reach 'UGR mainstem 1 (U1)' and then eastward to reach 'UGR mainstem 15 (U15)'. The riparian zone in each reach is further divided into distinct units using aerial photos and each unit is given one of 10 vegetation/land use types (Table 1). Among these vegetation/land use classes, agricultural land (AG), emergent vegetation (EM), herbaceous upland (HU) and scrub/shrub (SS) are the sites for potential restoration activities. The decision whether restoration efforts are implemented or not is made at the vegetation type level in each reach.

3.2. Conservation practices and costs

While a variety of conservation activities are available for stream restoration, we focus on passive and active riparian restoration because they are the most popular ones in the basin (Grande Ronde Model Watershed Program, unpublished data, 2002). Passive restoration allows a riparian zone to recover vegetations naturally by eliminating activities causing degradation, such as cattle grazing. The primary means of passive restoration is building fences along the stream to prevent livestock grazing or other disturbances in riparian areas. Active restoration includes vegetation planting and silvicultural options to accelerate riparian forest development (Kauffman et al., 1997). Whether passive or active restoration should be selected depends partly on the relative effectiveness of each restoration activity. In order to incorporate this aspect in the study, three restoration scenarios are examined. For the active restoration, it is assumed that seedlings with the height of 0.5–1.0 m are planted in year 0. For passive restoration, in the first scenario, trees do not emerge for the first 3 years following construction of fences. In the second and third scenarios, trees do not emerge for the first 7 and 10 years, respectively. These three scenarios are designed as sensitivity analyses to verify the robustness of the results.

The tree species associated with restoration activities are then identified based on literature review and personal communications with foresters and others who practice restoration activities in the basin. The species identified are conifer, cottonwood and shrub (willow and alder), which grow in each vegetation/land use type (Table 2). No active restoration is implemented in HU and SS because it is difficult to establish trees due to the lack of adequate moisture. In the case of passive restoration in agricultural land, shrub, cottonwood, and conifer are assumed to have an equal probability of survival. The growth curves of each tree species are then estimated (Fig. 3). A growth curve for conifer was estimated based on the site index curves for Douglas-fir (King, 1966) and the information contained in the TMDL document on potential maximum height of ponderosa pine, Douglas fir, and Grand fir in the Upper Grande Ronde basin (ODEQ, 2000). A growth curve for cottonwood was also obtained from a black cottonwood site classification table (USDA-FS, 1965) and the information contained in the TMDL document. The tree growth curve for shrub was estimated from studies undertaken in the Grande Ronde River basin (Brookshire et al., 2002; Case and Kauffman, 1997; Green and Kauffman, 1995; and Lytjen, 1998).

Table 2
Vegetation class and types of trees grown/planted

	AG	EM	SS	HU
Passive restoration	Shrub/Cotton-wood/Conifer	Shrub	Shrub/ Conifer	Conifer
Active restoration	Shrub/Cotton-wood/Conifer	Shrub	NA	NA

Note: Shrub primarily represents willow and alder.

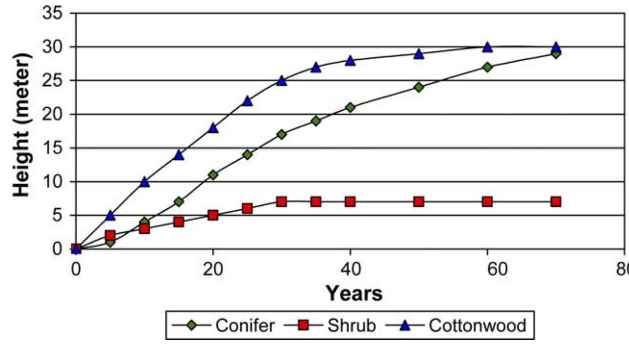

Fig. 3. Tree growth curves.

Using these tree growth curves, potential maximum tree heights in respective vegetation class as a result of passive and active restoration are estimated. Then, using cost data from past projects in the basin (Grande Ronde Model Watershed Program, unpublished data, 2002) as well as information from the Oregon Department of Forestry and other conservation agencies, the minimum-cost restoration portfolios are determined for each vegetation type (Table 3), and the costs of the portfolios are then calculated. It is assumed that all restoration activities are implemented in year 0. The cost of expanding the width of restoration activities beyond 5 m is zero in the case of passive restoration (Table 3). This is because the primary activity in the study basin is grazing, and the cost of setting aside riparian land for restoration activities is minimal for landowners.

3.3. The relationship between riparian vegetation and water temperature

A state-of-the-art temperature model, WET-temp, was used to estimate the water temperature under various configurations of riparian vegetation. WET-temp models the effects of riparian vegetation on water temperatures downstream by simultaneously solving individual sub-reach scale energy balances across the entire stream network. The WET-temp was developed by Cox (2002) and was

Table 3
Cost of minimum-cost restoration portfolios, by land use and time frame

		20 years	40 years
Restoration activity	AG	Active restoration/cottonwood	Active restoration/cottonwood
	EM	Active restoration/shrub	Passive restoration
	SS	Passive restoration	Passive restoration
	HU	Passive restoration	Passive restoration
Cost per meter height per stream km for 5 m width in dollars	AG	418	283
	EM	1390	938
	SS	820	469
	HU	729	328
Cost for additional 5 m of width per stream km in dollars	AG	73	49
	EM	229	0
	SS	0	0
	HU	0	0

Note: These costs represents the first scenario of passiver restoration. (Trees emerge 3 years after fences have been built.)

previously applied to a sub-watershed of the South Santiam River in western Oregon. A desirable feature of the WET-temp model is its ability to directly incorporate spatially explicit data such as vegetation and topography, which allows it to produce temperature results for specific locations in the context of the entire stream network. It is also less information intensive than other temperature models such as the Heat Source model used by the Oregon Department of Environmental Quality. The WET-temp model provides estimates of water temperature every 15 min at every 100 m along the stream. Since we are interested in maximum water temperatures, the WET-temp model was calibrated to observed maximum daily temperatures at three points in the UGR mainstem. In general, WET-temp calibrates well for the mainstem of the upper Grande Ronde River (within 1 °C of daily maximum temperature at each site for which field data were available). In some of the tributaries, the WET-temp estimates have divergences from observed temperatures.[3] For those tributaries, the WET-temp estimates are adjusted using the ratio of actual to estimated data. This ensures that the estimates more closely follow the actual temperature patterns.

Since the conservation practices (passive and active) primarily affect the height and width of riparian vegetation, vegetation height and width are the control variables in WET-temp. In estimating the relationship between vegetation height/width and water temperatures, 2000 runs were made for each time frame, each of which consists of different combinations of vegetation height and width in each vegetation type in each reach. Then, maximum water temperatures at representative points estimated by the WET-temp model are regressed against vegetation height and width in each vegetation type in each reach located in their upstream area. The following regression model was used to estimate the maximum water temperature at point $\tilde{j}$ in reach j

$$\text{temp}(\tilde{j}) = \alpha\tilde{j} + \sum_{i=1}^{j}\sum_{k=1}^{4}\beta_{ik}h_{ik} + \sum_{i=1}^{j}\sum_{k=1}^{4}\gamma_{ik}h_{ik}^2 + \sum_{i=1}^{j}\sum_{k=1}^{4}\delta_{ik}w_{ik}h_{ik} \quad (1)$$

where i, reach ($i=1,\dots,j$ are located in the upstream area of reach j); k, vegetation class ($k=$AG, EM, SS, and HU); h_{ik}, riparian vegetation height in reach i, vegetation class k; w_{ik}, riparian vegetation width ($w_{ik}=1$ if width is 10 m, $w_{ik}=0$ if 5 m).

The entire study basin consists of reaches numbered from 1 to I, and they are ordered such that a reach with a lower number is located in the upstream area of a reach with a higher number. This model was applied to all points at which WET-temp estimates are available. The R-squares of these regressions estimated here exceed 0.95, with the majority (except for 3 models) higher than 0.97.

3.4. The relationship between water temperature and salmonid density

Increases in the number of juvenile chinook salmon are assumed to be the primary benefit of temperature decreases. To measure this fishery benefit, a density model for juvenile chinook salmon is estimated (Table 4). Details of the data and site selection are found in Ebersole (2001); Ebersole et al. (2003). By applying the fish density model and using the information on habitat conditions in each reach, the total juvenile chinook salmon populations are estimated. We focus on juvenile salmonid because juveniles are the life stage that is most immediately affected by changes in water quality and riparian conditions. The information on habitat

[3] These divergences occurred primarily because the WET-temp was not calibrated to the tributaries. It is difficult to calibrate the WET-temp model to all tributaries in the basin. We chose points in the mainstem as the sites for calibration because the mainstem is the primary habitat of chinook salmon and habitat data are available. Other factors such as hyphoreic inflows may be driving these divergences on water temperatures in tributaries, however, it is difficult to pinpoint these factors because of lack of data.

Table 4
Estimated coefficients for juvenile chinook salmon density models

	Chinlook salmon	
	Coefficient	t-statistics
Intercept	−1.1668**	−4.91
7-day max water temperature	0.0930**	4.44
7-day max water temperature squared	−0.0023**	−4.37
Fines	−0.6268*	−1.74
Fines squared	1.5115**	2.87
Mean channel depth	3.3480**	2.97
Mean channel depth squared	−7.0261**	−2.61
R-square	0.68	
Number of observations	26	

Note: Two and one asterisks indicate statistical significance at the 5 and 10% levels, respectively. Fines refers to the proportion (percent) of substrate transect points intersecting fine substrates (less than 16 mm in size). Fish density and mean channel depth are log-transformed. The incipient lethal limit for juvenile chinook salmon is set at 25.5 °C based on data in Ebersole (2001); ODEQ (2000). If the temperature is above this level in any reach, it is assumed that chinook salmon are not present.

conditions is obtained from the Aquatic Inventories Project (ODFW, 1999). Although, the Aquatic Inventories Project provides the most comprehensive habitat dataset for Oregon, it includes only a limited number of variables on habitat conditions. These are used in estimating the density model. In the regression analysis, the step-wise method is employed, including unsquared and squared terms of all the variables, and only those variables that are significant at a 10 percent level are used in the model. Since the primary habitat area of chinook salmon in the upper Grande Ronde river basin is limited to the UGR mainstem and Sheep creek, only those streams are considered in estimating the total number of chinook salmon.[4]

The density model assumes that summer conditions, especially water temperatures, are limiting factors for salmonid populations. While we are aware that populations are also affected by factors such as the abundance and distribution of adult spawners, availability of cover or thermal refuges, productive foraging habitat and food, we focus on water temperature because it is the most critical factor for the existence of salmonid species in the basin. Passive and active restoration can result in changes to instream habitat as well as stream temperature, thereby affecting fish abundance directly. However, due to limitations in the temperature model, the effects of passive and active restoration activities on geomorphology, spawning substrates, coldwater patches, and instream community dynamics are not considered. We also assume that fish densities within individual stream reaches are not influenced by conditions elsewhere (i.e. movement between reaches is minimal). Finally, the water temperature model was calibrated to 1999 data, while fish data were collected in 1997. Information on air temperature and precipitation in the basin suggests that both years are within the standard deviation of the historical means for each parameter. Therefore, integrating temperature and fishery analyses across two different years is not expected to change the results of this study significantly.

[4] Habitat data are not available for reaches UGR mainstem 7 and 8. Thus, these reaches are excluded from the simulation analyses associated with chinook salmon.

3.5. Policy options

Three policy options are specified to examine alternative restoration efforts. The first policy option relates to the first goal of this study. This policy is represented by an optimization problem that selects restoration activities to achieve a certain temperature reduction at a given point at minimum cost.

$$\min_{h_{ik},w_{ik}} \sum_{i=1}^{j}\sum_{k=1}^{4}[C_h(h_{ik}) + C_w(h_{ik}w_{ik})] \tag{2}$$

$$\text{s.t. } \Delta\text{temp}_j = \Delta\text{temp}_j(h_{11}, w_{11}, \ldots, h_{ik}, w_{ik}, \ldots, h_{j4}, w_{j4}) \le \Delta T \tag{3}$$

where Δtemp_j, *change in* water temperature at a given point in reach j; $C_h(h_{ik})$, restoration cost associated with vegetation height; $C_w(h_{ik}w_{ik})$, restoration cost associated with vegetation width; ΔT, temperature change target.

Since the change in temperature is negative, the constraint (3) means that the reduction in temperature needs to be larger than a targeted temperature change (ΔT). This model is applied to different points in the basin to verify the robustness of the results.

The second and third policy options are concerned with the second goal, which is to compare the allocations under two distinct goals: reducing water temperatures and increasing fish populations. The temperature reduction goal (policy option 2) is specified to maximize stream length where water temperature is reduced by a selected amount with a given budget constraint.

$$\max_{h_{ik},w_{ik}} \sum_{i=1}^{I}[s_i L_i] \tag{4}$$

$$\text{s.t. } \Delta\text{temp}_{\hat{j}} = \Delta\text{temp}_{\hat{j}}(h_{11}, w_{11}, \ldots, h_{ik}, w_{ik}, \ldots, h_{j4}, w_{j4}) \quad j = 1, \ldots, I \tag{5}$$

$$s_j = 1, \text{ if } \Delta\text{temp}_{\hat{j}} \le \Delta T \tag{6}$$

$$s_j = 0, \text{ if } \Delta\text{temp}_{\hat{j}} > \Delta T \quad j = 1, \ldots, I \tag{7}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{4}[C_h(h_{ik}) + C_w(h_{ik}w_{ik})] \le B \tag{8}$$

where $\Delta \text{temp}_{\hat{j}}$, change in the highest water temperature in reach j; s_i, dummy variable; L_i, length of reach i; B, budget.

It is assumed that once the point that has the highest water temperature in a reach is decreased by a certain amount, water temperatures in the entire reach also decrease by the same quantity, and the length of the entire reach is thus included in the objective function.

On the other hand, a fish population goal (policy option 3) is specified to maximize fish numbers subject to a given budget constraint

$$\underset{h_{ik},w_{ik}}{\text{Max}} \sum_{i=1}^{I} [\text{Fish}_i(\text{temp}_{\bar{i}}, a_i) L_i] \tag{9}$$

$$\text{s.t. } \text{temp}_{\bar{j}} = \text{temp}_{\bar{j}}(h_{11}, w_{11}, \ldots, h_{ik}, w_{ik}, \ldots, h_{j4}, w_{j4}) \quad i = 1, \ldots, I \tag{10}$$

$$\sum_{i=1}^{I} \sum_{k=1}^{4} [C_h(h_{ik}) + C_w(h_{ik} w_{ik})] \leq B \tag{11}$$

where $\text{temp}_{\bar{i}}$, average water temperature in reach i; fish_i, fish density in reach i, predicted by the fish density model in Table 4; a_i, other variables that affect fish density.

These optimization models are specified as mixed integer nonlinear programming models (MINLP), and the GAMS-DICOPT solver is used to solve these problems.

4. Results

In this section, we first examine alternative restoration efforts when the target is to decrease water temperatures by means of shading. Subsequently, we compare the allocations of riparian restoration efforts under the two policy goals (reducing water temperatures versus increasing fish populations).

4.1. Choice of restoration activities

One important question in current policy discussions is whether conservation programs should focus on passive or active restoration activities. To gain insights on this issue, the allocations of conservation efforts that attain temperature reductions in 20- and 40-year time frames with minimum costs are estimated using the policy option 1. As for the spatial aspects of monitoring, a point in reach 'UGR mainstem 15 (U15)' that has the highest water temperature in the mainstem under the current condition is selected.

The analyses show that a larger share of budget should be allocated to passive restoration in the 40 year time frame than in the 20 year time frame (Fig. 4). In addition, the share of passive restoration decreases as the magnitude of desired temperature reduction increases. These findings are commonly observed in the three passive restoration scenarios. Applying the same analysis to other points in the mainstem yields similar results, which suggests that conservation programs should focus on passive restoration activities when the time span considered is long and/or the magnitude of desired temperature reductions is small. However, Fig. 4 also indicates that the share of passive restoration varies substantially among the three scenarios, particularly in the 20 year time frame. This implies that in the choice of restoration activities, the effectiveness of passive restoration relative to active restoration should be carefully examined.

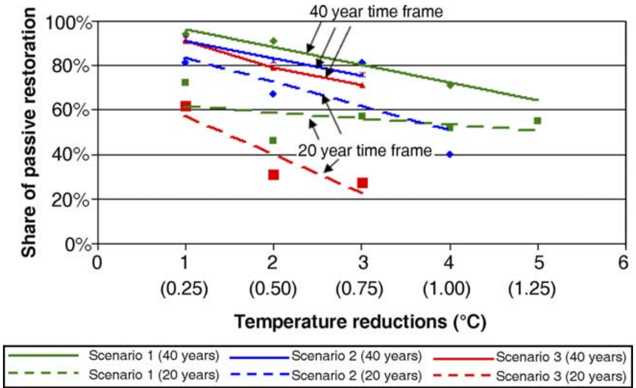

Fig. 4. Share of conservation funds allocated to passive restoration to attain temperature reductions at minimum costs, 20 and 40 year time frames. Note: The vertical axis represents the cost share of passive restoration when water temperature at a point in 'UGR mainstem 15' is decreased by 1–4 °C degrees in a 40 year time frame and 0.25–1.25 °C degrees in a 20 year time frame. The share of passive restoration refers to the ratio of the budget allocated to passive restoration. On the horizontal axis, the values in the upper row refer to temperature reductions in a 40 year time frame, and those in the lower row (values in parenthesis) refer to temperature reductions in a 20 year time frame case. The three scenarios are designed as sensitivity analyses to verify the robustness of the results in the first scenario, trees do not emerge for the first 3 years following construction of fences. In the second and third scenarios, trees do not emerge for the first 7 and 10 years, respectively.

4.2. Width of restoration activities

The effect of varying the width of restoration activities on water temperature is examined in a representative tributary for a 40-year time frame. Specifically, Fig. 5 presents longitudinal temperature profiles for Fly Creek when the width of riparian restoration efforts is 5, 10 or 20 m. Expanding the width beyond 10 m does not decrease water temperatures primarily because trees beyond 10 m have little additional effects on the shading on the surface water. The same outcome is also observed in other streams in the study basin, which indicate that although wider riparian buffers may influence water temperatures and improve aquatic habitat via other mechanism, there appears to be little increase in effective shade for buffers wider than 10 m.

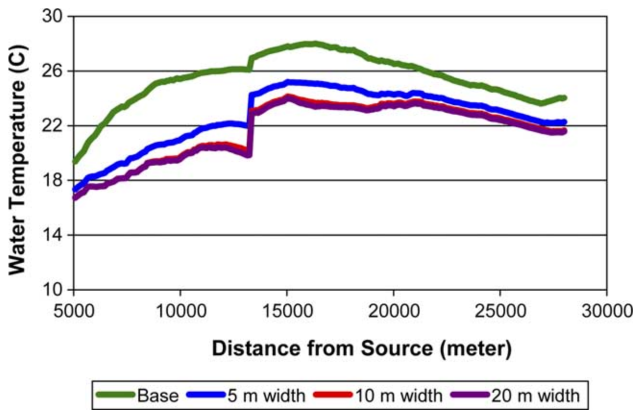

Fig. 5. Longitudinal temperature profile of Fly Creek in a 40-year time frame at riparian restoration width of 5, 10, or 20 m.

While there appears to be no temperature benefit for buffers wider than 10 m, it is important to examine benefits of buffers less than 10 m. Here we explore the efficacy of a 5-m buffer and a 10-m buffer. We find that the share of restoration activities (in terms of length) with a 5-m buffer increases for both 20- and 40-year time frames as the magnitude of temperature reduction increases (Fig. 6). The logic behind this result is that expanding the width of riparian restoration from 5 to 10 m is less costly than extending the restoration activities along the length of the reach. However, the former has a smaller impact on water temperatures. Therefore, when a greater level of temperature reduction is desired, it becomes necessary to switch from expanding the width of buffers to extending restoration activities longitudinally with a 5-m buffer.

However, Fig. 6 also indicates that the share of a 5 m buffer varies across the scenarios and the time span to be considered, particularly when the magnitude of desired temperature reduction increases. In addition, if it is costly to expand the width of the buffer beyond 5 m in the case of passive restoration (which is the case when riparian land has a higher opportunity cost), then the above results may vary. These observations suggest that resource managers must consider the costs of riparian land and the effectiveness of passive restoration relative to active restoration in determining the appropriate width of restoration activities, even when water temperature and the effects of shade are the only concerns.

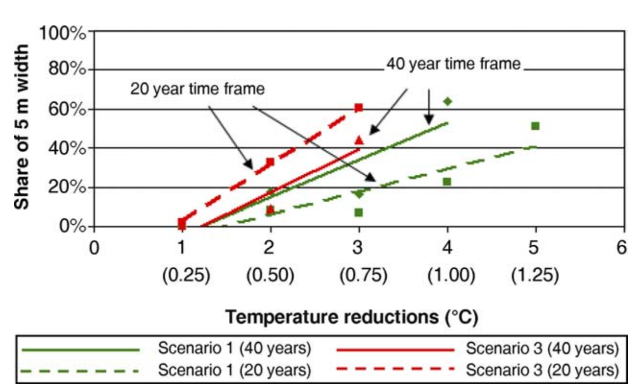

Fig. 6. Share of riparian length with a 5 m buffer to attain temperature reductions at minimum costs, 20 and 40 year time frames.

4.3. Site selection

The next analysis concerns the identification of vegetation types for water temperature reductions. In this study, agriculture (AG), emergent vegetation (EM), scrub-shrub (SS), and herbaceous upland (HU) are the vegetation types at potential restoration sites, and they are distributed in the basin in a heterogeneous manner.

In all the passive restoration scenarios, when the desired decrease in water temperature is small (e.g. 1 °C in 40 year time frame, and 0.25 °C in 20 year time frame), herbaceous upland (HU) should receive the largest share of budget (Table 5). This is primarily because trees grow relatively fast, and the costs with a 10 m buffer are lower in HU than other vegetation types. However, as the magnitude of desired temperature reduction increases, the allocation of conservation funds among vegetation types becomes more complex. For example, in Table 5, if the target is to decrease water temperature by 0.75 °C in 20 years, AG is the priority when passive restoration is not very effective (the second and third passive restoration scenarios), while HU is the priority when passive restoration is effective (the first scenario). On the other hand, if the time span considered is extended to 40 years and a decrease in water temperatures by 3 °C is targeted, SS is the priority sub-reach. These results are obtained because the growth rate of trees and the maximum height of riparian vegetation are different across vegetation types. In addition, if other points are taken as sites for monitoring, the minimum cost allocations are also different. These observations suggest that the selection of vegetation type across restoration sites should be based on the time span considered, the effectiveness of passive restoration relative to active restoration as well as the distribution of vegetation types in the basin.

4.4. Spatial allocation of conservation efforts: water temperature vs. fish populations

We now move to the second goal of this study: to compare the minimum cost allocations of restoration efforts under two distinct goals: water temperature reductions and fish population increases. The first passive restoration scenario is used in this analysis. The temperature targeting policy (policy option 2) is to maximize the stream length where water temperature is reduced by at least one degree in a 40 year time frame. Reaches with maximum temperatures lower than 20 °C (68 °F) are not subject to this temperature reduction because their temperature levels are already sufficiently low to meet salmonid goals. This policy is politically attractive because it implements riparian restoration efforts in the entire basin, and therefore the burden of riparian restoration efforts are not borne by a few land

Table 5
Allocations of conservation funds (percentages) across vegetation types to attain temperature reductions at minimum cost, 20 and 40 year time frames

Temperature reduction		20 year time frame					40 year time frame			
		1.25 °C	1.0 °C	0.75 °C	0.5 °C	0.25 °C	4.0 °C	3.0 °C	2.0 °C	1.0 °C
Scenario 1	AG	42%	42%	42%	52%	28%	29%	19%	10%	6%
	EM	4%	6%	1%	1%	0%	4%	1%	0%	0%
	SS	31%	16%	13%	16%	0%	31%	46%	17%	0%
	HU	23%	36%	44%	30%	72%	36%	34%	73%	94%
	Budget needed	296,148	121,885	51,394	42,633	9759	1,032,271	139,013	42,025	8888
Scenario 2	AG		48%	61%	26%	18%		24%	18%	8%
	EM		12%	5%	7%	1%		5%	0%	0%
	SS		27%	13%	39%	0%		41%	41%	0%
	HU		13%	21%	28%	81%		31%	41%	92%
	Budget needed		734,648	209,040	86,658	17,448		240,985	66,536	10,582
Scenario 3	AG			63%	63%	35%		29%	21	9%
	EM			10%	6%	2%		7%	2%	0%
	SS			14%	8%	0%		41%	36%	0%
	HU			13%	23%	62%		23%	42%	91%
	Budget needed			412,808	121,538	26,780		394,181	65,414	11,546

Note: Under scenario 2, it is not possible to attain a 1.25 °C reduction in 20 years, and a 4.0 °C reduction in 40 years. In scenario 3, it is not even possible to decrease water temperatures by 1.0 °C in 20 years.

owners. Under this policy option, reaches in tributaries are the primary target (Fig. 7) because discharge is smaller than the mainstem and the streams are narrower, thus making shading more effective.

On the other hand, Fig. 8 shows the allocation of restoration efforts under the fishery increase criterion (policy option 3) for the same amount of budget (US$100,000) and the same time frame (40 years) as the previous analysis. We find that restoration efforts should be implemented primarily in the UGR mainstem and Sheep Creek.[5] It is important to note that the distribution of restoration efforts in Fig. 8 is quite different from the one in, although the total budget is the same and the time span is the same. This divergence occurs primarily because of the heterogeneity of fish distribution and riparian conditions, as well as the distribution of absolute temperature levels. Comparing Figs. 7 and 8 indicates that it is important to identify the goals of the conservation efforts, i.e. reducing water temperatures vs. increasing juvenile salmonid populations. If the objective is the recovery of salmonid populations, then the fishery benefit should be directly targeted.

[5] In deriving this conclusion, we assume that chinook salmon habitat is limited to the mainstem and Sheep creek even after riparian restoration efforts have been implemented. This assumption is reasonable because there is no model of recolonization of key habitat with the improvements of water temperatures in the basin. Also recolonization of chinook salmon is constrained by discharge levels in tributaries. If the discharge is small, adult chinook salmon will not be able to migrate into the tributary even if water temperatures have been improved. In this case, recolonization will be incomplete.

5. Conclusions

This paper integrates economic, physical, and biological models to explore the efficient allocations of conservation efforts for water quality protection and salmonid population increases in the Grande Ronde basin, Oregon. We focus on the effects of shading due to riparian restoration efforts on water temperatures because water temperatures are one of the primary reasons for impaired water quality, which has led to deterioration of salmonid rearing and spawning

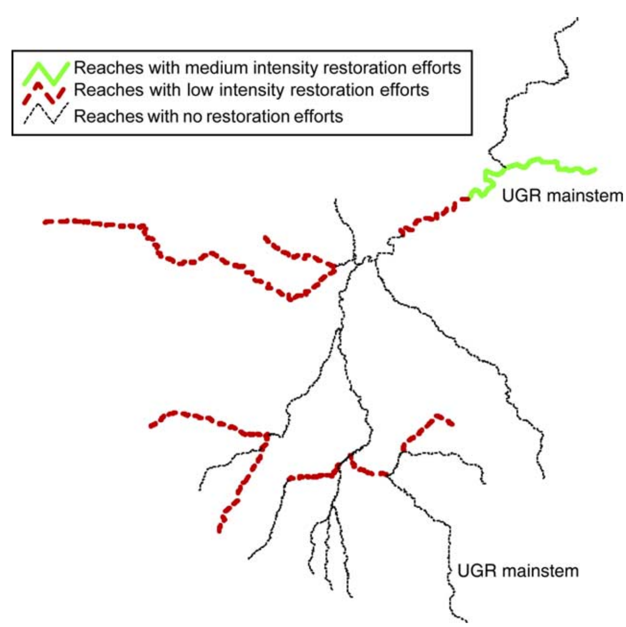

Fig. 7. Restoration sites, by reach, to maximize stream length where water temperature decreases by at least 1 °C with a budget constraint ($100,000).

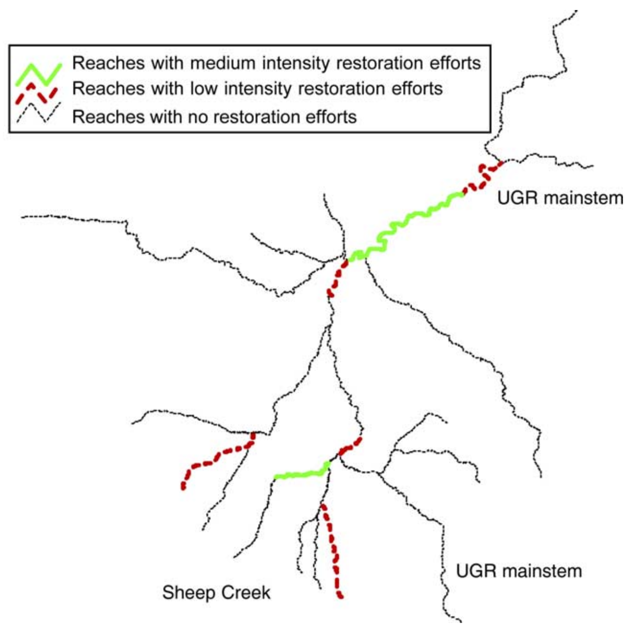

Fig. 8. Restoration sites, by reach, to maximize juvenile chinook salmon populations with a budget constraint ($100,000). Note: Reaches with medium and low intensity restoration sites mean that restoration activities are implemented in between 33 and 67 percent and less than 33 percent of the stream length of potential restoration sites in each reach (AG, EM, SS, and HU).

habitat areas. Through a series of simulation analyses, we examined the effectiveness of alternative conservation efforts. Our results indicate that a riparian buffer wider than 10 m has little effect on water temperatures by means of shading, although there should be ancillary benefits. Stream miles of riparian restoration with a narrow buffer (5 m width) will be increased as the magnitude of temperature reduction increases. With regard to the choice between passive and active restoration, the share of active restoration should be increased as the time span considered decreases and as the magnitude of desired temperature reduction increases. Among vegetation types across restoration sites, herbaceous uplands have the highest potential when the magnitude of temperature reduction is small but the priority vegetation type varies as the magnitude of temperature reduction increases.

It is important to note that these findings largely depend on the relative effectiveness of passive and active restoration. In considering the relative effectiveness of restoration activities, resource managers should consider not only biological aspects such as the kinds of trees to be regenerated but also economic aspects such as the cost of riparian land. In addition, the time frame considered in the restoration efforts and the magnitude of temperature reductions also affect the efficient combinations of restoration activities. Finally, if the objective of conservation efforts is to increase fish populations, then fishery benefits should be directly targeted. Targeting other criterion such as water temperatures would result in different allocations of conservation efforts, and therefore is not efficient.

While this study provides important insights for conservation managers, it can be improved in several aspects. First, as we have stressed in this paper, the relationships between riparian restoration, water temperature, and fish abundance are more complex than those captured by the present model. More complex interactions should be addressed in future research. Second, a more comprehensive study would also consider the effects of riparian restoration on the abundance of other salmonid species such as rainbow trout. It is known that rainbow trout exist in the study basin, but the lack of data on riparian conditions in some tributaries prevents their inclusion in this analysis.

Finally, coldwater patches should be considered in future research. A coldwater patch is defined as a discrete pocket of water more than 3 °C colder than the adjacent ambient stream flow (Ebersole, 2001). Given high ambient water temperatures in the basin, coldwater patches play an important role in determining the populations and the distribution of salmonid species (e.g. Nielsen et al., 1994; and Ebersole, 2001). Coldwater patches are created either by surface tributary or groundwater inflows, and riparian restoration efforts have implications for the frequency of both types of coldwater patches. Incorporating the effects of restoration efforts on coldwater patches in the simulation analyses was not feasible due to the lack of data on patch location. Since they play an important role in defining the abundance and distribution of salmonid species, it is important to collect information on coldwater patches in future research.

Despite these limitations, this modeling approach provides guidance for how restoration efforts might be more efficiently applied to meet specific water temperature and fish abundance objectives. Refinement of model parameters and assumptions with improved information will provide additional insights. Given existing information, and current needs to prioritize restoration actions in an effective and efficient manner, this approach provides a useful first step.

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