AN ABSTRACT OF THE THESIS OF

Luis Francisco Madriñán for the degree of Doctor of Philosophy in Fisheries Science presented on March 31, 2008.
Title: Biophysical Factors Driving the Distribution and Abundance of Redband/Steelhead Trout (*Oncorhynchus mykiss gairdneri)* in the South Fork John Day River Basin, Oregon, USA

Abstract approved:

Hiram W. Li   Guillermo R. Giannico

The overall goal of this study was to identify multiple scales of habitat use and habitat electivity by redband/steelhead trout and define the limiting factors affecting the distribution patterns of this species during summer flows.

The main objective in chapter 2 was to identify the most important habitat associations that control the distribution patterns of threatened populations of redband/steelhead trout in the South Fork John Day River Basin. I found that the factors influencing the distribution patterns of trout in the basin were dependent on the thermal context and spatial extent of analysis. The inclusion of water temperature alone at large spatial scales explained most of the distribution of trout at the basin scale and that channel morphology was a very important factor at small spatial scales.

The main objective in chapter 3 was to identify geophysical factors influencing the distribution pattern of threatened populations of redband/steelhead trout in the basin at multiple spatial scales. I found that the trout distribution patterns in the area could be described as a clustered distribution, with a strong selection for upstream-cold water reaches and small, well oxygenated, running

water pools. My study reveals that the most influential factor at large spatial scales was water temperature and smaller scale channel morphology.

Chapter 4 examines whether longitudinal-summer-stream temperature profiles in semi arid-environment streams can be used to index carrying capacities of threatened populations of redband/steelhead trout. My results show that, in the South Fork John Day Basin, stream temperature can be used as indicator of trout carrying capacity. The distribution redband/steelhead trout in summer is largely determined by the- physiologically influenced-preference that individuals have for habitats within specific temperature ranges.

Biophysical Factors Driving the Distribution and Abundance of Redband/Steelhead trout (O*ncorhynchus mykiss gairdneri*) in the South Fork John Day River Basin, Oregon, USA

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of
Doctor of Philosophy

Presented March 31, 2008

Commencement June 2008

Doctor in Philosophy thesis of Luis Francisco Madriñán presented on March 31, 2008.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Luis Francisco Madriñán, Author

ACKNOWLEDGMENTS

First of all, I would like to thank my major professors, Hiram W. Li and Guillermo Giannico, for giving me the opportunity to be in their lab and for their support and guidance during the course of my doctoral program.

I would like to acknowledge Dr. Stanley Gregory and Dr. Blake Feist for serving on my committee, and Dr. Steven Strauss for serving as my Graduate Council Representative.

I would like to especially thank Michael Newsom and the Bureau of Reclamation (BOR) for their financial support and Chris Jordan (NOAA Fisheries) for his unconditional support and valuable assistance to acquire research funds.

I'm grateful to Jim Ruzycki, Scott Heppell, Peter Bayley, Nick Bowes, Russ Faux and Christian Torgersen for their logistic support and helpful scientific discussions that helped refine the work presented here.

Many people have contributed to this research, but principally I would like to thank the OSU desert basins research group: Seth White, Joseph Feldhaus, Ian Tattam, George Boxall, Jeremiah Osborne-Gowey, for their efforts collecting data, scientific discussions and their unconditional friendship.

I need to give an especial note of acknowledgments to Wayne Wilson, Tim Unterwegner, Jeff Neal and the John Day ODFW office for their logistic support and for helping this project in many different ways.

Also I would like to thank Jim Davis, Jens Lovtang, Virgil Mueller, Josh Togstad, Nick Weber, Jean Philipe Grotogussiat and Matt Webber for their help during the data collection process.

Thanks to all my professors at OSU, Julia Jones, Phil Rossignol, Carl Schrek, Selina Heppell, and to Dan Edge and all the staff at the Department of Fisheries and Wildlife.

But most of all I would like to thank my wife, Claudia F. Bravo for all her support, her encouragement, her energy and her love; without her I couldn't have done it. Thanks Claudia.

CONTRIBUTION OF AUTHORS

Hiram W. Li, and Guillermo Giannico were the principal or co-principal investigators of the research projects that resulted in the manuscripts presented here. Their collective contributions included: assistance with initial development of the research questions, guidance with methodology and interpretation of the results. Blake Feist, Scott Heppell, Seth White and Joseph Feldhaus contributed with field data collection, improvement of the quality of the writing of the chapters 3 and 4.

Russell Faux collaborated with analysis and interpretation of LiDAR and FLIR images presented in chapter 4.

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CHAPTER I

GENERAL INTRODUCTION

In 1965 Hutchinson introduced the concepts of the "Ecological Theatre" (The physical space where organisms are located) and the "Evolutionary play" (the interaction between the organisms and their environment). According to his conceptual model the organisms evolve; they are continually adapting in response to changes in the environment and the environment, being partially influenced by the organisms, reciprocally responds. All these interactions are played on various scales of space and time; therefore, in order to understand the drama unfolding in the ecological play, it is necessary to see it at the appropriate scale. However, until recent years many ecologists conducted studies as if patterns in nature and the processes that produce them were insensitive to differences in scale, and designed their research projects with little explicit attention to scale.

Spatial scales and our ability to detect ecological patterns and processes is a function of both the *extent* and the *grain* of analysis. Extent is the overall area encompassed by a study, and grain is the size of the individual units of observation. Combined, extent and grain define the upper and lower limits of resolution in a study. Any inferences about scale dependency in a system are constrained by both the extent and grain of the investigation. On the one hand, the findings of a study cannot be generalized beyond its extent without the assumption that the observed patterns and processes are scale independent, which is not true (O'Neill 1986). Whereas on the other hand, it is impossible to detect the elements of patterns below the grain. For logistical reasons, expanding the extent of a study usually also entails enlarging its grain. The enhanced ability to detect broad-scale patterns carries the cost of a loss of resolution of fine-scale details (Wiens 1989). However, if very high resolution samples are collected over a large extent it is possible to study large areas while keeping the resolution constant.

Large-scale studies are usually affected by other problems beyond the loss of fine scale resolution. Because of logistical considerations, comparable replicates are limited and collecting data over large spatial extents is difficult. These studies also tend to measure highly integrated "output" variables such as stream flow or total production, which are affected by a host of factors, making it difficult to understand the mechanisms by which changes occur (Lewis et al. 1996). Despite these problems, large-scale comparisons are essential for certain questions, because are able to reveal important relationships between land use and ecological variables.

In the last fifteen years the interest in the effect of scale on a variety of ecological processes has increased as recent reviews addressing scale in aquatic habitats show. For example, Lewis et al. (1996) identified scale as being considered in a large number of fish habitat conservation and restoration programs. Poff (1997), in his review of landscape filters and species traits found that scale dependency is addressed in most studies, including those on salmonids, that examine the effect of environmental constraints on species distribution and abundance.

, Salmonid species are a good model for evaluating the importance of scale because processes affecting their growth, reproduction, survival, and evolution cover a wide range of temporal and spatial scales. Pacific salmon undergo major ontogenetic shifts in behavior and habitat use (Berman and Quinn 1991), are relatively long-lived (2–7 years, depending on the species), occupy a broad geographical range (California to Alaska, and the Kamchatka peninsula to northern Japan), and disperse and migrate over extremely long distances (from hundreds to thousands of kilometers). As a result of this complex life history, a number of important questions about Pacific salmon cannot be adequately addressed without taking spatial scales into consideration. For example, the impacts detected on streams from forestry or agricultural activities will differ with spatial scale. The effects of increased light penetration on in-stream temperature and primary productivity due to canopy opening are likely to be evident at relatively small spatial scales (~500 m) (Li et al. 1994). However, the effects of this same activity on the stream sediment load, channel morphology, and large woody debris location are likely to extend beyond the stream reach where the impact was generated (larger spatial scale) and may take several years following the disturbance event (larger temporal scale) to manifest itself. Moreover, effects at the large scale can also feed back over longer time periods to shape small-scale food web processes through their influences on life cycles and interactions among species (Power et al. 1996)

For these reasons when studying salmonid fish species a basin-wide management approach is needed and an expansion from single or few sites to sites across the range of habitats and conditions in the basin have to be implemented (Folt et al. 1998). Stream fishes (including salmonid species) respond to thermal heterogeneity and require specific ranges to survive and reproduce (Peterson and Rabeni 1996). Stream temperatures typically increase when riparian vegetation is removed through forestry and agriculture, reducing shade cover, causing channel widening and affecting fish populations across the basin (Torgersen 1999).

Steelhead trout east of the Cascade Mountains are considered to be part of the redband trout complex (Behnke 1992) and they are referred to as redband/steelhead trout (*Oncorhynchus mykiss gairdneri*). Although this subspecies can tolerate stream temperatures in excess of 26ºC (Behnke 1992, Zoellick 2004), during summer low flow periods the prevailing high water temperatures east of the Cascades may negatively affect their condition and survival (Filbert and Hawkings 1995). This subspecies is a stock of steelhead from the Mid-Columbia and in 1999 was listed under the Endangered Species Act (ESA) (Federal Registry Office 71FR834) as a threatened Evolutionary Significant Unit. As the John Day Basin fails to meet the 303d criteria for stream temperatures Total Maximum Daily Loads, its, populations of redband/steelhead trout are thought to be limited by elevated stream temperatures.

The John Day River is the largest of the Oregon tributaries to the middle portion of the Columbia River that sustain wild populations of redband/steelhead trout. This basin supports native, naturally reproducing steelhead and sympatric resident redband trout. At this time it is not certain whether these represent reproductively isolated populations or whether they are two phenotypes of the same breeding population of *O. mykiss* (Li et al. 2007). A large number of habitat improvement actions have occurred, or are undergoing in this basin. The effectiveness of these actions, however, remains unclear.

The research presented in this dissertation describes a set of independent models developed to understand how the distribution patterns of redband/steelhead trout in the South Fork of the John Day River are shaped by physical factors (temperature, geomorphology, large wood, etc.) that operate at different spatial scales. The overall goal of this study was to identify multiple scales of habitat use and habitat electivity by redband/steelhead trout and define the limiting factors affecting the distribution patterns of this species. Within this overall goal I proposed the following two objectives first:

1) To define the principal habitat associations for redband/steelhead trout and

2) To determine the spatial extent at which large scale habitat variables (e.g.: water temperature) operate.

These objectives are addressed in chapter 2, where I present an exploratory method using an information theoretic approach derived from the Akaike Information Criteria (AIC). This approach considers the entire range of possible hypothesis that have biological realism and ranks them accordingly to the principle of parsimony. I decided to use this approach instead of traditional parametric statistical methods, because the probability of incurring in a type II error increases with spatial extents and the effects of local heterogeneity are averaged out at larger scales (Wiens 1989). This is due to the increased likelihood of finding highly correlated variables and emergent properties derived from their interactions in a large spatial context. The AIC approach provides a simple way to select the best model from a candidate set of models and doesn't rely on hypothesis testing.

From the results obtained in chapter 2, I derived the following objectives for chapter 3:

3) To determine which factors control the distribution of redband/steelhead trout at the sub-basin, reach and habitat unit scales.

4) To identify redband/steelhead trout habitat preferences during summer base flows.

My prediction was that trout carrying capacity per pool would be higher in stream reaches with lower water temperature than in cooler reaches. In this chapter I examined trout habitat associations with micro-habitat and surrounding landscape features, taking into consideration the physiological responses of trout to temperature and testing for habitat electivity at the habitat unit, reach and tributary scales.

After concluding that water temperature was a critical factor at explaining the distribution patterns of redband/steelhead trout at different spatial scales, I developed the following objectives in chapter 4:

5) To determine if water temperature can be used as a carrying capacity indicator for redband/steelhead trout.

6) To locate the sites with the highest redband/steelhead trout biomass.

7) To identify the factors that contributes to high biomass in those sites during summer base flow.

In order to avoid a biased sampling approach I relied on continuous sampling for my study. Continuous trout distribution patterns where compared to spatially continuous longitudinal stream temperature profiles and physical habitat features across the South fork of the John Day River. Spatial statistical analyses were used to avoid falling into the "ecological fallacy" (Robinson 1950). This fallacy assumes that all members of a group exhibit characteristics of the group at large and the only way to overcome it is to test for spatial autocorrelation and to compare each individual observation to all the other samples available in the data set. I used geo-statistical methods because the individual observations of fish abundance are not normally distributed and are highly heterogeneous. The spatial analysis used in this chapter gives more weight to the data points that are found in the tails of the normal distribution, and can detect anomalies in the data across large landscape extents regardless of how heterogeneous data are.

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CHAPTER 2

A riverscape perspective on habitat associations and distribution patterns of redband/steelhead trout (Oncorhynchus mykiss gairdneri)

Introduction

In recent years the increasing interest in understanding ecological processes at large spatial scales (from ecosystems to basins) contributed to viewing rivers not just as linear features across the landscape but as a multi dimensional combination of biotic and abiotic elements operating at different spatial and temporal scales (Fausch et al. 2002). Stream systems have long been recognized as having a hierarchical spatial structure (Strahler 1964); nevertheless, the understanding of fish distribution patterns across multiple spatial scales is still incomplete.

Predicting which factors will regulate the distribution patterns of stream fishes across the landscape remains a challenge. The definition and identification of the correct temporal and spatial scale of observation and the hierarchical order of factors regulating fish distribution are necessary to predict such patterns (Folt et al, 1998). Scale dependence in patterns and processes that control fish distribution have been long recognized across ecosystems, but current knowledge about the effects of spatial scale on fish distribution patterns is rudimentary and non-quantitave (Feist et al. 2003).

The variables that control fish distribution patterns are regulated by both higher and lower order processes. A higher level regulation (large-scale variables) often affects the manifestation of lower level factors such as a decrease in primary productivity due to dense riparian canopy, water velocity or stream gradient affecting food availability and consequently fish community composition. The interaction among habitat patches may have a lower level regulation (local environmental variables) generating higher complexity and affecting fish assemblage composition, thus, the interaction of variables defined at different spatial scales may result in contextual effects in which the influence of a local environmental variable is contingent upon the level of another, larger scale variable (Deschênes and Rodriguez, 2007). For example, in Japanese streams Inoe et al. (1997) found that at the habitat unit level salmon density was positively related to the abundance of cover; however, at the scale of stream reaches, this relationship was only true when cover was scarce.

During the last 30 years the scientific literature has documented connections between streams and their surrounding landscapes (Hynes 1975, Vannote et al. 1980; Amoros and Roux 1988; Naiman and De´camps 1997, Deschênes and Rodriguez, 2007). The Riverscape Concept (Faush et al. 2002) reflects this by including all the habitat features across the landscape that can be found along rivers the active channel, its floodplain (i.e., area of land regularly covered with water as a result of stream flooding), and riparian areas (i.e., land adjacent to the stream that directly affects the stream; includes woodland, and floodplain) as an integrated ecological unit (Wiens 2002).

The riverscape perspective recognizes the heterogeneous habitat types within the stream corridor as a single, integrated ecological unit operating across spatial scales (Mazeika et al. 2006).

When fish distribution patterns are studied at the Riverscape scale, a problem emerges: microhabitat scales are too small for fish distribution studies because is impossible to detect landscape constraints imposed upon the organisms, and whole catchment scales are impractical because they require too many resources of time, and manpower to study them completely. Faush et al (2002) recommended using a scale that encompasses the needs of all life history stages of the species in question. The challenges however, are that riverscapes are interactive, open systems, characterized by high levels of natural disturbance and interconnected ecotones (Ward 1989; Sullivan et al. 2007), and the identification of environmental gradients that influence population distribution is not an easy task in streams (Rahel and Hubert 1991). Studies in stream fish populations have shown that abiotic factors such as temperature, substrate and discharge can determine the distribution of individual species as well as influence fish community composition (Matthews 1985).

The goal of this study was to identify the most important habitat associations that control the distribution patterns of threatened populations of redband/steelhead trout (*Oncorhynchis mykiss gairdneri*) in the South Fork of the John Day River Basin. This study combined landscape-level ecological analyses with trout distribution patterns in order to uncover hidden attributes and emergent properties associated with these variables.

The objectives of this study were to (1) define the principal habitat associations for redband/steelhead trout, and 2) determine the spatial extent on which large scale habitat variables (e.g.: water temperature) operate. I hypothesized that large spatial scale variables like water temperature are a direct function of the spatial extent and that their importance in shaping trout distribution patterns will decrease from heterogeneous to homogeneous grain.

Methods

Study Area

The John Day River basin has three primary tributaries: the North, Middle, and South forks. The John Day River is the second-longest free-flowing stream in the continental United States, and one of only two river systems in the Columbia River Basin managed exclusively for wild anadromous fish (Behnke 1990).

The South Fork of the John Day River is located in Grant County, Oregon, and flows northward from the Ochoco and Aldrich mountains, entering the mainstem John Day River at Dayville. The South Fork John Day drains an area of approximately 1,637 square kilometers (Leitzinger 1993), and ranges in elevation from 710 to 1,646 meters above sea level. The climate in the region is semi-arid with precipitation ranging from 254 mm to 508 mm per year. Peak precipitation occurs between November and January and comes as snowfall; a secondary peak of precipitation occurs between May and June in the form of rain. The annual average temperature is 10 ºC; the coldest average monthly temperature is 1.1ºC in January, and the warmest is 20.5 ºC in July (DeLorme, 2004, State of Oregon, WRD, 1986).

Within the South Fork John Day River basin, four major tributaries provide spawning habitat for adult summer steelhead. I focused my work on two of these tributaries (Black Canyon Creek and Murderers Creek) and on the mainstem of the South Fork John Day between the town of Dayville and an upstream barrier to anadromous fish, Izee Falls (river kilometer 46.7). Black Canyon Creek flows west to east, draining the Black Canyon Wilderness Area. Murderers Creek flows east to west and its lower section flows through the Murderers Creek Wildlife Preserve (Figure 2.1).

Most of the sub-basin is managed by the Federal Government (United States Forest Service and Bureau of Land Management) and the Oregon Department of Fish and Wildlife. Private lands tend to be concentrated in the lower reaches and above Izee Falls. The two major land cover types are coniferous forest and grassland. Although the area under agriculture is relatively small and limited to the lowermost and uppermost portions of the sub-basin, it is likely to have an important influence on stream temperature because of water withdrawals during summer. Cattle's grazing is the major land use in the system, with lower elevation rangelands characterized by poorer conditions than upland zones (DeLorme, 2004, State of Oregon, WRD, 1986)

Fish and habitat

I classified reaches of the mainstem and the two tributaries based on geomorphologic features (i.e., elevation, channel slope, and aspect) obtained from a 10 m digital elevation map. Reach breaks were delimited based on transitions from valley to canyon and changes in gradient (> 2%), aspect, and elevation. Some of these reaches were further subdivided if FLIR imagery showed they included zones that differed in water temperature by more than 3°C.

Geographic locations of habitat units (pools and riffles) were recorded using a portable Trimble Geoexplorer-3 global positioning system (GPS) with differential correction (accuracy of 10 m).

After the reaches were defined continuous snorkeling surveys were conducted in the summers of 2004 and 2005. The mainstem was surveyed from reach 2 (river km 4) up to Izee Falls (river km 48). Murderers Creek's surveys were only conducted for the lower 18 river km because pools became too shallow for snorkeling above that distance. Black Canyon Creek was surveyed up to the point where the stream gradient was higher than 6º making the type of habitat encountered above this gradient to different from the other streams, thus making it not comparable to the rest of the dataset. A total of 8 river km where surveyed in Black Canyon Creek.

Snorkel surveys were carried out between 09:00 and 17:00 hrs to ensure maximum visibility. The number of days required for these surveys was minimized as much as possible by employing three simultaneous snorkeling crews for a total of 11 days each year. Each two-person crew consisted of one diver and one data recorder. A total of 72 river km (1,285 habitat units) were surveyed between July 5 and July 21, 2005. To estimate snorkeling efficiency, pools were closed to fish migration by placing block nets in both the upstream and downstream riffles immediately adjacent to the pools. Nets were set 2 m into each riffle, thus creating "refuge" zones at both ends of the pools. The snorkeler identified species, assigned size classes, and counted fish as they moved through each pool first in the upstream direction and then, after reaching the head of the pool, back in the downstream direction. Pools were then allowed to rest for 40 minutes to let fish return to their holding and feeding locations. Following this rest period, the snorkeler crawled the pool in a downstream direction, creating maximum disturbance across the width of the pools to "herd" as many fish as possible into a bagged-seine net held in place by two crew members. The position of the bag seine was set downstream of the pool in various locations depending on pool morphology and size. This process was repeated several times until a herding pass yielded no trout. The "refuge" zones on riffles were not sampled so fish could have escape options similar to those available during regular snorkeling surveys without block nets. Captured fish were anesthetized with MS-222. Non-salmonids were identified to species, counted, fin-clipped (caudal fin) and released. All trout were measured (fork length to the nearest 1 mm), weighed (to the nearest 0.1 g), and PIT tagged in the peritoneal cavity (Prentice et al. 1990) or recorded as a recapture if previously tagged. Trout were allowed to recover in a dark, well oxygenated container until they demonstrated the ability to maintain equilibrium. They were then released at the location of capture. A third round of fish capture was initiated after a minimum 60 minute resting period from the time fish were released at the end of the second round. This process consisted of again applying the snorkel-herding method as described above, followed by 2 pass electro-herding with a Smith-Root 12-B POW electrofisher (Vancouver, WA) at "low" settings (300 V, 25Hz, pulse length 200 Wattz) to force fish into a seine net. Based on these data, Bayley et al. (unpublished report) estimated that snorkel capture efficiencies for redband/steelhead trout ranged from 22% to 37%, depending on sampling crew.

Data analyses

Stream habitat information in each habitat unit was collected during the snorkeling surveys. The variables measured were: maximum and tail pool depths, tail, middle and head wetted width, thalweg length, dominant and subdominant substrate, embededdness, number of pieces of large wood, and percentage of undercut banks.

The data analysis was based on the information theoretic method (Burnham and Anderson 1998; Anderson et al. 2000). The construction of a set of ecologically meaningful candidate models was a crucial step in the modeling process applied in this study (Lebreton et al. 1992, Burnham and Anderson 1998).

Explanatory models for the catchment, tributary basins and reaches:

A global linear regression model was developed containing all the physical variables collected during the snorkel surveys at each one of these spatial scales (basin, tributaries and reaches), and a set of *a priori* models was created having selected independent variables thought to be crucial to control the spatial distribution of trout at the channel unit scale. All variables included in the regression models carried an F statistic with $P < 0.05$. Each model generated an Akaike's Information Criterion (AIC) based on the following formula:

$$(1): AIC = n \log [RSS/n] + 2k$$

Where n is the number of observations, log is the natural logarithm, RSS is the residual sum of squares (also called error sum of squares, SSE), and k is the number of estimable variables in the model (Burnham and Anderson 1998).

When $n / k < 40$, it is recommended to use AICc (Hurvich and Tsai's 1989) as a sample adjustment to AIC:

$$(2): AICc=AIC + 2k (k+1)/n-k-1$$

Note that AICc converges to AIC as the number of observations increases relative to the number of estimable variables in a model. In other words, as n increases relative to k in the second term in Eq. 2, the denominator increases relative to the numerator and the whole term approaches zero. For large n / k ratios, the second term essentially drops out, leaving only the AIC term. Hence, AICc can be routinely used in place of

AIC because its adjustment to AIC is necessary for smaller *n* / *k* ratios, whereas it is essentially equivalent to AIC for larger *n* / *k* ratios.

Using the RSS, the model with the lowest AICc was considered the most parsimonious model. Each of the potential models was ranked against the best model (Di = AICc,i - AICc), thus creating the best (Di = 0) and alternate models for each dependent variable. Akaike weights were calculated to indicate the probability that a model was the best among all models in its set:

(3): (wi = exp (Di /2) / *P* [(min, r = 1; max, R) exp (Dr/2)]

I used a correlation analysis to test for highly correlated (r > 0.80) independent variables (Perkins et al. 2003, Mazeika et al. 2007), and avoided using any of these correlated variables in the same model (Burnham and Anderson 2002). At the same time I created an *a priori* hypothesis for each model run and only ran models that had some ecological significance for redband/steelhead trout.

The model with the lowest AIC score (1) best balances goodness-of-fit (small first term) with simplicity (large second term). The balance of these two terms represents the best combination of explanatory power and parsimony when considering the factors controlling the distribution of juvenile redband/steelhead trout (Agresti 1990). This approach was used instead of traditional parametric statistical methods, because the probability of incurring in a type II error rises as large spatial extents increases and the effects of local heterogeneity are averaged out, indicating that no pattern exists when in fact one does (Wiens 1989). This is due to the increased likelihood of finding highly correlated variables and emergent properties derived from their interactions in a large spatial context. The AIC approach provides a simple way to select a best approximating model from a candidate set and doesn't rely on hypothesis testing. When changing the extent of the data analyzed, the AIC approach renders the most likely explanation of which factors control the spatial distribution of redband/steelhead trout at any given spatial scale.

Results

Fish and habitat

The South Fork John Day basin has a very heterogeneous morphology, from wide, meandering low slope stream valleys to narrow, high slope stream channels. However, not all areas in the system were used in the same way by redband/steelhead trout. This species was present in most habitats throughout the surveyed reaches. Young-of-the-year and small parr (65 – 100 mm) were principally associated with the cooler temperatures and higher gradients (> 4º) of the tributary streams, mid-size trout (100 to 200 mm) where present in most of the pools in the entire basin with low densities in the lower reaches of the mainstem, and large trout (>200 mm) where predominantly found at the lower reaches of the mainstem Murderers Creek (Figure 2.2).

Twenty-three distinct reaches were identified using the geomorphologic variables and longitudinal temperature profiles as criteria: 17 for the mainstem, and 3 each for Murderers Creek and Black Canyon Creek. The largest reach was 8.5 km and the shortest 0.78 km.

Data analyses:

The inclusion of highly correlated variables into the same model was avoided. However, only a few pairwise correlations with $r > 0.8$ were found: River km and stream temperature, and middle pool width with head pool width and tail pool width. River km, head and tail pool width where dropped and stream temperature was kept along with middle pool width.

The model selection approach illustrates how the redband/steelhead trout population in the South Fork John Day was related to various habitat characteristics of the riverscape, all the in stream physical variables mentioned in the method section where included.

I found that the best model explaining the distribution patterns of trout at the basin scale was the general model (the model including all the variables considered) being 76 times better than the next available model (Table 2.1). The hypothesis generated for this model was: deep, wide and large pools, with large undercut banks and large boulders and cobles, low embededdness and many pieces of large wood, located in cold water reaches will have the greatest biomass of trout. However, two single variables (embededdness and water temperature) conferred most of the weight. Embededdness was homogeneous across the watershed, only differing significantly in one tributary (Black Canyon Creek). The analysis indicates that water temperature alone was responsible for shaping the distribution of trout at this spatial scale

Nevertheless, to determine the spatial extent at which these variables operate and following the principle of parsimony (Thorburn, 1918). It was necessary to reanalyze the data at smaller spatial scales, thus avoiding emergent properties derived from the interactions of variables at large spatial scales.

Further analyses were performed to characterize 3 streams of the study area (Black Canyon Creek, Murderers Creek and the Mainstem South Fork John Day

River) (Tables 2.2, 2.3 and 2.4). This analysis resulted in the number of variables affecting the distribution of trout being reduced, thus increasing the parsimony on the top linear models. The best explanatory models for each of the streams were characterized by many fewer variables than those at the watershed scale. However, at the tributary scale the models with the best explanatory power did not contain a single variable. In Black Canyon Creek, the best explanatory model included five variables, and the second ranking model relied on all the initial variables included at this spatial scale. Water temperature was present in the top models of the two tributaries but was absent from the top models of the mainstem. The mainstem of the South Fork had homogeneous water temperatures for most of its length, with 92.4% of the pools ranging from 21 ºC to 23ºC, 2.2% below 21 ºC, and 7.6% above 23ºC. Hence, water temperature in the mainstem did not explain much of the observed variation in trout distribution at this scale, but channel morphology did. In Murderers Creek 19% of the pools had water with temperatures below 21 ºC while 32.3% were above 23 ºC. This tributary was less homogeneous than the mainstem with water temperature appearing in the third best model (Table 2.3), and pool area (length width) explaining most of the trout distribution. Finally, 35% of the pools in Black Canyon Creek were below 15 ºC, 25% between 14 ºC and 18 ºC, and 40 % between 18 ºC and 21 ºC, this tributary was the most heterogeneous in the basin and it was dominated by cool and cold water temperatures, in this case water temperature was a persistent factor in all three top models (Table 2.4).

To test if water temperature was a function of the extent considered the analysis was repeated for the two tributaries (Murderers Creek and Black Canyon Creek) using the reach scale (1 to 8 km) (Tables 2.5 and 2.6).

This showed that fine-scale variation in fish distribution masked patterns observed at larger spatial scales. Spatially continuous sampling of stream habitat and fish abundance throughout the network revealed a high degree of spatial variation that was unaccountable at coarser resolutions. The distribution of redband/steelhead trout was strongly correlated with pool area (pool length and width) in most of the reaches across the basin, and water temperature was absent in all the top models as predicted by the hypothesis that water temperature was a direct function of the spatial extent.

Black Canyon Creek showed different patterns compared to the other streams. The top model controlling trout distribution in reach 1 in Black Canyon Creek was a positive relationship with maximum pool depth (M) and a negative relationship with embededdness , and the top model in reach 2 was a combination of pool area and dominant substrate, while the top model in reach 3 included the variables length and maximum depth (Table 2.6).

Discussion

I found that the factors influencing the distribution patterns of trout in the basin were dependent on the thermal context and spatial extent of analysis. The inclusion of water temperature alone at large spatial scales explained most of the distribution of trout at the basin scale and that channel morphology was a very important factor at small spatial scales and decreased in significance at large spatial scales. However, several of these explanatory variables operating at small spatial scales (e.g., pool area, large wood and undercut banks) acted as covariates with water temperature and the interpretation of the results would depend on the spatial scales that are analyzed (Lessard and Hayes 2002, Wiens 1989).

Given the complexity of natural and anthropogenic patterns on the riverscape, it is unlikely that investigation at any single spatial scale will be effective for detecting associations between fish abundance and land-use practices (Fausch et al. 2002). It has also been found that for some species single scale models may not capture the full range of spatial variation in resources to which this species may respond. For mobile animals like trout that range across heterogeneous areas selection models that integrate resources occurring at a number of spatial scales or continuous sampling are recommended (Johnson et al. 2005). Thus, the spatially continuous sampling approach used on this paper provides the flexibility to detect patterns over a range of spatial scales.

Even though it is difficult to identify the upper and lower limits (thresholds) of a given landscape attribute (Cooper et al. 1998), the method used in this study is a useful quantitative approach to uncover the appropriate scale for understanding patterns in freshwater fish species distribution. The appropriate scale is one that provides the most coherent explanation of the phenomena.

One of the advantages of extensive underwater surveys is that the spatial variability on fish distribution patterns and how these relate to several habitat attributes can be evaluated over a range of spatial scales. I found that by using the information theoretic approach based on Akaike Information Criteria it is possible to determine how the effects of local heterogeneity are averaged out at larger spatial scales by changing the extent of the analysis.

The information theoretic approach used on this paper is more useful than traditional parametric methods to detect trout spatial distribution patterns because no null models are rejected or accepted based on fixed alpha levels, but rather all the possible models are evaluated based on the best assumptions. The clear advantage of using AIC over traditional parametric methods is that what would be the statistical hypotheses (both null and alternative) in this approach in traditional test are developed *a priori* as models about relations between the system of interest (Burnham and Anderson 2002). In this case rejecting or failing to reject a null hypothesis has clear implications about how researchers see the existence of diverse patterns under investigation. Committing a type II error would indicate that no pattern exist when in fact one does. This kind of error can be problematic in fisheries science, because this could lead a biologist to conclude that there is not relationship among the variables analyzed and the dependant variable, when in fact there is one. For this reason, identifying what is a meaningful biological effect is perhaps on of the biggest challenges when studying complex systems (Steidl and Thomas 2001).

The use of AICc as described on this paper besides uncovering direct fish-habitat associations also provides additional information related to different land uses and extreme events. For example the top distribution models in Black Canyon Creek reach 1 were dominated by the relationship between pool depth and embeddedness because a wild fire affected reach 2 in the summer of 2003 and by 2004, when the survey was conducted; large quantities of silt have been washed down from reach 2 into reach 1. This also explains why the top models in reach 2 were dominated by larger pools and dominant substrate (large boulders in pools where associated with higher fish abundance). Almost all the riparian cover in this reach was gone with the fire. However, in the reach that wasn't affected by the fire (Reach 3) pool area alone was the top model, as predicted by the original hypothesis for this reach.

One problem of using AIC is that if the analysis is conducted at small scales the results can be misleading due to small sample size and lack of spatial variability. Nonetheless the AIC method will still select the best available set of models, thus reaching false conclusions. By contrast, when the analysis is carried out at large spatial scales the effect of the controlling factors that operate at the riverscape scale will conceal completely the local heterogeneity. For these reasons, this methodology can be used as a framework to build models that can identify causality and the mechanisms behind patterns in nature, testing independently for the effects of single variables at large and small spatial scales.

In conclusion, working at the appropriate scale helps to effectively allocate restoration money and resources in a watershed. However, few restoration efforts are designed within a strategic framework that takes into consideration the constraints of the larger scale upon the smaller one and, as a result, inappropriate actions have been implemented and failed. Most restoration actions in this basin have been assessed at the habitat unit scale for logistic reasons; however, to track their effect successfully both thermal context and spatial extent should be considered. The approach used in this study can at large spatial scales, identify the factors controlling fish distribution across the basin and rank the quality of habitats; whereas, at small scale to find areas that have the greatest restoration potential. The approach used in this study is useful to generate new hypotheses; however, it does not address cause-and-effect relationships that may explain fish distribution patterns. Since I conclude that the relevance of water temperature as an explanatory variable was a function of the spatial extent of the analysis, in the next chapter I used this result as a framework to understand how the different life stages of trout respond to landscape elements as a function of the spatial extent.

Acknowledgments

I would like to thank S. White, I. Tattam, J. Feldhaus, P. Bayley, S. Heppell, J. Davis, B.V. Mueller, J. Togstad, D. Myers, N. Weber, and P. Grotobussiat for assistance collecting data in the South Fork of the John Day. We thank C. Moore of ODFW for providing us a field camp at the Murderers Creek Ranch. This project was funded by the U.S. Bureau of Reclamation, Pacific Northwest Region, through M. Newsom.

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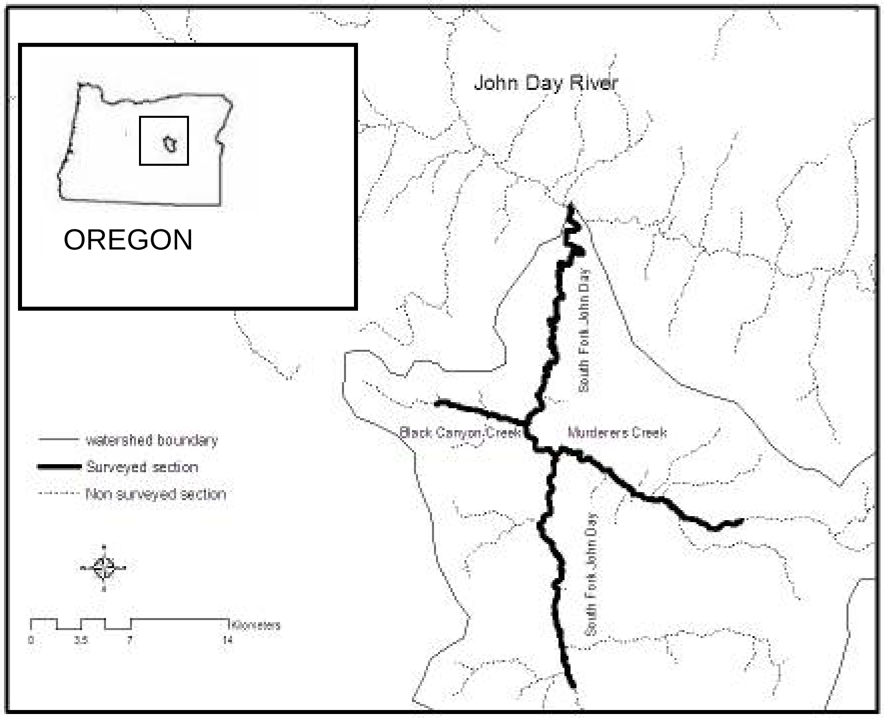

Figure 2.1: Study area: South Fork John Day River basin in Northeastern Oregon, The South Fork John Day River flows from South to North. Sections of the South Fork John Day River that were snorkeled are delineated in a solid black line

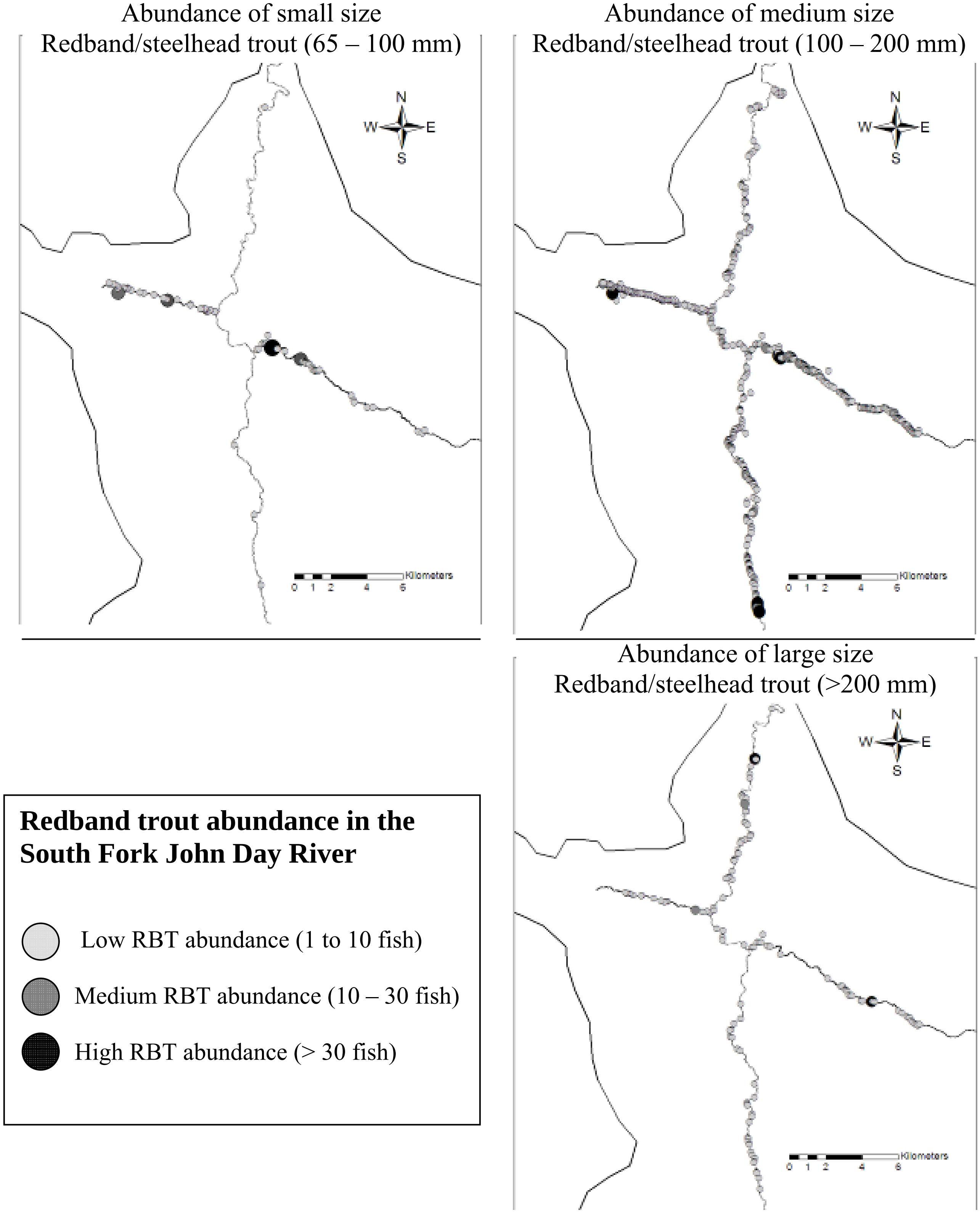

Figure 2.2: Redband/steelhead trout abundance in the South Fork John Day River by size class

Model	AICc	k	Wi	Evidence ratio
U, D, M, E, Lw, L, W, T	2555.039	8	0.68	75.98
(+) (+) (+) (-) (+) (+) (+) (-)				
U, D, M, Lw, L, W	2563.7	7	0.009	39.42
U, D, M, L, W	2571.04	6	0.0002	

Table 2.1: Model selection at the watershed scale. Independent variables are presented in columns labeled model. AICc = the spell out for small samples. K = the number of variables for each model. Wi= weight of the model compared to the other candidate models. Evidence ratio = indicates how many times a particular model is better than the next model in the set of candidate models. U = Undercut bank; D = Dominant substrate; M = Max. Pool depth; E = Embeddedness; Lw = Large woody debris; L = Pool Length; W = pool width; T = Water temperature. The sign (+ or -) in the top model indicates positive or negative correlations.

Model	AICc	k	Wi	Evidence ratio
W, M, D	516.45	4	0.50	54.20
(+) (+) (+)				
W, M, D, E	516.70	5	0.42	57.14
W, M	522.15	3	0.02	

Table 2.2: Model selection for the mainstem. Independent variables are presented in columns labeled model. AICc = the spell out for small samples. K = the number of variables for each model. Wi= weight of the model compared to the other candidate models. Evidence ratio = indicates how many times a particular model is better than the next model in the set of candidate models. D = Dominant substrate; M = Max. Pool depth; E = Embeddedness and W = pool width. The sign (+ or -) in the top model indicates positive or negative correlations.

Model	AICc	k	Wi	Evidence ratio
L , W , U	1433.33	4	0.78	6.10
(+) (+) (+)				
L, U	1436.95	3	0.12	2.25
L, U, T	1438.58	4	0.05	

Table 2.3: Model selection for Murderers Creek. Independent variables are presented in columns labeled model. AICc = the spell out for small samples. K = the number of variables for each model. Wi= weight of the model compared to the other candidate models. Evidence ratio = indicates how many times a particular model is better than the next model in the set of candidate models. Where U = Undercut bank; L = Pool Length; W = Pool width; and T = Water temperature. The sign (+ or -) in the top model indicates positive or negative correlations.

Model	AICc	k	Wi	Evidence ratio
L, M, D, E, T (+) (+) (+) (-) (-)	550.84	6	0.58	3.41
L, M, D, Lw, U, E, T	553.29	8	0.17	1.31
L, M, T	553.83	4	0.13	

Table 2.4: Model selection for Black Canyon Creek. Independent variables are presented in columns labeled model. AICc = the spell out for small samples. K = the number of variables for each model. Wi= weight of the model compared to the other candidate models. Evidence ratio = indicates how many times a particular model is better than the next model in the set of candidate models. U = Undercut bank; D = Dominant substrate; M = Max. Pool depth; E = Embeddedness; Lw = Large woody debris; L = Pool Length and T = Water temperature. The sign (+ or -) in the top model indicates positive or negative correlations.

Reach	**Model**	**AICc**	**k**	**Wi**	**Evidence ratio**
1	L (+)	209.69	2	0.68	1.83
1	L, D	210.91	3	0.37	1.45
1	L, W	211.66	3	0.25	1.00
1	L, M	211.67	3	0.25	1.07
2	L, W (+) (+)	889.35	3	0.68	1.06
2	L	889.48	2	0.64	1.28
2	L, M, W	889.98	4	0.49	1.76
2	L, M	891.12	3	0.28	1.06
3	W (+)	316.56	2	0.68	1.19
3	L, W	316.91	3	0.57	2.17
3	L, M, W	318.47	4	0.26	1.04
3	M, W	318.56	3	0.25	2.67

Table 2.5: Model selection for Murderers Creek reaches. Independent variables are presented in columns labeled model. AICc = the spell out for small samples. K = the number of variables for each model. Wi= weight of the model compared to the other candidate models. Evidence ratio = indicates how many times a particular model is better than the next model in the set of candidate models. U = Undercut bank; D = Dominant substrate; M = Max. Pool depth; E = Embeddedness; Lw = Large woody debris; L = Pool Length; W = Pool width; and T = Water temperature. The sign (+ or -) in the top model indicates positive or negative correlations.

Reach	**Model**	**AICc**	**k**	**Wi**	**Evidence ratio**
1	M, E (+)(-)	269.01	3	0.68	1.20
1	L, M, E	269.38	4	0.56	1.37
1	M, E, D	270	4	0.41	1.22
1	M	270.4	2	0.34	1.2
2	M, D, L(+)(+)(+)	259.46	4	0.68	2.33
2	M, D	261.15	3	0.29	1.89
2	D, L	262.42	3	0.15	1.3
2	D	262.94	2	0.12	1.04
3	L, M(+)(+)	187.31	3	0.68	2.06
3	M	188.76	2	0.33	1.26
3	L, M, E	189.23	4	0.26	1.48
3	L, M, E, W, D	190.02	6	0.17	1.44

Table 2.6: Model selection for Black Canyon Creek reaches. Independent variables are presented in columns labeled model. AICc = the spell out for small samples. K = the number of variables for each model. Wi= weight of the model compared to the other candidate models. Evidence ratio = indicates how many times a particular model is better than the next model in the set of candidate models. U = Undercut bank; D = Dominant substrate; M = Max. Pool depth; E = Embeddedness; Lw = Large woody debris; L = Pool Length; W = Pool width; and T = Water temperature. The sign (+ or -) in the top model indicates positive or negative correlations.

CHAPTER 3

A Multi-scale Spatial Analysis of Factors Affecting the Distribution of Redband/steelhead Trout (Oncorhynchus mykiss gairdneri) in The South Fork John Day River, Oregon

Introduction:

The study of fish species in stream systems is inherently a difficult task. Most of the actual knowledge on river and fish ecology and the best empirical understanding of ecological processes and patterns in fish distribution and behavior have been collected at fine scales (Urban 2005, Fausch et al. 2002, Levin 1992); however, management decisions and environmental policy need to be developed for large scales, and the mismatch of scales makes restoration and conservation efforts very hard to apply.

Several studies in stream ecology (e.g. Fausch et al. 2002; Cummins 1974) have recognized that streams are strongly influenced by the surrounding landscape in which they flow. It is generally believed that fish assemblage structure will change in a predictable way from the headwaters to downstream reaches following a geomorphologic and temperature gradient in which cold water species are replaced by cool and warm water species (Torgersen et al. 2006, Rahel and Hubert 1991, Li et al. 1987, Vannote et al. 1980). However, there is a very limited understanding of spatial heterogeneity of fish distribution in relation to biotic zones and the effects of spatial scale on observed fish assemblages (Torgersen 2006, Faush et al. 2002). Physical habitat has an enormous influence on stream fish communities. However, it is difficult to establish explicit links between the abundance, distribution or population status of a species and habitat attributes, due to the lack of contiguous fish presence data across large extents of stream systems (Feist et al. 2003).

It is difficult to link habitat attributes to fish distribution when examined only at one spatial scale because patterns of association change depending upon the scale of observation. What is important at one scale may not be at another (Cooper et al. 1998). Scale dependence in patterns and processes that control fish distribution have been long recognized across ecological systems, but the current understanding of the effects of spatial scale o fish distribution patterns is rudimentary and non-quantitave (Feist et al. 2003). The importance of identifying the most useful scale for ecological inquiry is self evident; yet, relatively few studies deal with analyses at multiple spatial scales (Feist et al. 2003, Labee and Fausch 2000, Torgersen et al 1999). For these reasons "scaling" (i.e., the explicit extrapolation of details at fine grain and small extent, to their implications over larger extent and generally coarser resolution) is one of the main challenges that fish ecologist are facing today (Urban 2005). Although the scale dependence of ecological patterns and processes is recognized by freshwater ecologist many questions remain unanswered: how and why do observed patterns change with scale? To what degree can the results from small scale experiments be extrapolated to whole systems? And how are small scale processes integrated to produce large scale patterns?

To link population abundance and distribution patterns at the landscape level it is necessary to understand which forming factors are important for habitat attributes at different spatial scales. It has been recognized that attributes at the habitat unit scale are greatly influenced by local factors such as in-stream structures and hydraulic conditions at bankfull stage, large woody debris, and individual manmade structures, that will determine the habitat preferences of fish species (Frissel et al. 2005, Hawkings et al. 1993). At the reach scale (1 to 8 km), these attributes are likely defined and controlled by differences in mass movement inputs, bounding landform, bank material, and riparian vegetation; and at the tributary scale habitat attributes are shaped by climate, natural vegetation, geology and other soil forming factors (McDowell, 2001). In the long run, the interactions of this forming factors control the physiological performance of fish and their community interactions. The identification of all the components of stream habitat is essential to accurately assess environmental change, understand ecological segregation or determine stream enhancing projects (Bisson et al. 1982).

The objective of this study was to identify geophysical factors influencing the distribution pattern of threatened populations of redband/steelhead trout (*Oncorhynchis mykiss gairdneri*) in the mid-Columbia Basin at multiple spatial scales. This study combined landscape-level ecological analyses with trout distribution patterns and physiological information.

The specific objectives of this study were: 1) to determine which factors control the distribution of redband/steelhead trout at the sub-basin, reach and habitat unit scales, and 2) to identify redband/steelhead trout habitat preferences during summer base low flow. This approach used continuous sampling of trout, their micro-habitats, surrounding landscape features, and longitudinal-water temperature profiles, and subsequently analyzed the data at different spatial scales (i.e., habitat unit, reach, tributary). The criteria for these scales are presented in the methods section.

Based on the work of Kaeding (1996) and Nielsen (1994) I developed the working hypothesis that at cold water temperatures (< 18 C) an increase in pool area would be positively correlated with an increase in redband/steelhead trout biomass.

Methods:

Study Area

The John Day River basin has three primary tributaries: the North, Middle, and South forks. The John Day River is the second-longest free-flowing stream in the continental United States, and one of only two river systems in the Columbia River Basin managed exclusively for wild anadromous fish (Behnke 1990).

The South Fork of the John Day River is located in Grant County, Oregon, and flows northward from the Ochoco and Aldrich mountains, entering the mainstem John Day River at Dayville. The South Fork John Day drains an area of approximately 1,637 square kilometers (Leitzinger 1993), and ranges in elevation from 710 to 1,646 meters above sea level. The climate in the region is semi-arid with precipitation ranging from 254 mm to 508 mm per year. Peak precipitation occurs between November and January and comes as snowfall; a secondary peak of precipitation occurs between May and June in the form of rain. The annual average temperature is 10 ºC; the coldest average monthly temperature is 1.1ºC in January, and the warmest is 20.5 ºC in July (DeLorme, 2004, State of Oregon, WRD, 1986).

Within the South Fork John Day River basin, four major tributaries provide spawning habitat for adult summer steelhead. I focused my work on two of these tributaries (Black Canyon Creek and Murderers Creek) and on the mainstem of the South Fork John Day between the town of Dayville and an upstream barrier to anadromous fish, Izee Falls (river kilometer 46.7). Black Canyon Creek flows west to east, draining the Black Canyon Wilderness Area. Murderers Creek flows east to west and its lower section flows through the Murderers Creek Wildlife Preserve (Figure 3.1).

Most of the sub-basin is managed by the Federal Government (United States Forest Service and Bureau of Land Management) and the Oregon Department of Fish and Wildlife. Private lands tend to be concentrated in the lower reaches and above Izee Falls. The two major land cover types are coniferous forest and grassland. Although the area under agriculture is relatively small and limited to the lowermost and uppermost portions of the sub-basin, it is likely to have an important influence on stream temperature because of water withdrawals during summer. Cattle grazing is the major land use in the system, with lower elevation rangelands characterized by poorer conditions than upland zones (DeLorme, 2004, State of Oregon, WRD, 1986)

Stream temperature

I used forward-looking infrared (FLIR) imagery to map the longitudinal stream temperature profiles. The FLIR was flown when stream flows were at base level in late summer 2003 (August 20) over the main stem of the South Fork John Day River and in early autumn 2004 (September 12) over the mainstem as well as over Black Canyon Creek and Murderers Creek. This technology relies on thermal infrared sensors that measure the infrared energy reflected by the water surface. The sensors can accurately measure stream temperatures for the water column when it is thoroughly mixed, thus providing a contiguous snapshot of the stream's longitudinal distribution of temperature (Torgersen et al. 1999). I assumed my system had a mixed water column because average depth of the study streams did not exceed 1 m. Information from two analyses of thermal imagery (i.e., 2003 and 2004) were used to help detect warm and cold water sources , such as tributary junctions and flood irrigation canals. We used Oregon Water Resources Department gauging station discharge and water temperature data from Murderers Creek Station (UTM (Universal Transverse Mercator) = 11T 297905mE, 4910076mN; elevation = 908 meters, stream kilometer 0.6), and South Fork John Day River Station upstream of Izee Falls (UTM = 11T 300646mE, 4888621mN; elevation = 1198 meters) to calibrate the FLIR information with stream discharge levels.

Optic Stowaway temperature loggers (HOBO®) were used to "ground truth FLIR images and to capture temporal dynamics of stream temperature. To assess the accuracy of the FLIR, maximum water temperature data from the HOBO loggers were averaged for the seven day period immediately prior to the aerial survey and compared to the maximum water temperatures recorded through thermal imagery for the nodes at which the temperature loggers were placed. Water temperature was recorded on an hourly basis from early June to late September during both 2003 and 2004 using. 18 loggers were placed at the locations where FLIR imagery detected the biggest changes in stream water temperatures.

It was assumed that maximum daily stream temperatures were the most relevant measure of temperature for this study because they have been show to strongly influence trout distribution patterns (Ebersole et al. 2003, Gowan and Faush, 2002). The physiological reason is that stream temperatures above 22-23^{o} C induce protein deformation (Feldhaus 2006) and death can result due to cumulative exposure. In other words, the physiological response to exposure to temperatures above the Upper Incipient Lethal Temperature (UILT) is dose dependent.

GIS analysis and reach classification

I classified reaches of the mainstem and the two tributaries based on geomorphologic features (i.e., elevation, channel slope, and aspect) obtained from a 10 m digital elevation map. Reach breaks were delimited when an important change in the geomorphologic features was encountered (i.e., change from valley to canyon, change in gradient > 2%, change in aspect, and change in elevation). Some of these reaches were further subdivided if FLIR imagery showed they included zones that differed in water temperature by more than 3° C.

Geographic locations of habitat units (pools and riffles) were recorded using a portable Trimble Geoexplorer-3 global positioning system (GPS) with differential correction (accuracy of 10 m).

Average maximum reach temperature was used to assign reaches into four habitat categories based on the physiological index for trout condition proposed by Feldhaus (2006) for the South Fork John Day Basin. This index relies on the temperature-induced expression of heat shock proteins (specifically Hsp70) in selected fish tissues to determine physiological stress levels. The four habitat categories thus established were: optimal (<18.0º C), suboptimal (18.1 to 21.0º C), marginal (21.1 to 23.0° C), and poor (>23° C).

Fish and habitat

Contiguous snorkeling surveys were conducted in the summers of 2004 and 2005. The main stem of the South Fork John Day River was surveyed from reach 2 (river km 4) up to Izee Falls (river km 48). Murderers Creek's surveys were only conducted for the lower 18 river km because pools became too shallow for snorkeling above that. Black Canyon Creek was surveyed up to the point where the stream gradient was higher than 6º, for a total survey of 8 river km.

Snorkel surveys were carried out between 09:00 and 17:00 hrs to ensure maximum visibility. The number of days required for these surveys was minimized as much as possible by simultaneously employing three snorkeling crews for a total of 11 days. Each two-person crew consisted of one diver and one data recorder. A total of 72 river km (1285 habitat units) were surveyed between July 5 and July 21, 2005.

To estimate snorkeling efficiency, pools were closed to fish migration by placing block nets in both the upstream and downstream riffles immediately adjacent to the pools. Nets were set 2 m into each riffle, thus creating "refuge" zones at both ends of the pools. The snorkeler identified species, assigned size classes, and counted fish as they moved through each pool first in the upstream direction and then, after reaching the head of the pool, back in the downstream direction. Pools were then allowed to rest for 40 minutes to let fish return to their holding and feeding locations. Following this rest period, the snorkeler crawled the pool in a downstream direction, creating maximum disturbance across the width of the pools to "herd" as many fish as possible into a bagged-seine net held in place by two crew members. The position of the bag seine was set downstream of the pool in various locations depending on pool morphology and size. This process was repeated several times until a herding pass yielded no trout. The "refuge" zones on riffles were not sampled so fish could have escape options similar to those available during regular snorkeling surveys without block nets. Captured fish were anesthetized with MS-222. Non-salmonids were identified to species, counted, fin-clipped (caudal fin) and released. All trout were measured (fork length to the nearest 1 mm), weighed (to the nearest 0.1 g), and PIT tagged in the peritoneal cavity (Prentice et al. 1990) or recorded as a recapture if previously tagged. Trout were allowed to recover in a dark, well oxygenated container until they demonstrated the ability to maintain equilibrium. They were then released at the location of capture. A third round of fish capture was initiated after a minimum 60 minute resting period from the time fish were released at the end of the second round. This process consisted of again applying the snorkel-herding method as described above, followed by 2 pass electro-herding with a Smith-Root 12-B POW electrofisher (Vancouver, WA) at “low” settings (300 V, 25Hz, pulse length 200 Wattz) to force fish into a seine net. Based on these data, Bayley et al. (unpublished report) estimated that snorkel capture efficiencies for redband/steelhead trout ranged from 22% to 37%, depending on sampling crew.

Spatial scale and habitat classification

Tributary scale: Trout abundance and pool area where used to calculate trout density and biomass in each of the tributaries (Black Canyon Creek and Murderers Creek) and in the mainstem of the South Fork John Day River. To estimate the average biomass of trout, weight data from 1,340 pit tagged individuals was averaged by size class. These data in combination with trout numbers per size class and with pool areas were used to determine biomass per unit area (Tattam 2006).

Reach scale: I classified reaches (valley segments) of the main stem and the two tributaries based on geomorphologic features (i.e., elevation, channel slope, and aspect) obtained from a 10 m digital elevation map. The reach breaks were delimited when an important change in the geomorphologic features was encountered (i.e., change from valley to canyon, strong change in gradient, etc.). Some of these reaches were further subdivided if FLIR imagery showed they included zones that differed in water temperature by more than 3°C.

Habitat unit: To separate the influence of water temperature from other factors associated with channel morphology, we classified all the units in the basin into 5 different types using Bisson's et al. (1982) habitat unit classification during summer low flows:

-*Pocket pools:* Found along channel margins, principally caused by eddies behind pieces of large wood or boulders. This pool type has a maximum depth of 40 cm in average and tends to be dominated by fine grain substrate, with low current velocity (Pool area between 1.3 to 11 m^2, length between 3 to 8 m).

-*Trench pools:* Found in deep slots in stable substrate, this type of pool is long and the channel cross sectional area is usually U-shaped. They have swift and mostly uniform flow direction (Area of surveyed pools between 2.6 to 12 m^2, length between 8 to 10 m).

-*Plunge pools:* Pools created when the stream passes over a complete or nearly complete channel obstruction and dropped vertically into the stream bellow, scouring a depression. This pools are usually deep (>1m) with highly variable substrate composition (Area of surveyed pools between 4.6 to 18 m^2, length between 10 to 14 m).

-*Lateral scour pools:* Pools created where the flow is directed to one side of the stream by a partial channel obstruction, usually long and with average depth of 80 cm (Area of surveyed pools between 6 to 42 m^2, length between 15 to 22 m).

-*Glides:* is a habitat type with characteristics of a riffle and a pool defined by shallow water and an even flow that lacked pronounced turbulence (Area of surveyed pools between 15 to 160 m^2, length between 22 to 84 m).

Physiological response of trout and habitat classification:

Once the reach breaks were determined, we used Feldhaus' (2006) classification of heat shock protein induction under different temperatures as a basis for a physiological classification of habitat. Heat shock proteins appear to reinforce protein structure when it begins to deform under heat stress (Feldhaus, 2006). Based on these findings, I reclassified habitats at the reach and habitat unit scales into 4 major classes: Optimal (<18 °C), Suboptimal (18.1 to 21 °C), marginal (22.1 to 23 °C) and poor (>23 °C). GIS analysis allowed us to quantify each class by amount, proportion and by location.

Testing for habitat electivity:

In order to quantify habitat utilization by redband/steelhead trout it was necessary to relate the fraction of the population found within a particular habitat unit type to the relative abundance of that habitat unit in the stream. The following terms where defined: The *abundance* of a habitat type is the quantity of that habitat type in the environment, as defined independently of the user (redband/steelhead trout). The *availability* of that habitat type is its accessibility to the user (Johnson 1980).

To measure habitat electivity we used the method proposed by Johnson (1980) in which a measure of preference is calculated using the difference between the rank of usage and the rank of availability of different habitat types. Averages for different habitat types can then be compared to determine which are more preferred. The different habitat types in the basin were ordered by the average differences, and where ranked from least elected to most.

In order to understand the differences between the different life stages of redband/steelhead trout we run Johnson's electivity analysis with small (65 – 100 mm) and large (> 200 mm) trout, to see if these life stages were selecting habitat in a different way

Results

Stream temperature

The longitudinal temperature profile maps revealed that the thermal environment of the South Fork John Day was spatially heterogeneous during both study years (2003 and 2004); however, it was dominated by temperatures between 22 and 23°C, with isolated patches of relatively cooler (18 – 21°C) and warmer (>23°C) water.

GIS analysis and Reach classification

Reach classification resulted in 17 reaches for the main stem of the South Fork John Day River, and 3 reaches each in Murderers Creek and Black Canyon Creek (Figure 3.2). The largest reach was 8.5 km and the shortest 0.78 km. The combination of FLIR profiles and thermal imagery mosaics facilitated the detection of patterns in stream temperatures at reach and habitat-unit spatial scales across the entire basin. The resulting habitat classification showed that 3.6 % of the South Fork John Day River area was considered physiologically optimal (<18°C), 14% was suboptimal

(18 to 21°C), 25.4% was marginal (21.1 to 23°C) and 51.9% was unsuitable (>23°C) for redband/steelhead trout.

Fish and habitat::

Tributary scale:

The South Fork John Day basin has a very heterogeneous morphology, from wide, meandering low slope stream valleys to narrow, high slope stream channels. However, not all areas in the system were used in the same way by redband/steelhead trout, from my data analysis it is evident that the availability of pool habitat surpasses its usage (Figure 3.2 A and B).

Redband/steelhead trout biomass per pool ranged from 24.2 g/m^2 in the optimal habitat category to 1.71 g/m^2 in the poor habitat category. It was estimated that 68% of the trout biomass was concentrated in 7.4% of the total area in a single tributary (Black Canyon Creek). This tributary is characterized by two main attributes, its cold water temperature from 13 to 20 ºC and its high gradient from 3.2º to 5.7º. Murderers Creek has nearly 30% of the pool habitat available in the system but it only contains 18% of the total trout biomass. Water temperature in this tributary ranges from 20 to 24º C, and stream gradient from < 1º to 1.5º. Finally, the main stem of the South Fork John Day contains nearly 64% of the total pool habitat available in the basin, however it supports only 14% of the total trout biomass (Figure 3.2 A and B). This stream is the warmest in the basin, ranging from 19 to 25 ºC and with an overall stream gradient < than 1º.

Reach scale:

Observations of the distributions patterns of RBT suggested that temperature plays a major role in controlling trout carrying capacity. In the optimal category (<18 ºC) I found a significant relationship between trout biomass and pool area (Figure 3.3A) in which a continuous increase in biomass was observed with an increase in pool area. This same relationship was observed for the suboptimal category (18 – 21 ºC) (Figure 3.3B), but the slope of the regression of fish abundance on pool area was less than steep that in stream reaches <18 ºC. In stream reaches classified as marginal or poor, pool area was not correlated with trout biomass (Figure 3.3 C, D).

With these findings at the reach scale it was evident that trout biomass in the pools with optimal water temperature had a very strong linear relationship with pool area, however in all other categories the individual habitat units presented a great deal of variation in trout biomass compared to their pool areas.

Habitat unit scale:

The Johnson's electivity analysis showed that redband/steelhead trout were principally associated with small pools, and were highly correlated with maximum depths between 40 cm to 80 cm and with fine grain substrate (pebbles and gravels), 49% of trout were associated with habitat units with surface areas between 1.3 to 12 m^2, and thalweg lengths between 3 to 10 m (Figure 3.4). Even though pocket and trench pools were scarce in the basin, trout seems to utilize this type of habitat out of proportion to their relative abundance during summer low flows. Lateral scour were used accordingly to their availability, plunge pools were elected in a lesser proportion to their availability and glides were negatively elected in all cases (Table 3.1).

I found that small trout seemed to prefer pocket pools as their habitat of choice, but used lateral scour and trench pools in a lesser proportion as well, but as in the previous analysis this life stage negatively selected glides. Finally for large RBT, we also observed that they favored pocket pools but to a lesser degree, and that they use all the other habitats accordingly to their availability, but negatively elected plunge pools.

Finally, when the different types of habitat units where compared with the physiological classification of reaches it was determined that 96% and 46% of the pools at the optimal and suboptimal temperatures respectively where pocket pools. However, at the marginal and poor temperature categories all pool types where equally represented and pocket pools didn't show higher trout biomass than other pool types (Figure 3.5).

Discussion

Based on my observations the distribution patterns in the three study streams could be described as a clustered distribution, with a strong selection for upstream-cold water reaches and small, well oxygenated, running water pools. The expression of habitat electivity along the longitudinal stream gradient will vary depending upon the scale of observation. My study reveals that the most influential factor at large spatial scales was water temperature. Several studies have shown that maximum stream temperature is negatively associated with redband/steelhead trout density (Li et al. 1994, Ebersole et al. 2003). My results indicate that water temperature plays a very important role controlling the distribution of trout in the basin. This is made evident by the fact that although only 17.6% of the basin area falls in the optimal or suboptimal water temperature categories, nearly 70% of the trout biomass is found in it.

Trout habitat choice will vary with age or size class. Roper et al. (1994) found in the south Umpqua River, Oregon, that age-1 and older trout were most abundant in the middle reaches; whereas young-of-the-year individuals were predominant in the headwaters. This pattern has been observed in other salmonid species as well. Stain et al. (1972) documented in Sixes River, Oregon, a change in habitat preferences during summer months by coho salmon overlapped in timing and location chinook salmon distribution patterns. During the early spring both species were distributed throughout most of the river system, however once water temperature increased coho avoided the mainstem of the river, and moved into the cooler tributaries

In the South Fork John Day River redband/steelhead trout seems to follows the same pattern than coho salmon in Sixes River, Oregon. Large individuals (150-250 mm) were found at the highest densities in the middle and lower reaches of the main stem associated with marginal water temperature pools. Medium-size individuals (100 – 150 mm) showed a relatively uniform distribution over the entire system and across all habitat unit types (optimal to poor). Whereas small trout were only present in the tributaries and mostly associated with optimal water temperature pools. These findings do not necessarily imply that larger trout prefer warmer water, but that trout distribution is affected by factors other than water operating at different spatial scales.

At smaller spatial scales, we observed that redband/steelhead trout were strongly associated with smaller (pocket and trench) pools. These habitat types are usually found in upstream reaches that have abundant overhanging riparian vegetation.

Recent work has revealed that terrestrial invertebrates may strongly influence trout and other salmonids (Nakano, Miyasaka & Kuhara, 1999; Allan, et al. 2003). Salmonids usually feed on drifting larval aquatic and terrestrial insects that fall into the water surface (Newman 1987). The lower reaches of the South Fork John Day River contain a large number of glides and lateral scour pools that have a limited amount of riparian vegetation limiting the terrestrial inputs, thus, trout competes for aquatic invertebrates with other fish species.

However, it is important to point out that fish strong preference for pocket pools may be due to the fact that most of these pools where located in cold water reaches (optimal and suboptimal water categories). In warmer water reaches trout numbers were not larger in pocket pools than in other pool types.

Distribution patterns of redband/steelhead trout in relation to habitat heterogeneity at different spatial scales is poorly understood (Fausch et al. 2002). Most fishes in small streams are habitat specialist and utilize specific locations of the stream (Gorman and Karr 1978). For salmonids in general, competition plays a very important role in habitat utilization when food is the limiting factor. Competition thus, determines density dependant interactions that result in habitat partitioning and coexistence of several fish species and multiple age classes (Bisson et al. 1982). Water temperature can significantly limit the carrying capacity for salmonids, and temperature is driven in large part by landscape-scale features. Longitudinal-summer-stream thermal profiles could be used to link stream condition and carrying capacity to landscape attributes (Torgersen 1999).

However it has been difficult to test these findings due to the fact that in field studies and laboratory trials, the number of samples used to evaluate these relationships is too small (Torgersen et al. 2006). In this study, this problem was overcome by collecting a large number of samples in a continuous manner, covering all the possible habitat units available in the study area; by doing so, it was possible to identify the effect of spatial scale. In addition, a compilation of the spatial heterogeneity of habitat types helped to avoid small spatial scale bias towards a particular habitat type (Cooper et al. 1998).

In this study I consistently found that a combination of different factors (e.g. elevation, gradient, pool type) interacting at several spatial scales (basin, reach and habitat unit) resulted in emergent properties that shaped the distribution of redband/steelhead trout in the South Fork of the John Day. These properties of which water temperature is a prime example are unlike their isolated components and cannot be reduced to their sum or their difference (Morowitz, 2002, Lewes 1875).
Detailed studies of the spatial distribution of fishes within entire basins (10–100 km) are useful for evaluating how fish–habitat relationships change across scales and in different spatial contexts (Fausch et al. 1994). However, there are large logistical constraints to sampling large river segments, particularly when this sampling needs to be conducted in short periods of time. At the same time investigations of the effects of scale on observed patterns of species diversity and distribution are less common (Wilson et al. 1999). The value of this analysis is reflected in that the resolution of its data and the extent to which it can be applied to explain distribution patterns of fish under natural conditions, allowing to conduct spatial analysis while varying the spatial

dimensions of the data set. The importance of a continuous sampling strategy is fundamental to understanding the distribution patterns of this species where the relative roles of temperature and channel morphology are known to change as the spatial extent and location in the drainage are altered (Matthews 1998).

My study has important implications for salmonid restoration projects because it emphasizes on the importance of multi-scale sampling so that patterns can be examined at different spatial scales, and considers changes in the habitat types occupied by different life stages of trout. An application of this type of study at large spatial scale would be to partition the biomass supported within the basin by temperature classes, and then predict how much biomass might increase as a result of restoration activities that reduce water temperature. At the same time is possible to use for small scale restoration projects, where habitat units can be engineered to fit habitat preferences of a particular trout size class – age group, and identifies which areas have the biggest restoration potential. The results from these analyses could be very informative for managers, because they would partition the system into several compartments (higher to lower priority) accelerating the decision making process and resource allocation towards restoration. This study found that a physiologically based model is consistent throughout several spatial scales.

Acknowledgments

I would like to thank S. White, I. Tattam, J. Feldhaus, P. Bayley, S. Heppell, J. Davis, B.V. Mueller, J. Togstad, D. Myers, N. Weber, and P. Grotobussiat for assistance collecting data in the South Fork of the John Day. I'm grateful to Jim Ruzycki, Scott Heppell, Peter Bayley, Nick Bowes, Russ Faux and Christian Torgersen for their logistic support and helpful scientific discussions that helped refine the work presenter here. We thank C. Moore of ODFW for providing us a field camp at the Murderers Creek Ranch. This project was funded by the U.S. Bureau of Reclamation, Pacific Northwest Region, through M. Newsom. Finally I would like to thank Dr. Blake Feist who provided extensive comments which greatly improved the manuscript

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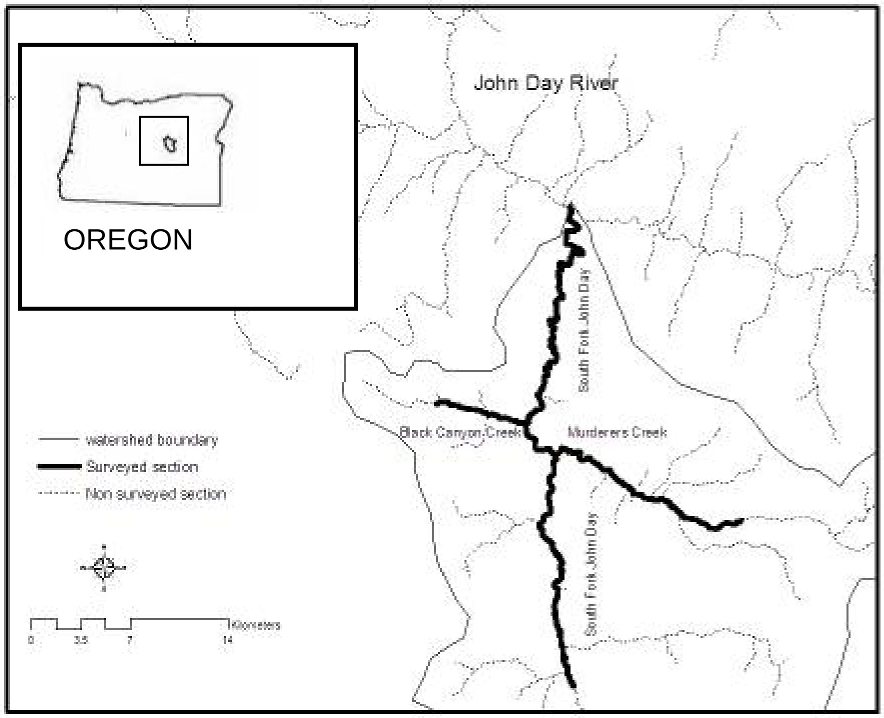

Figure 3.1: Study area: South Fork John Day River basin in Northeastern Oregon, The South Fork John Day River flows from South to North. Sections of the South Fork John Day River that were snorkeled are delineated in a solid black line

Figure 3.2(A): Distribution of redband/steelhead trout biomass in the three tributaries of this study. Values are given in percentage

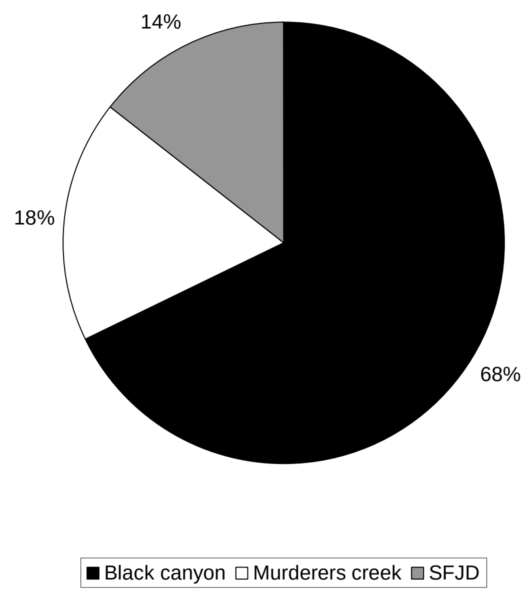

Figure 3.2(B): Total pool habitat area available for trout in the three tributaries of this study. Values are given in percentage

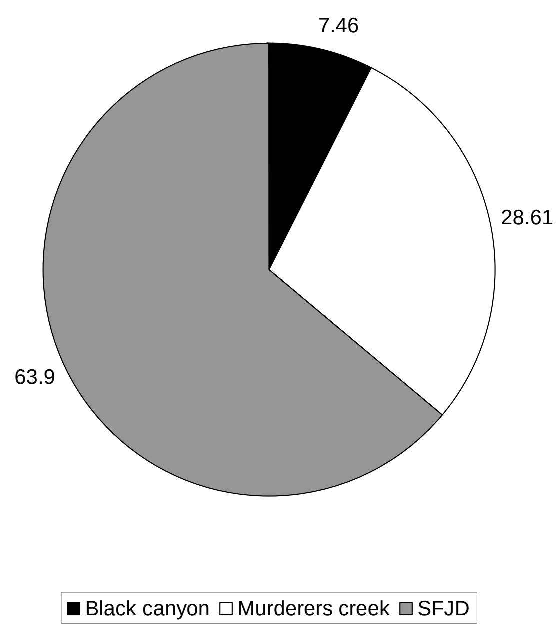

Figure 3.3: Biomass (g) vs. pool area by habitat temperature category. Optimal (<18 C., Suboptimal (18.1 to 21 C°). Marginal (22.1 to 23 C°). Poor (>23 C°). Horizontal axis shows the pool area in m². Vertical axis shows trout biomass in grams per pool (note that scales in each graph are different depending on total values found in each temperature category).

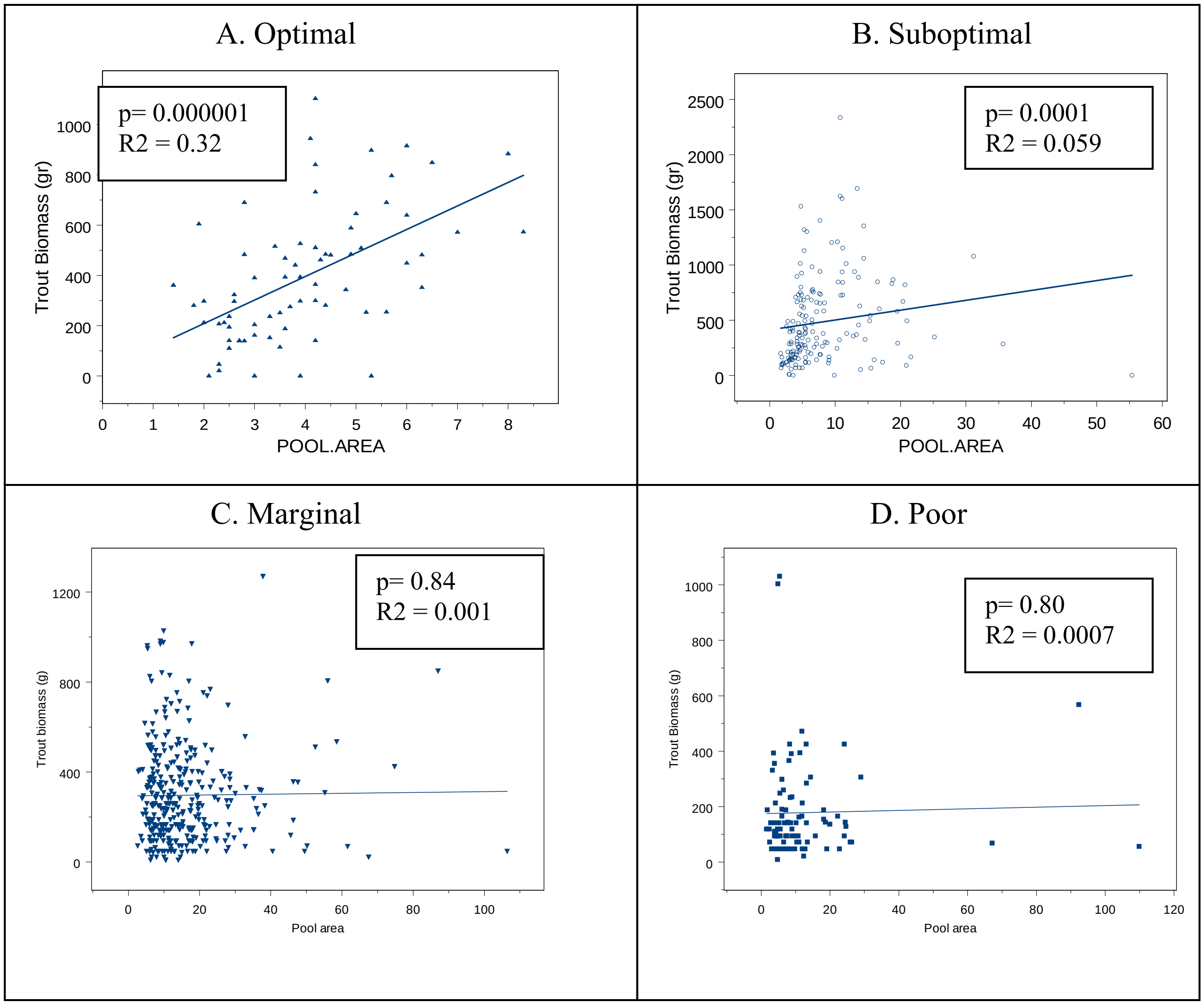

Figure 3.4: Total area and redband/steelhead trout biomass by habitat type. Bars denote the total area that corresponds to each habitat unit type. The secondary vertical axis (and the line) denotes the sum of all trout biomass found in each habitat type

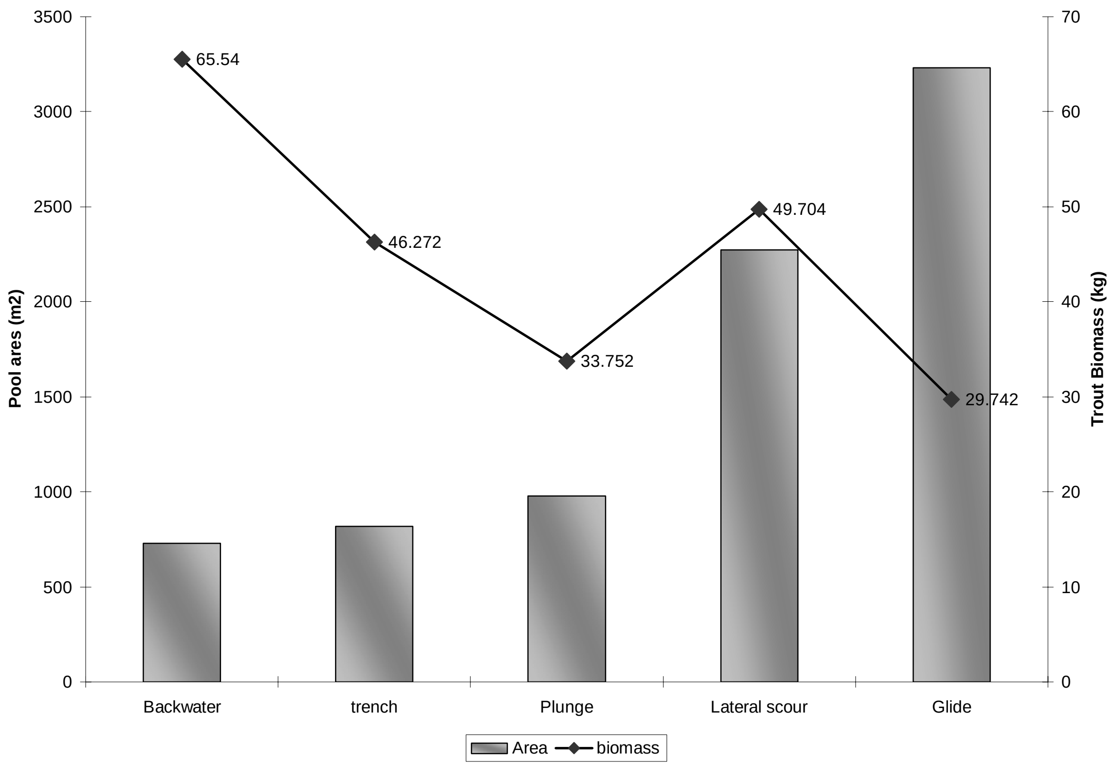

Figure 5: Percentage of pool types per habitat category in all study streams. Optimal (<18 °C). Suboptimal (18.1 to 21 °C). Marginal (22.1 to 23 °C). Poor (>23 °C)

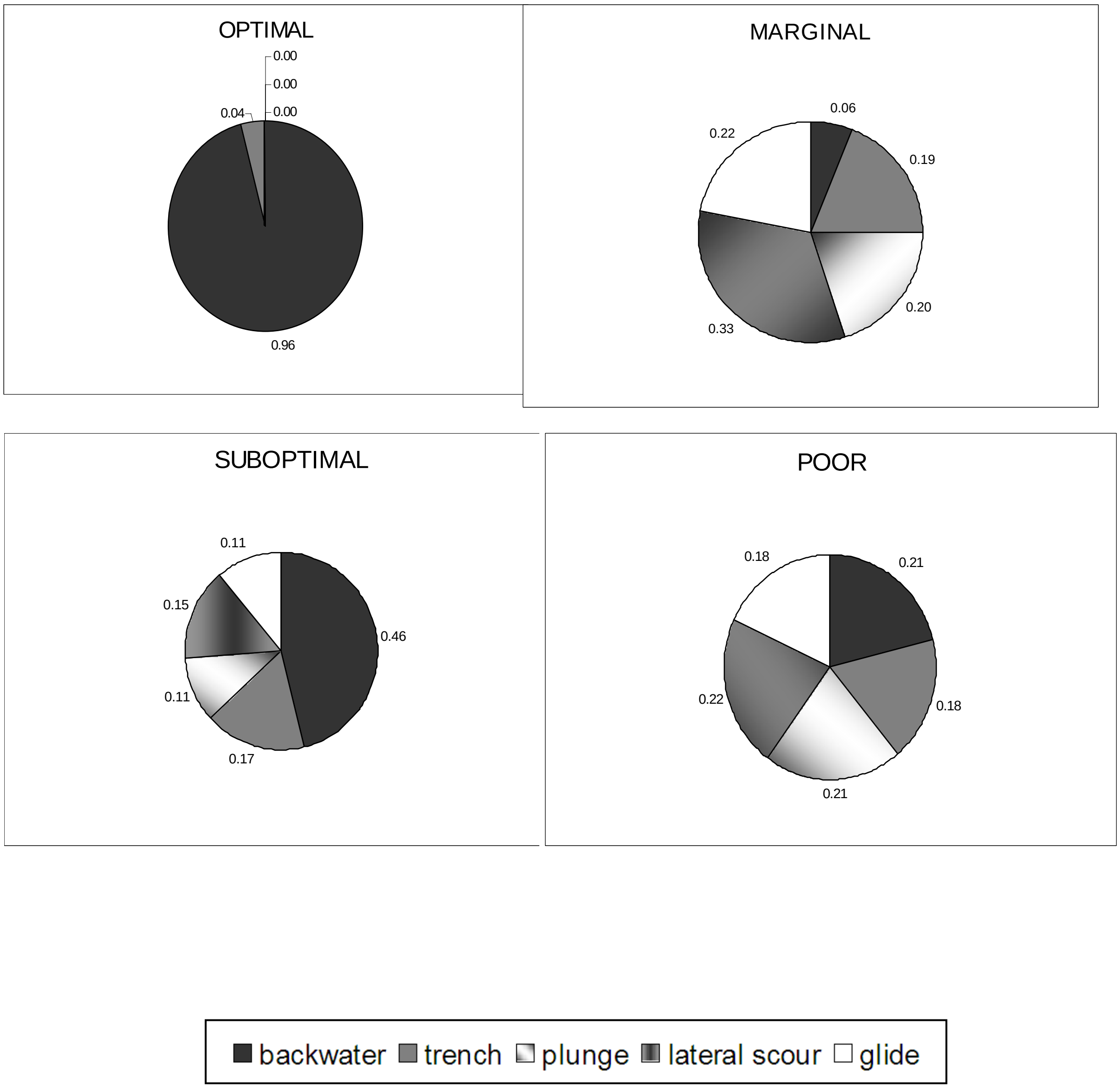

Table 3.1: Johnson electivity analysis for all trout in all habitat types in study. 1 is the highest and 5 the lowest rank for use and availability. The larger the positive number the highest the electivity value (4 highest, -4 lowest)

	All trout				
	Lateral scour	Plunge pool	pocket pool	Trench	Glide
Availability %	28.2	11.38	8.19	9.32	42.89
Utilization %	22.8	15	29.1	20.5	13.2
Rank avail	2	3	5	4	1
Rank use	2	4	1	3	5
Electivity	0	-1	4	1	-4

Table 3.2: Johnson electivity analysis for small and big trout in all habitat types in study. 1 is the highest and 5 the lowest rank for use and availability. The larger the positive number the highest the electivity value (4 highest, -4 lowest)

	Small trout (65 - 100 mm)				
	Lateral scour	Plunge pool	pocket pool	Trench	Glide
Availability %	28.2	11.38	8.19	9.32	42.89
Utilization %	19.39	13.06	41.83	13.97	11.73
Rank avail	2	3	5	4	1
Rank use	2	3.5	1	3.5	5
Electivity	0	-0.5	4	0.5	-4

	Big trout (>200 mm)				
	Lateral scour	Plunge pool	pocket pool	Trench	Glide
Availability %	28.2	11.38	8.19	9.32	42.89
Utilization %	19.77	10.33	17.84	12.46	39.58
Rank avail	2	3	5	4	1
Rank use	2	5	3	4	1
Electivity	0	-2	2	0	0

CHAPTER 4

Temperature as an Index of Juvenile Redband/Steelhead Trout Carrying Capacity in a Semi Arid Basin

Introduction

Stream temperature controls fish metabolic rates, influences habitat use, and regulates behavioral responses to a variety of environmental stimuli. Temporal and spatial changes in stream temperature shape not only fish distribution patterns but fish community composition, because it influences the differential survival and reproduction of species across watersheds (Nielsen et al. 1994, Tait et al. 1994, Peterson and Rabeni 1996). In semi arid-environment streams, temperature is perhaps the main factor controlling the spatial distribution of fishes.

Several studies (e.g., Fausch et al. 2002, Cummins 1974) have recognized that streams are strongly influenced by the landscape through which they flow. Elevated stream temperatures are the result of ecological and physical processes interacting at the same time, and are directly related to human land-use practices, often with negative consequences for the aquatic ecosystems (Torgersen et al. 1999).

The physical factors that control stream temperature operate at different spatial scales (McDowell 2001). For example, at a small scale, habitat-unit temperature is likely controlled by local factors such as groundwater input and in-stream structures, either natural or human-made (i.e., beaver dams and push-up dams). However at intermediate scales, stream reach temperature is likely driven by differences in geomorphology, discharge, water sources, gradient, sediment inputs, and riparian vegetation (McDowell 2001). Therefore, in order to understand the influence of temperature on the distribution of fish within a system it is very important to collect water temperature data in such a way that can be analyzed to study processes at different spatial scales.

Monitoring continuous longitudinal-summer-stream temperatures presents one approach for rapidly assessing stream carrying capacity for threatened and endangered salmonids (Torgersen 1999). Because of their sensitivity to high water temperatures, salmonids thermoregulate behaviorally by moving to cooler areas such as cold springs and confluences with cold tributaries when surrounding temperatures exceed their tolerance (Berman and Quinn 1991). Since temperature can significantly limit the stream carrying capacity for salmonids, and temperature is driven in large part by landscape-scale features, longitudinal-summer-stream thermal profiles could be used to link stream condition and carrying capacity to landscape attributes (Torgersen 1999).

Although discontinuity in suitable thermal habitat patches may impose excessive energetic constraints to fish movement at both medium and large spatial scales (Rieman and McIntyre 1995), until recently most of the literature on stream fish ecology focused on relatively short river segments (< 1km) (e.g., Lohr and Fausch 1997, Schlosser 1995, Fausch et al. 1994, Bisson et al. 1982, Chapman and Kndusen 1980). Few studies have considered larger spatial scales to examine how physical factors influence fish distribution patterns at a landscape level (Torgersen et al. 2006; Labbe and Fausch 2000, Gowan and Fausch 2002, Baxter and Hauer 2000, Roper et al. 1994).

This study examines whether longitudinal-summer-stream temperature profiles in semi arid-environment streams can be used to index carrying capacities of threatened populations of redband/steelhead trout (*Oncorhynchis mykiss gairdneri*) in the mid-Columbia Basin. This was based on the premise that the classification of stream reaches into different temperature segments and the subsequent calculation of their trout biomass potential would allow the indexing of trout carrying capacity. Previous observations by Li et al. (1994), Tait et al. (1994) and Torgersen et al. (1999) contributed to the development of this concept by showing that maximum stream temperatures during summer were inversely related to trout standing crops. Therefore, the specific objectives of this study were: 1) to determine if water temperature can be used as a carrying capacity indicator for redband/steelhead trout, 2) to locate the sites with the highest redband/steelhead trout biomass, and 3) to identify the factors that contribute to high biomass in those sites during summer base flow. This study combined landscape-level ecological analyses with trout distribution patterns and physiological information. I carried out continuous sampling of trout, their micro-habitats, surrounding landscape features, and longitudinal-water temperature profiles, and analyzed data at different spatial scales (i.e., habitat unit, reach, tributary).

Methods

Study Area

The John Day River basin has three primary tributaries: the North, Middle, and South forks. The John Day River is the second-longest free-flowing stream in the continental United States, and one of only two river systems in the Columbia River Basin managed exclusively for wild anadromous fish (Behnke 1990).

The South Fork of the John Day River is located in Grant County, Oregon, and flows northward from the Ochoco and Aldrich mountains, entering the mainstem John Day River at Dayville. The South Fork John Day drains an area of approximately 1,637 square kilometers (Leitzinger 1993), and ranges in elevation from 710 to 1,646 meters above sea level. The climate in the region is semi-arid with precipitation ranging from 254 mm to 508 mm per year. Peak precipitation occurs between November and January and comes as snowfall; a secondary peak of precipitation occurs between May and June in the form of rain. The annual average temperature is 10 ºC; the coldest average monthly temperature is 1.1ºC in January, and the warmest is 20.5 ºC in July (DeLorme, 2004, State of Oregon, WRD, 1986).

Within the South Fork John Day River basin, four major tributaries provide spawning habitat for adult summer steelhead. I focused my work on two of these tributaries (Black Canyon Creek and Murderers Creek) and on the mainstem of the South Fork John Day between the town of Dayville and an upstream barrier to anadromous fish, Izee Falls (river kilometer 46.7). Black Canyon Creek flows west to east, draining the Black Canyon Wilderness Area. Murderers Creek flows east to west and its lower section flows through the Murderers Creek Wildlife Preserve (Figure 4.1).

Most of the sub-basin is managed by the Federal Government (United States Forest Service and Bureau of Land Management) and the Oregon Department of Fish and Wildlife. Private lands tend to be concentrated in the lower reaches and above Izee Falls. The two major land cover types are coniferous forest and grassland. Although the area under agriculture is relatively small and limited to the lowermost and uppermost portions of the sub-basin, it is likely to have an important influence on stream temperature because of water withdrawals during summer. Cattle's grazing is the major land use in the system, with lower elevation rangelands characterized by poorer conditions than upland zones (DeLorme, 2004, State of Oregon, WRD, 1986)

Fish and habitat

Trout diel movement patterns were recorded using surgically implanted pulse radio tags with external whip antennas (Advanced Telemetry Systems, Isanti, MN). Twelve trout, measuring from 170 to 210 mm (Total fork length), received 1.7 g radio transmitters. An additional four individuals above 210 mm in length were tagged with 2.1 g transmitters. These fish were tracked on a daily basis for approximately 3 months starting on July 12 until September 2004, through the life of the radio tags' batteries.

Contiguous snorkeling surveys were conducted in the summers of 2004 and 2005. The main stem of the South Fork John Day River was surveyed from reach 2 (river km 4) up to Izee Falls (river km 48). In addition to redband/steelhead trout, chinook salmon (*Oncorhynchus tshawytscha*), northern pikeminnow *(Ptychocheilus oregonensis)*, redside shiner (*Richardsonius balteatus*), suckers (*Catostomus spp*), mountain whitefish *(Prosopium williamsoni)*, Pacific lamprey (*Lampetra tridentata*), speckle dace *(Rhinichthys osculus),* Longnose dace *(Rhinichthys cataractae)*, and sculpins (*Cottid spp*) were observed.

Snorkel capture efficiencies for trout ranged from 22% to 37%, depending on sampling crew (See chapter 3 for additional information about this method).

Stream temperature

Forward-looking infrared (FLIR) imagery was used to map the longitudinal stream temperature profiles in the study area. The FLIR was flown when stream flows were at base level in late summer 2003 (August 20) over the main stem of the South Fork John Day River, and in early autumn 2004 (September 12) over the mainstem, Black Canyon Creek and Murderers Creek. FLIR relies on thermal infrared sensors that measure the infrared energy reflected by the water surface. The sensors can accurately measure bulk water temperatures where the water column is thoroughly mixed, thus providing a snapshot of surface water temperatures in a continuous manner (Torgersen et al. 1999). I assumed that surveyed reaches had a mixed water column because average depth of the streams did not exceed 1 m. Information from two thermal imagery datasets (i.e., 2004 and 2005) were used to help detect warm and cold water sources, such as tributary junctions and flood irrigation canals. The Oregon Water Resources Department gauging station discharge and water temperature data from Murderers Creek Station (UTM = 11T 297905mE, 4910076mN; elevation = 908 meters, stream kilometer 0.6), and South Fork John Day River Station upstream of Izee Falls (UTM = 11T 300646mE, 4888621mN; elevation = 1198 meters) where used to calibrate the FLIR information with stream discharge levels.

In addition to FLIR images, water temperature was recorded on an hourly basis from early June to late September, both in 2003 and 2004, using Optic Stowaway temperature loggers (HOBO®). Eighteen loggers were placed along the stream at sites (nodes) where FLIR imagery detected the biggest changes in stream water temperatures, Maximum daily stream temperatures were used in this study because they have been shown to strongly influence trout distribution patterns (Gowan and Faush 2002, Ebersole et al. 2003). To assess the accuracy of the FLIR, maximum water temperature data from the HOBO loggers were averaged for the seven day period immediately prior to the aerial survey and compared to the maximum water temperatures recorded through thermal imagery for the nodes at which the temperature loggers were placed.

GIS analyses

Habitat classification

Airborne Light Detection and Ranging (LiDAR) is an active remote sensing technology that uses a pulsed laser, aircraft attitude, and GPS to record precise elevation points. LiDAR data were collected in the South Fork John Day River study area on March 11, 2005 using an Optech ALTM 3100 system. The system is capable of recording up to 4-returns per laser pulse, which allowed measurement of the vegetation canopy (first return) and penetration through the canopy to the ground surface. The LiDAR mission was flown with a total field-of-view of 30^o ($\pm 15^o$ off nadir) and with 50% overlap on opposing flight lines. The flight was designed to minimize shadowing from the terrain and vegetation and achieve high ground return densities. The resulting data had an average return density of > 4-points/m^2 and a vertical accuracy of 2.5 cm RMSE (Root Mean Square error, computed based on 175 ground survey points). The raw LiDAR points were processed to remove noise and to classify ground returns. The ground classified returns were then used to create a GIS compatible 1-meter digital elevation model (DEM) representing the bare earth topography. The first return points were used to render a corresponding 1-meter elevation model representing the vegetation canopy.

Map templates were loaded in a geographical information system (GIS) for spatial analyses of redband trout distribution, stream temperature, and aquatic habitat. The bankfull width was calculated for all the streams in the study area, individual pools were identified and the locations of fish distribution and temperature data were added (Chapter 3).

Fish and temperature data from FLIR were added into the GIS. Using the LiDAR templates, average bankfull width was determined for all study reaches, and individual pools were mapped. To estimate pool area LiDAR images were used and calibrated with field data that included thalweg length and tail, middle and head widths for individual pools. Afterwards, trout abundance and pool area where used to calculate population density and biomass. To estimate the average biomass of trout, weight data from 1,340 pit tagged individuals was averaged by size class. These data in combination with trout numbers per size class and with pool areas were used to determine biomass per unit area (Tattam 2006).

Geo-statistical analysis

The spatial autocorrelation among pools for these variables was analyzed using Anselin Local Moran's I ($\alpha = 0.05$) (Tiefelsdorf 2002). This cluster analysis was used to group pools based on their fish density and biomass as well as to identify possible outliers (pools distinct from their neighbors). The method compared each individual pool with its 5 upstream and downstream neighbors. Subsequently, given that the individual observations of fish abundance are not normally distributed and are highly heterogeneous, I applied the Getis–Ord Gi statistic to assess whether pools had higher than expected values for fish density and biomass. The Getis–Ord Gi statistic (Hot Spot Analysis) (ArcGIS®, Spatial Statistics Tools) was used ($\alpha = 0.05$) to compare each pool with all other pools in the study reaches. This analysis gives more weight to the data points that are found in the tails of the normal distribution and can be used to determine whether pools with similar characteristics (e.g., high or low fish biomass) have a tendency to be near each other (Ord and Getis 1995). The Hot Spot Analysis allows to test if those spatial patterns of trout distribution among pools are statistically significant. This can produce a map showing the locations of pools that have higher or lower fish density or biomass than average and can potentially be used to identify high quality habitat units as well as sites that could be targeted for restoration actions.

Results

Fish and habitat

Trout were present in most habitats throughout the surveyed reaches. Young-of-the-year and small parr (65 – 100 mm) were principally associated with the cooler temperatures and higher gradients (> 4º) of the tributary streams, mid-size trout (100 to 200 mm) where present in most of the pools in the entire basin with low densities in the lower reaches of the mainstem, and large trout (>200 mm) where predominantly found at the lower reaches of the mainstem and at the lower reaches of Murderers Creek (Figure 4.3).

The telemetry study showed that trout in summer were mostly sedentary. The average distance they moved was 15 m, and the maximum distance recorded was 950 m (by an individual that after moving stayed in the new pool for the rest of the summer). These results suggest that trout biomass in pools was very stable throughout the summer. It ranged from 24.2 g/m² in optimal habitats to 1.71 g/m² in the poor habitats, and 70.1% of the total trout biomass in the basin was located within optimal and suboptimal habitats that added up to only 17.6% of the total area.

Stream temperature

The duration of FLIR flights across the mainstem and its tributaries did not exceed 1 h, during which time stream temperature increased by 0.8 – 1.2°C. The high resolution of the FLIR profiles (18 cm per pixel) allowed us to detect and compensate for thermal anomalies associated with irrigation channels, tributary inputs and riparian vegetation that otherwise would have created noise in the analysis. The accuracy of the FLIR in recording maximum water temperature was high, and had a standard deviation of less than 0.6°C compared to the seven day mean maximum temperature based on HOBO logger data.

The longitudinal temperature profile maps revealed that the thermal environment of the South Fork John Day was spatially heterogeneous during both study years (2003 and 2004); however, it was dominated by temperatures between 22 and 23°C, with isolated patches of relatively cooler (18 – 21°C) and warmer (>23°C) water (Table 4.1).

Habitat classification

The final reach classification resulted in 17 reaches for the mainstem, and 3 reaches each in Murderers Creek and Black Canyon Creek (Figure 4.2). The longest reach was 8.5 km and the shortest 0.78 km. The combination of FLIR profiles and thermal imagery mosaics facilitated the detection of patterns in stream temperatures at reach and habitat-unit spatial scales across the entire basin. The resulting habitat classification showed that 3.6 % of the mainstem area was optimal for trout physiology (<18°C), 14% was suboptimal (18 to 21°C), 25.4% was marginal (21.1 to 23°C) and 51.9% was unsuitable (>23°C) (Figure 4.2).

Geo-statistical analyses

The cluster and outlier analyses revealed that trout biomass and density estimates for individual pools were highly auto-correlated with those in neighboring pools. These analyses were not able to detect outliers of higher or lower trout biomass or density when compared to neighbors at the habitat unit scale (Figure 4.4), but they detected high biomass or density outliers at the reach scale.

The high density areas analysis (Hot spots) showed three overall areas of high density and biomass of trout: all of Black Canyon Creek, reach 2 of Murderers Creek, and reach 17 of the main stem (Figure 4.5A). A total of 13 individual pools of high trout density and biomass were located in these three areas: 8 in Black Canyon Creek (reaches 1, 2 and 3), 2 in Murderers Creek (reach 2), and 3 in the main stem (reach 17) (Figure 5B). In Black Canyon Creek, all of the pools that trout preferred had "optimal" water temperature; whereas in reach 2 of Murderers Creek they had "marginal" water temperature but were 1ºC cooler or more than neighboring pools. In the main stem, the three pools with high trout density and biomass were located at Izee Falls; one pool had "optimal" and two had "suboptimal" water temperatures (Figure 4.5(B)).

The two regression analyses performed using trout biomass (g/m^2) per pool and per reach against reach water temperature showed strong inverse significant relationships with water temperature (p = 0.0001 and p = 0.00001, respectively). Trout biomass at the reach scale explained a higher proportion of the data variation (r^2 = 0.62) than at the pool scale (r^2 = 0.27) (Figures 4.6A and 4.6B).

Discussion

My results show that, in the South Fork John Day Basin, stream temperature can be used as indicator of trout carrying capacity. The distribution redband/steelhead trout in summer is largely determined by the- physiologically influenced-preference that individuals have for habitats within specific temperature ranges. It was observed that the general temperature profile of the South Fork John Day River was highly variable, and that at very small scales trout selected relatively cooler waters. The FLIR thermal imagery revealed that the reaches containing the greatest density and biomass of trout were relatively colder reaches (< 21ºC). Ten of the 12 pools with high trout density and biomass had water temperatures below 21ºC; in the other 2 pools temperature was below 23ºC. The only trout-rich pools in the mainstem of the river were located at Izee Falls. Even though pools at Izee Falls were the coolest (19ºC) in the upper reaches of the mainstem, their higher than average trout biomass could also be attributed to the preference salmonids show for waterfalls (Giannico 2000) because of (a) the cover generated by water turbulence, and/or (b) the availability of fast-moving waters (i.e., foraging patches) next to slow-moving waters (i.e., resting patches) (Fausch 1993).

Several studies have shown that maximum stream temperature is negatively associated with trout density (Li et al. 1994, Ebersole et al. 2003); however, most of them did not use biomass because they were unable to identify fish size segregation between patches and assumed that all trout were of equal size. The classification of juvenile salmonids in different size classes is particularly important when their response to water temperature is being considered. Temperature mediated physiological constraints differ among salmonids of unequal size (Hughes and Grand 2000).

The results presented on this paper indicate that the trout population is characterized by a high degree of spatial variability both in the mainstem and in Murderers Creek. The analyses of the longitudinal temperature profiles at the reach scale (river segments from 1 to 8 km) revealed a patchy pattern with cold water segments occurring between warmer waters. This anomaly of water temperature distribution reflects reach-scale variation principally associated with land use, channel geomorphology and tributary inputs (Torgersen et al. 2006) Juvenile trout were widely distributed throughout the entire basin. However, large trout (150-250 mm) were found at the greatest densities in the middle and lower reaches of the mainstem, while small trout where only present in the tributaries. In contrast, medium-size individuals showed a relatively uniform distribution over the entire system, with the exception of the lower reaches of the mainstem. This is consistent with the findings of Roper et al. (1994) in the south Umpqua River, Oregon, which indicated that age-1 and older trout were most abundant in the middle reaches; whereas young-of-the-year individuals were predominant in the headwaters. At the habitat unit level, medium-size trout in the main stem of the South Fork John Day were most abundant in shallow pools within the warm reaches, while large trout were found in higher number in the deeper pools. This pattern of trout habitat association in the mainstem of the river cannot be entirely attributed to water temperatures alone, because other factors such as competition and predation by other species (e.g., pikeminnow) could help explain it (Reese and Harvey 2002). In contrast, in the coolest tributary (Black Canyon Creek) trout were found-regardless of size class-in higher numbers in the deepest pools within reaches of relatively high gradient. Torgersen et al (2006) reported similar results for trout and chinook salmon in the North and Middle forks of the John Day River.

The results of this study show that most high-density-trout pools were located in reaches with water temperature below 21ºC, and 70.15% of the total trout biomass in the basin occurred within 17.6% of the total area. This study found that the distribution of trout was highly correlated with both temperature and pool availability ($r^2 = 0.90$) and that most of the variation was attributable to temperature alone ($r^2 = 0.62$). This suggests that population distribution patterns are the result of the movement decisions (or behavior) of individuals, those behavioral expressions respond directly to physiological mechanisms.

There are logistical constraints to sampling large river segments, particularly when this sampling needs to be conducted in short periods of time in order to control for the possibility of fish movement within the sample period. However, the value of this analysis is reflected in the extent to which it can be applied to explain distribution patterns of fish under natural conditions. This is specifically true for trout biomass and densities that show a wide amount of variation among reaches. The importance of a continuous sampling strategy is fundamental to understanding the distribution patterns of this species. If sampling had been conducted in only a single reach or discreet sections of reaches, the estimates for the entire basin may have differed depending on the section surveyed. Furthermore, if the longitudinal temperature profile had not been collected in an essentially instantaneous and continuous manner, this study would not have had the capacity to explore the reasons for the heterogeneous distribution of redband within the system.

Many, if not all, habitat monitoring assume that fish biomass information can be used to determine habitat quality, but recent studies question that assumption (Bélanger & Rodriguez 2002). In practice, population patterns are correlated with physical environmental factors and then habitat quality is inferred from patterns of association.

This study has important implications for salmonid monitoring and restoration projects. It is now possible to partition the biomass supported within the basin by temperature classes, and then predict how much biomass might increase as a result of restoration activities that reduce water temperature. Also, it is possible to examine the distribution and quantity of habitats of different quality (for example using the physiological temperature tolerance classes) that occur during high and low flow years, thus tracking the dynamic nature of trout carrying capacity in the basin in a realistic manner.

Using this approach, it should be possible to assess a large number of watersheds in the Columbia River Plateau and rank them in terms of either potential productivity or restoration need. Furthermore, the physiology-based habitat classification scheme can be used to monitor restoration effectiveness in temperature-limited streams. These surveys can be conducted rapidly and for relatively low cost through remote sensing devices (e.g., LiDAR and FLIR). The data would consist of a GIS-based breakdown of stream area by temperature classes based on trout physiological responses, and indexed to trout biomass supported for the entire basin.

If specific biomass estimates and their distribution are required as a part of monitoring, then the accounting model of habitat quality and quantity in relation to standing crops should be calibrated with a continuous sampling survey such as the one used in the South Fork John Day in order to account for snorkeler efficiency and habitat variability.

In this study, the order in which multi-tiered biological assessment and monitoring is usually conducted was reversed. At present, Tier I monitoring is performed to identify population status, Tier II is then designed to determine recovery trends and the effectiveness of the recovery strategy. Tier III, Validation Monitoring, also known as Effectiveness Monitoring, is performed to identify cause-and-effect relationships (NOAA 1999). The purpose of establishing cause-effect relationships is to increase the predictive power of our models, so findings from one case study can be applied to other potential habitat restoration locations. I argue that a good restoration plan is designed with specific hypotheses, and that implicit in the study design is a means to test those hypotheses presumed cause-and-effect relationships. If cause-and-effect can be demonstrated, then it is possible to establish and index for future use, otherwise few implications can be drawn for how such efforts are applicable outside the system being manipulated. A temperature index like the one presented on this paper is valuable because it may save effort, time, and money, however many indices remain unproven. Few have tested the assumptions governing their function. For instance, Hilsenhoff's Index (Hilsenhoff 1988), the Index of Biotic Integrity (Cairns 1977), and the EPT indices (Lenat 1993) are associative or correlative in nature. Explanations governing the observed patterns are ambiguous at best. In order to improve these indices, the testing of the physiological mechanisms that drive fish behavioral responses will allow greater predictive capacity that can be expected based on correlative work

Acknowledgments

I would like to thank S. White, I. Tattam, J. Feldhaus, P. Bayley, S. Heppell, J. Davis, B.V. Mueller, J. Togstad, D. Myers, N. Weber, and P. Grotobussiat for assistance collecting data in the South Fork of the John Day. I'm grateful to Jim Ruzycki, Scott Heppell, Peter Bayley, Nick Bowes, Russ Faux and Christian Torgersen for their logistic support and helpful scientific discussions that helped refine the work presenter here. We thank C. Moore of ODFW for providing us a field camp at the Murderers Creek Ranch. This project was funded by the U.S. Bureau of Reclamation, Pacific Northwest Region, through M. Newsom.

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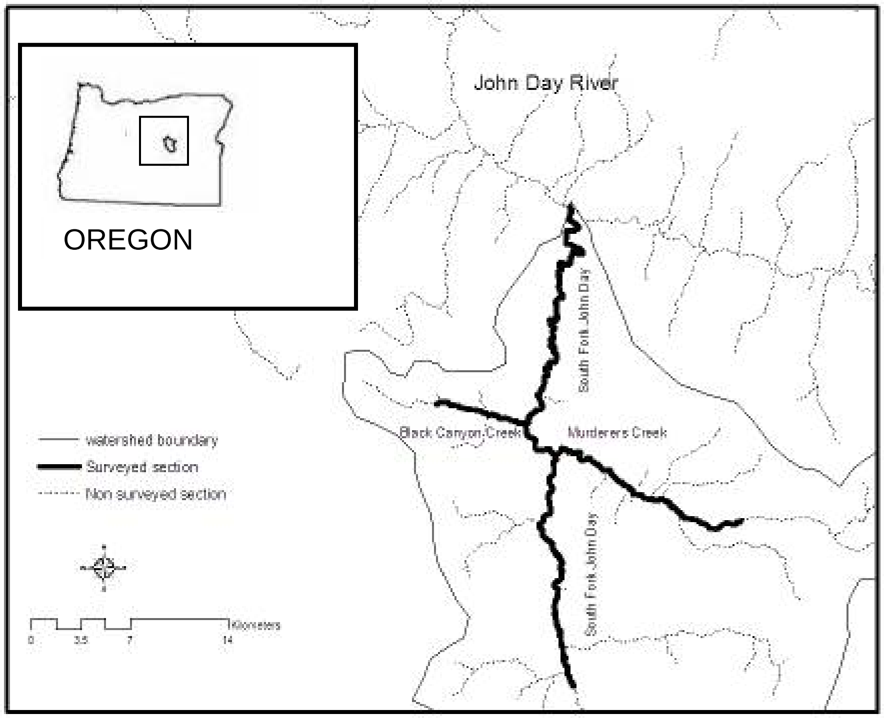


Figure 4.1: Study area: South Fork John Day River basin in Northeastern Oregon, The South Fork John Day River flows from South to North. Sections of the South Fork John Day River that were snorkeled are delineated in a solid black line

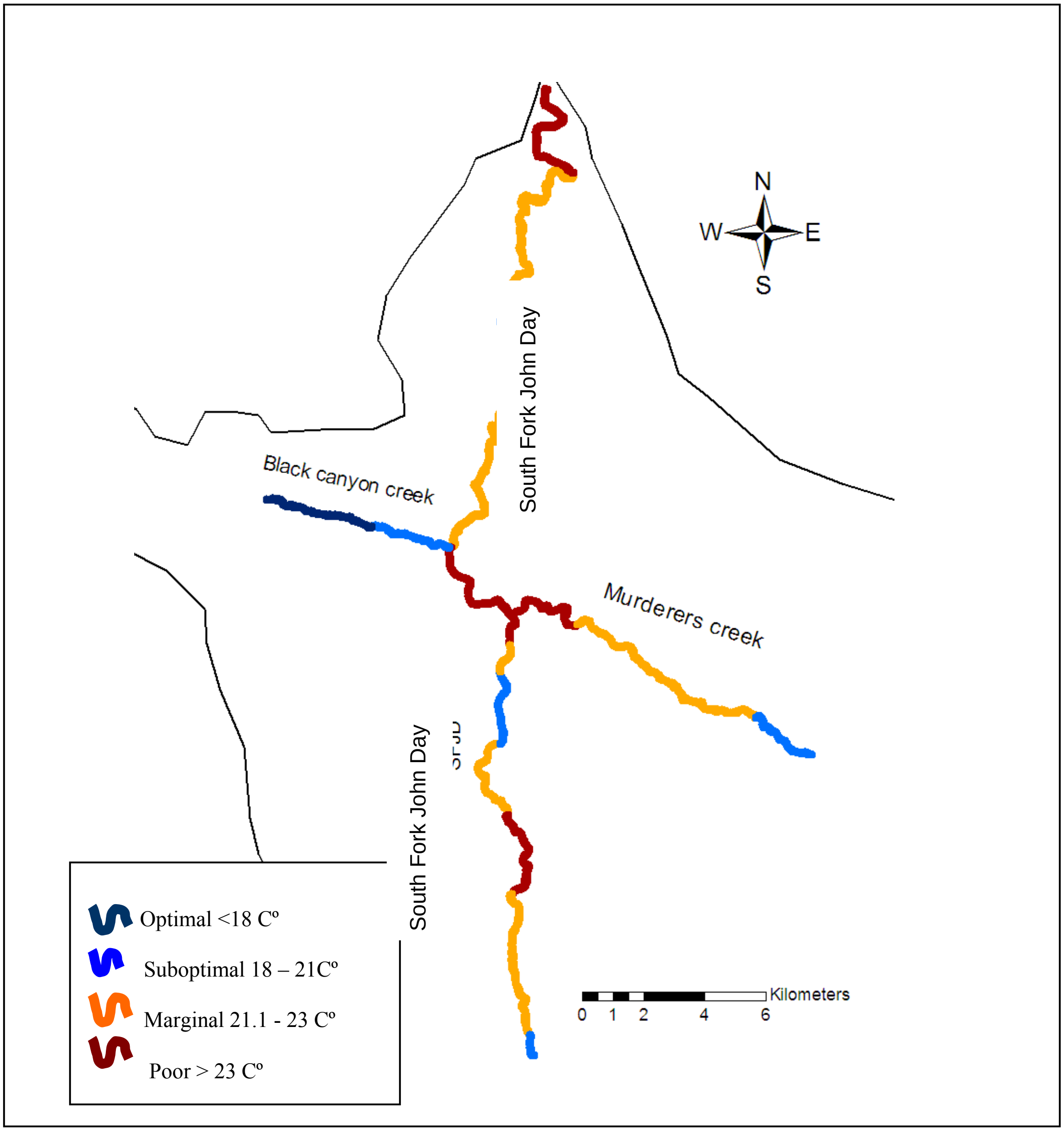


Figure 4.2: Reach classification by temperature classes based on redband/steelhead trout physiological responses

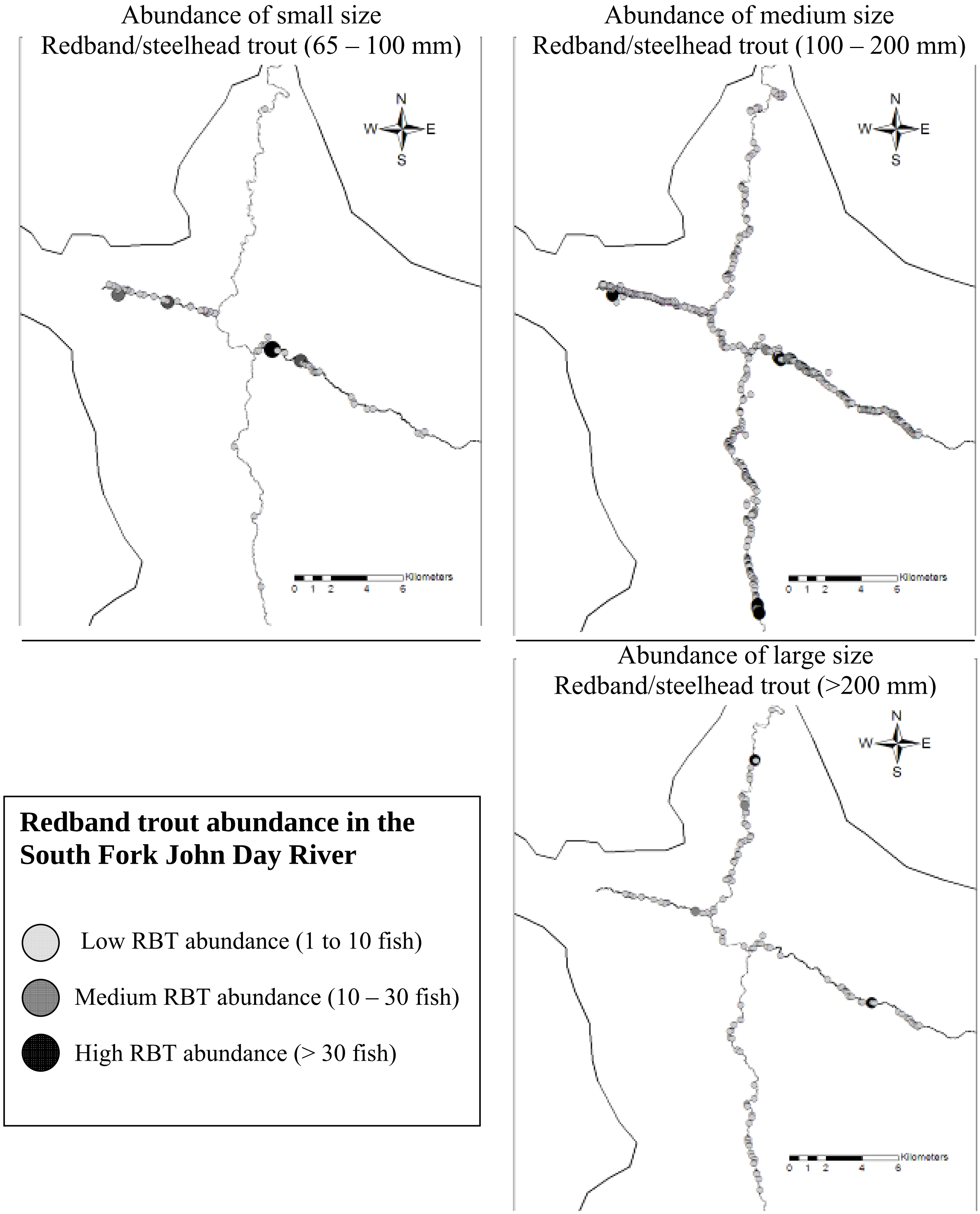


Figure 4.3: Redband/steelhead trout abundance in the South Fork John Day River by size class

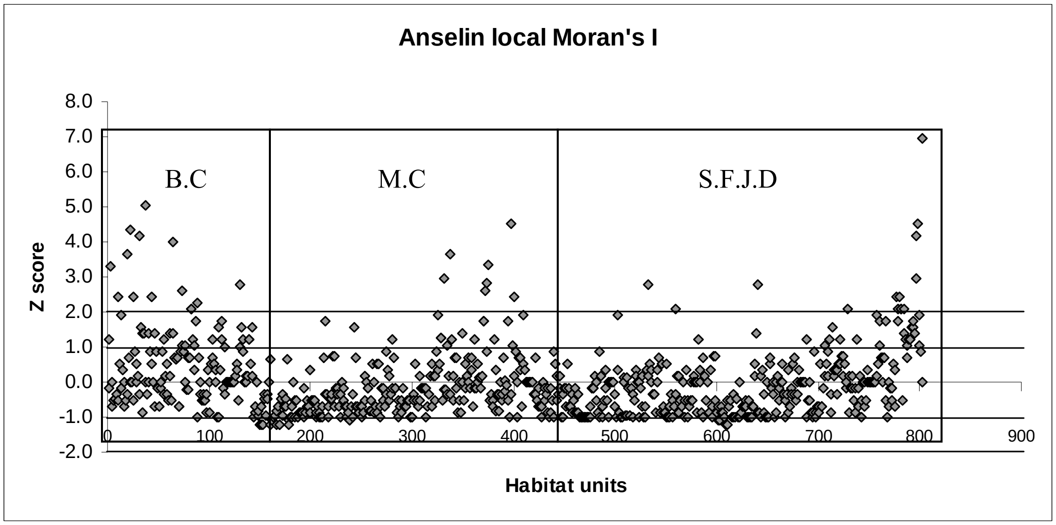


Figure 4.4: Anselin Local Moran's I (Z score): A high value for Z score (> 2) indicates that the feature is surrounded by features with similarly high or low values. A low Z score value indicates that the feature is surrounded by features with dissimilar values (< 2). From left to right, Black Canyon Creek (B.C), Murderers Creek (M.C) and Mainstem South Fork John Day (S.F.J.D)

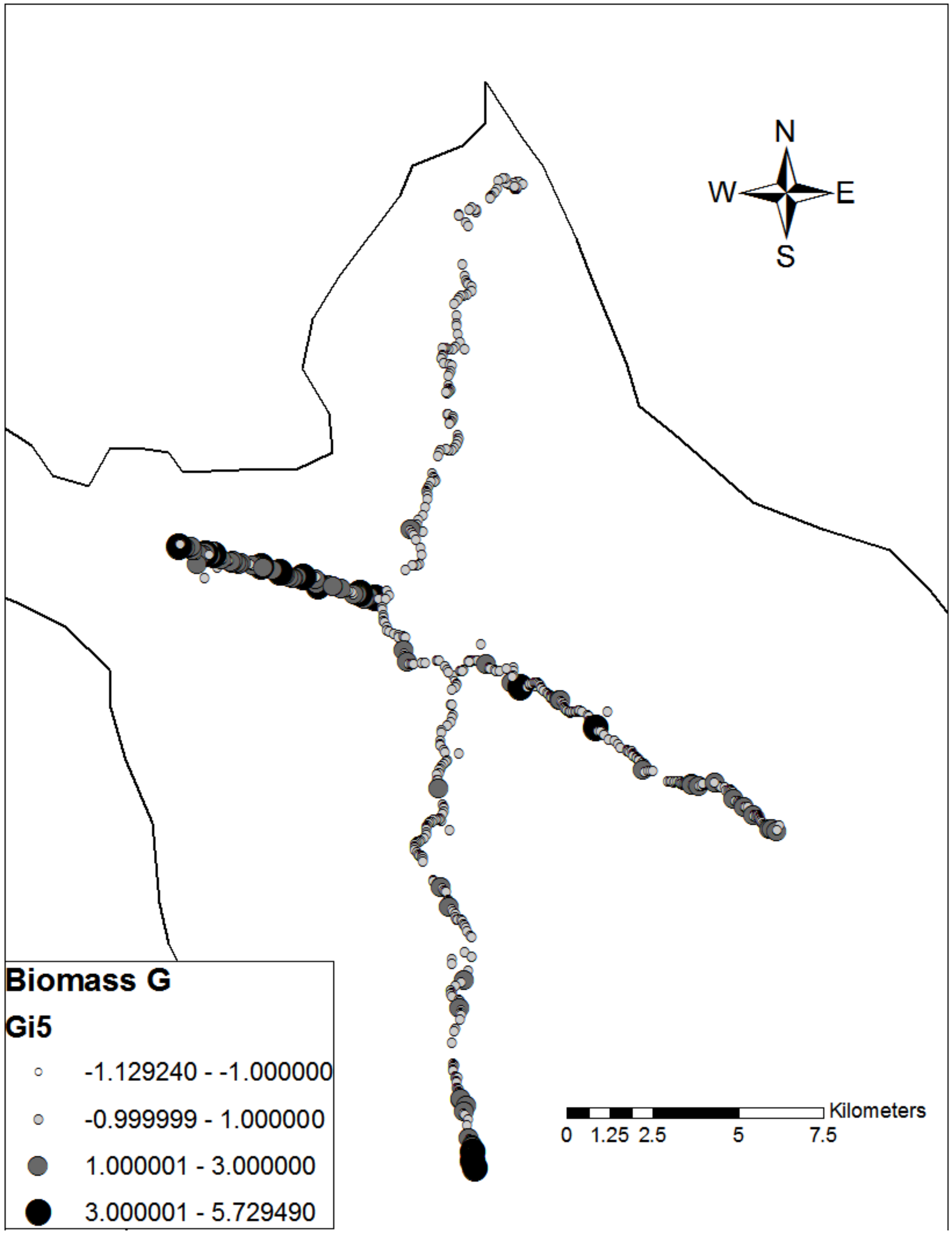
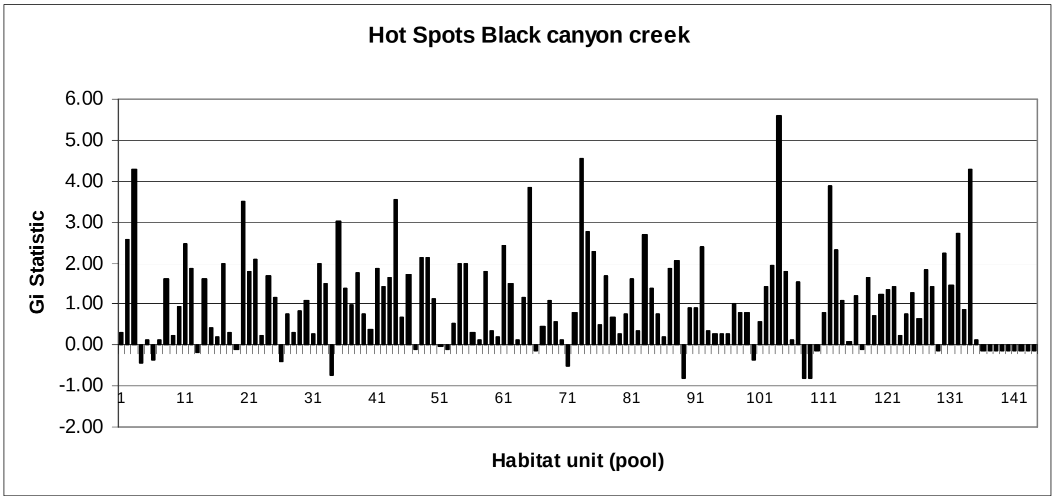
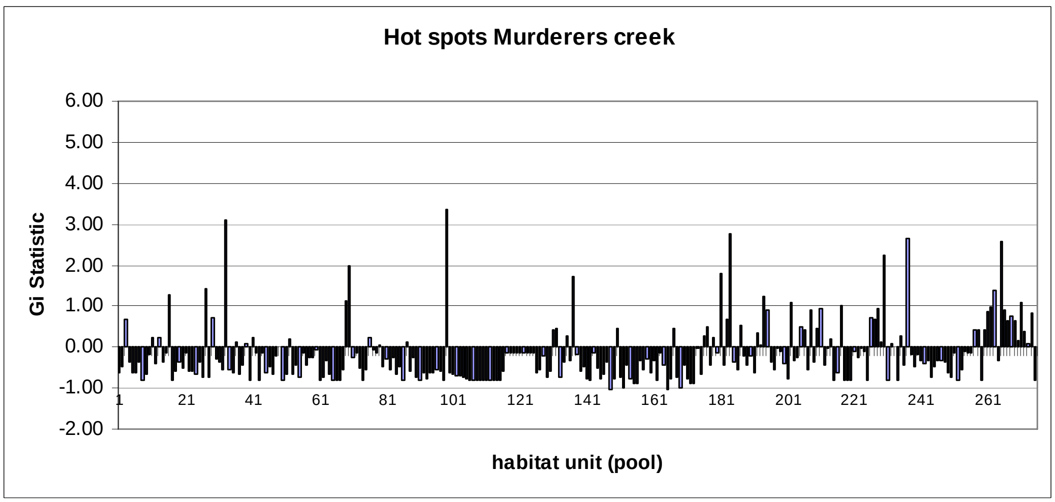


Figure 4.5(A): Spatial representation of redband/steelhead trout biomass distribution throughout the basin using “Hot Spot” Analysis (Gi -score)





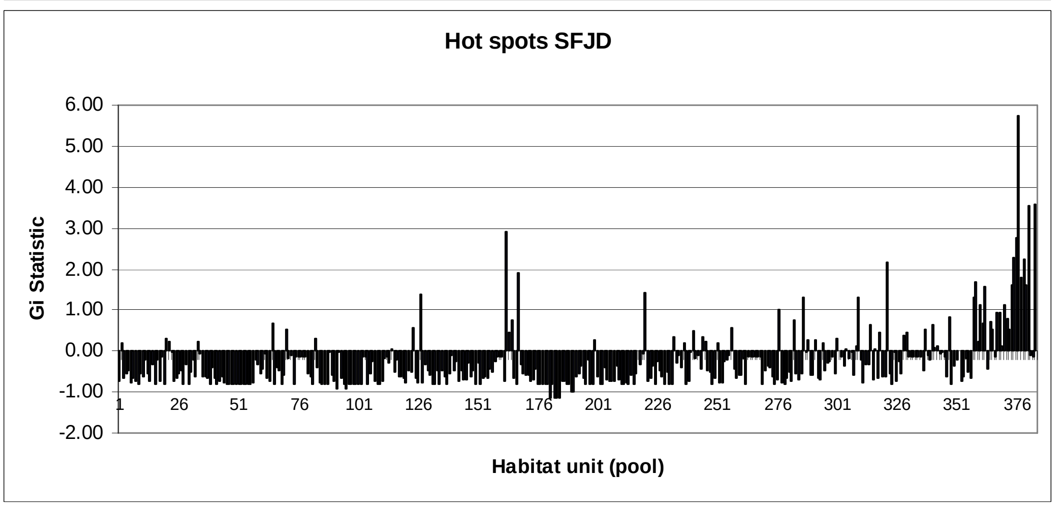


Figure 4.5(B): Gi statistic values by habitat unit: -1.19 to -1.0 = moderate spatial correlation of low values, -1.0 to 1.0, no significant spatial correlation, 1.0 to 3.0, moderate spatial correlation of high values, > 3.0, significant spatial correlation of high values. Bars above Gi =or > 3.0 are high density areas for redband/steelhead trout distribution

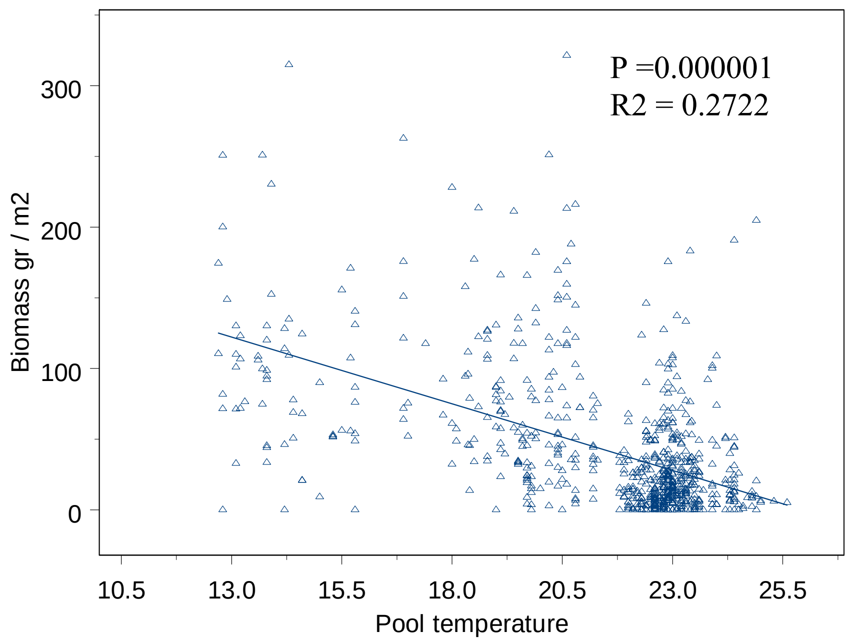


Figure 6 (A): Regression analysis between maximum temperature and trout biomass by habitat unit in all the streams

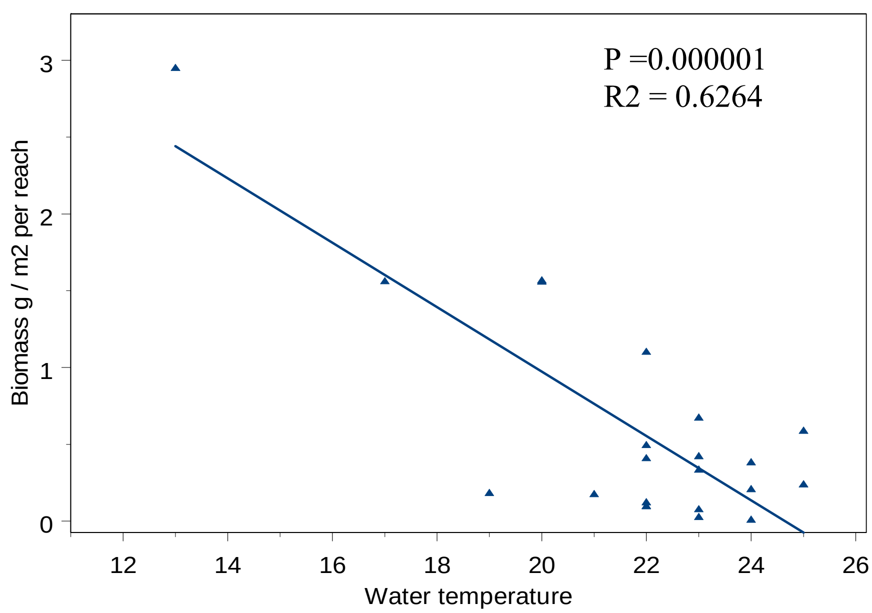


Figure 4.6 (B): Regression analysis between maximum temperature and trout biomass by stream reach

	Optimal	*Suboptimal*	*Marginal*	*Poor*
Temperature range	< 18 C°	18.1 - 21 C°	21.1 - 23 C°	>23 C°
Total pool area (m²)	356	1866.6	2482.2	5082.8
Habitat % (pool area m²)	3.64	13.96	25.36	51.93
# of Segments	2	4	6	10
Total biomass (kg)	1560	3516	1719	8328
Biomass g*m² (Average / St. Dev)	24.22 / 0.5	6.87 / 9.0	5.25 / 11.23	1.73 / 1.27

Table 4.1: Carrying capacity (Standing Crops) of redband trout in stream reaches of different physiological constraints.

CHAPTER 5

GENERAL CONCLUSIONS

I concluded that during summer low flows, water temperature can be a good predictor of stream carrying capacity for redband/steelhead trout in high desert basins in eastern Oregon and that the physiological index for stream temperature can be used to monitor restoration effectiveness in temperature-limited streams. The physiological classification allowed ranking habitat quality in a manner that was useful for two reasons. First, temperature influences physiological mechanisms responsible for limiting an individual's performance capacity in the environment. Second, water temperature is the result of multiple ecological processes acting on the landscape, including human influences. The combination of landscape-level ecological analyses and physiological information used in this study represents a comprehensive approach that brings together different disciplines to improve the understanding of redband/steelhead trout distribution patterns.

Because biophysical processes operate at different spatial scales, adopting a multi-scale approach was necessary for understanding ecological mechanisms that influence fish habitat quality in stream systems. At the basin scale, the main factor governing trout distribution was temperature. However, the signal my analyses revealed was noisy. This could be attributed to data over-dispersion due to unaccounted processes acting at smaller spatial scales. To filter that "noise", I chose to reduce sampling grain while keeping the extent constant. This led me to look at the tributary level scale, at which water temperature and channel morphology stood out as the most important factors in increasing the predictive power of my analyses. By reducing the sampling grain even further, to the reach scale, I detected a suite of homogeneous physical variables (i.e., valley shape, elevation, aspect and gradient) that were associated with density of trout biomass. Unfortunately, at this scale the influence of these factors could not be clearly separated from that of water temperature and further analyses at a smaller spatial scale (i.e., habitat unit) was required. At the habitat unit scale different microhabitat features (i.e., pool area, large wood and undercut banks) acted as covariates with water temperature. Hence, the final model I considered included all the habitat unit types by reach, where reaches were identified based on the physiological classification, and accounted for 90% ($r^2 = 0.90$) of the total observed variation in trout distribution. Within this variation, 62% ($r^2 = 0.62$) was attributable to temperature alone. The strong explanatory power of a model like this could be attributed to its consideration of different spatial scales in a nested design.

This research was a sequential learning process that contributed to the understanding of the implications for salmonid restoration projects at intermediate and large spatial scales. Its findings can be directly applied to carrying capacity determination. This can be done by partitioning the biomass supported within the basin by temperature classes, and predicting biomass increase in response to restoration actions.

My model is relevant regarding decisions about water quality standards that are part of the Federal Clean Water Act section 401 (33 USC 1341). This is evident in the particular case of the John Day Basin where the Oregon Department of

Environmental Quality has changed the water quality standards increasing the seven-day-average maximum temperature from 18o C to 20o C. The standard now reads: "The seven-day-average maximum temperature of a stream as having a migration corridor use may not exceed 20o C (68.0 degrees Fahrenheit). In addition, these water bodies must have coldwater refugia that are sufficiently distributed so as to allow salmon and steelhead migration without significant adverse effects from higher water temperatures elsewhere in the water body."

I consider that applying these new water quality standards in the South Fork John Day River may not be appropriate given the limited information available on this system. We have only an incomplete understanding of the distribution and sizes of cold water refugia. Hence, we won't know the proportion of trout that can be supported by those pockets of cold water. Nonetheless, based on crude estimates from FLIR imagery, the amount of refuge in some portions of the basin is relatively small, especially in the South Fork John Day mainstem, and fragmentation is high during summer low flows. This does not represent a problem to the migration of both anadromous and resident redband steelhead trout because such large-scale movements occur earlier in the year, when water temperatures are still uniformly cool. The real negative effect may be the interruption of smaller-scale trout movements associated with behavioral thermo-regulation during summer. This is because the relatively limited cold water refugia that would be available in the system under the new water quality standards should be out of reach to an increased proportion of the streams trout, which according to my telemetry data exhibit very limited movement once summer conditions set in. Based on the possibility of such an impact, the temperature standards for this sub-basin should be set at 18o C (i.e., optimal water temperature category).

By applying the physiological classification of reaches used in this thesis, it would be possible to asses how much biomass would increase as a result of certain restoration actions. Thus, if the entire extent of the South Fork John Day River basin were to have optimal water temperatures (<18 Cº) for salmonids, and assuming all pools were of equal size and food availability was constant, it would be possible to increase trout biomass by 520% compared to current conditions. However, if the temperature standard were increased in accordance with the Oregon Department of Environmental Quality recommendation to 20o C (i.e., sub-optimal water temperature category) trout biomass would only increase by 76%. Finally, if conditions in the basin were to deteriorate to poor water temperatures (>23 Cº), biomass in the system would decline to 43% of current values. The Section 303 water quality standards are concerned with defining acceptable limits for salmonid short-term survival response, but ignore other biological considerations such as the effects of elevated temperature on fish metabolic costs and their implications for survival in the longer term.

Based on my study results, it is possible to identify some of the principal factors operating at different spatial scales. Most of the habitat restoration projects have been conducted at small habitat unit scales. However, if these restoration activities are conducted without understanding the context controlling the distribution of trout at larger spatial scales, resources can be wasted (Bayley and Li, 2008).

My model provides the spatial context at large spatial scales by working from entire basins down to habitat units. This enables one to identify restoration needs and potential at different spatial scales; I suggest that an analysis of larger scales helps to develop overall restoration strategies while those at smaller scales identify restoration tactics. It follows that one could monitor restoration progress using the same approach: obtaining thermal imagery, tracking the improvement and number of different habitat unit types and estimating potential changes in carrying capacity as I explained using the example of possible new stream temperature standards for the John Day Basin.

Future research should include measurements of different life stages, including adult spawning locations, overwinter survival and smolt productivity by reach; thus adding temporal variation as well as testing the importance of these findings in a cohort as a whole. It is also necessary to describe patterns of fish behavior in the context of different environmental conditions and different species densities, as well as more empirical examinations of how network-scale processes affect stream community dynamics, and therefore spatial patterns of species diversity. Future research should also include possible climate change scenarios and their effect on fish community composition and shifts in redband/steelhead trout distribution patterns due to an increase in winter precipitation and warmer summers.

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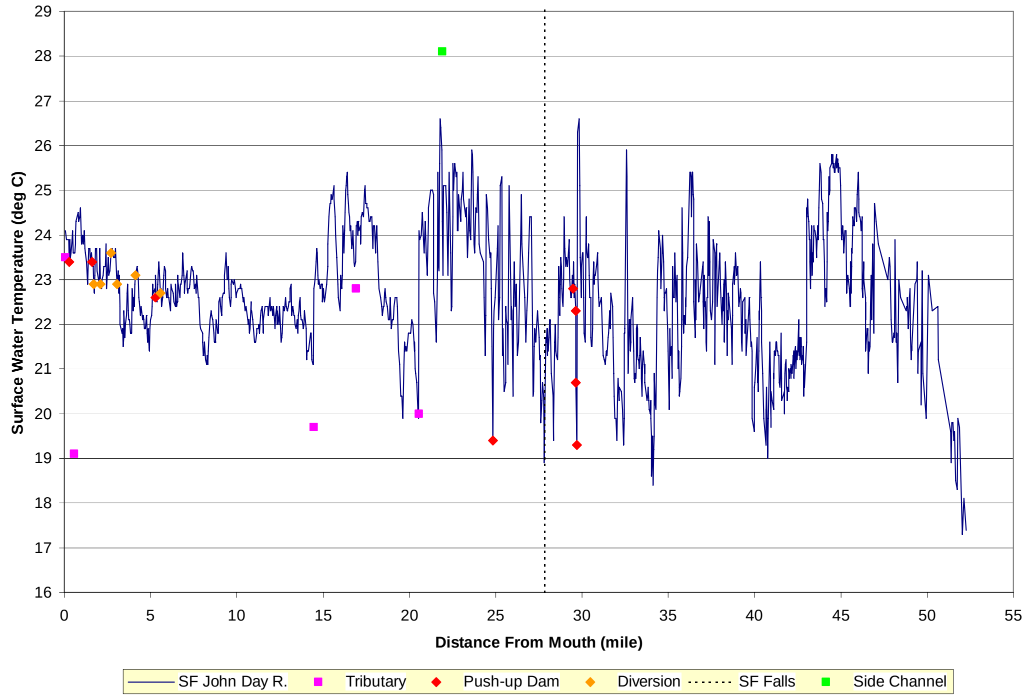
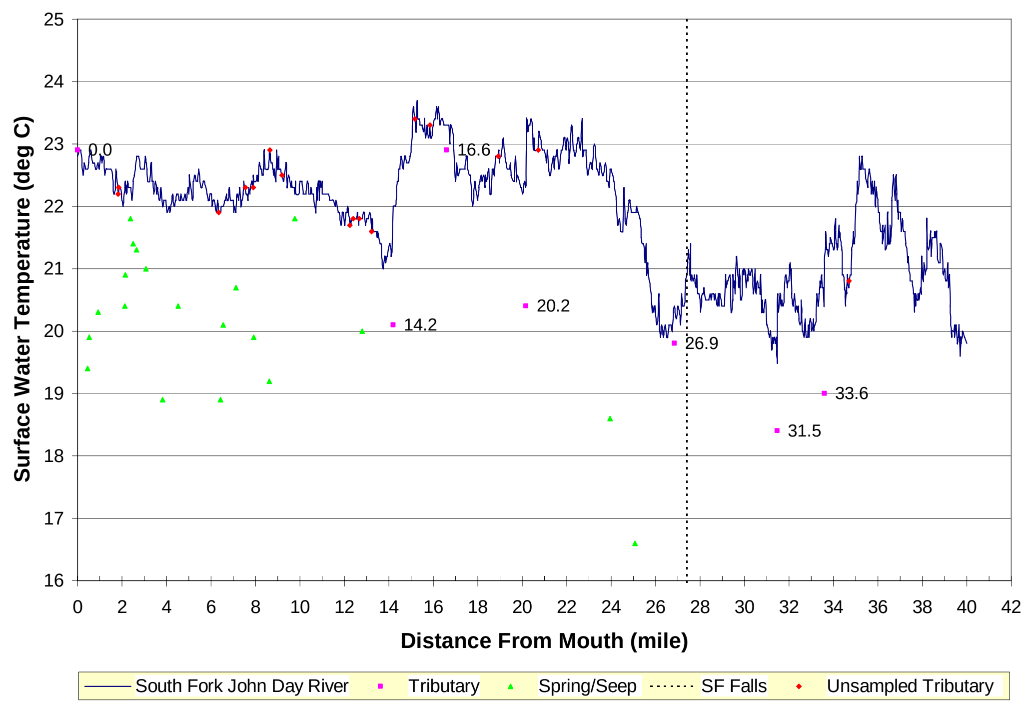
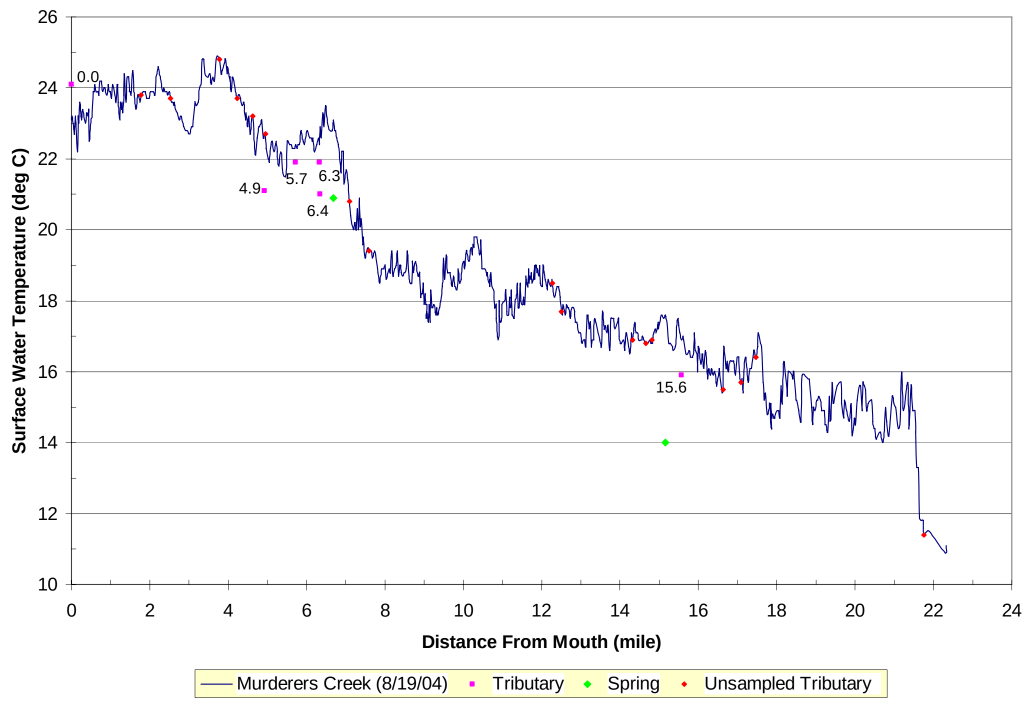
APPENDICES



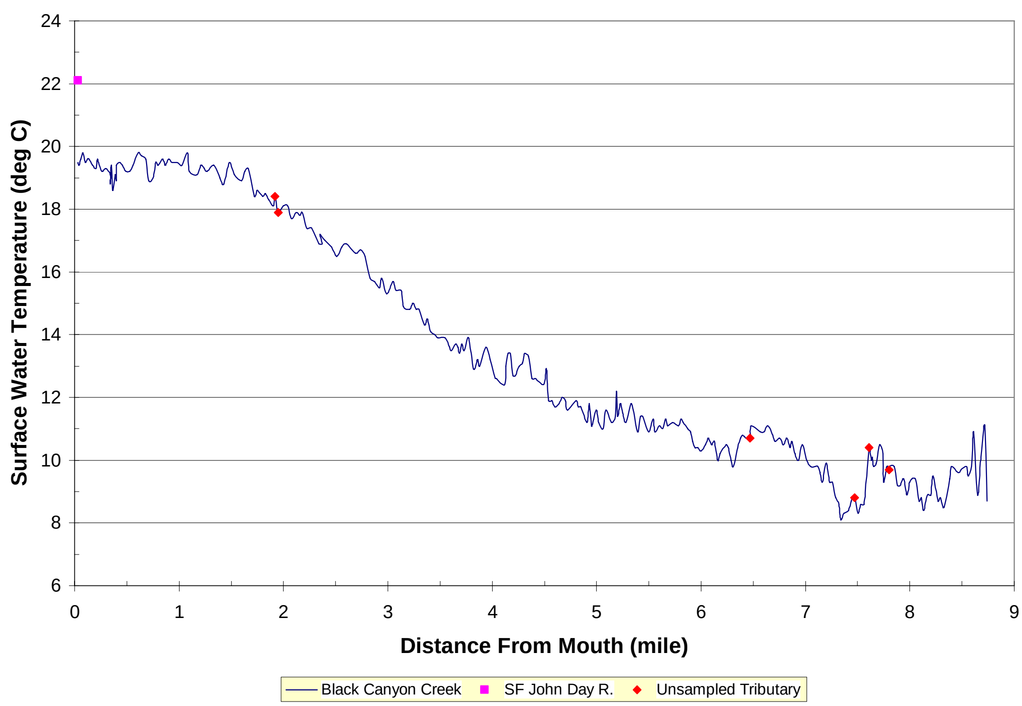
Appendix figure B1: Longitudinal Temperature Profile for the mainstem South Fork John Day River, summer 2003



Appendix figure B2**:** Longitudinal Temperature Profile for the mainstem South Fork John Day River, summer 2004



Appendix figure B3**:** Longitudinal Temperature Profile for Murderers Creek, summer 2004



Appendix figure B4: Longitudinal Temperature Profile for Black Canyon Creek, summer 2004

logger date	SFJD Reach 4 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	1:55:00 PM	22.5			
8/10/03	1:55:00 PM	22.2			
8/11/03	1:55:00 PM	23.4			
8/12/03	1:55:00 PM	23.9			
8/13/03	1:55:00 PM	23.0			
8/14/03	1:55:00 PM	22.3			
8/15/03	1:55:00 PM	22.3	22.9	22.6	23.6
Average		22.8			
St dev		0.6			
logger date	SFJD Reach 6 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	14:00	21.63			
8/10/03	14:00	21.8			
8/11/03	14:00	21.97			
8/12/03	14:00	22.13			
8/13/03	14:00	22.13			
8/14/03	14:00	22.3			
8/15/03	14:00	22.47	21.6	21.4	21.9
Average		22.1			
St dev		0.1			
logger date	SFJD Reach 8 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	14:20	22.16			
8/10/03	14:20	22.16			
8/11/03	14:20	22.33			
8/12/03	14:20	22.49			
8/13/03	14:20	22.49			
8/14/03	14:20	22.49			
8/15/03	14:20	22.66	23.1	22.9	23.5
Average		22.4			
St dev		0.8			
Logger date	SFJD Reach 10 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	14:35	20.81			
8/10/03	14:35	20.97			
8/11/03	14:35	21.13			
8/12/03	14:35	21.3			
8/13/03	14:35	21.47			
8/14/03	14:35	21.63			
8/15/03	14:35	21.63	22.3	21.9	22.7
Average		21.3			
St dev		1.0			

Appendix Table A1: Maximum temperature of temperature loggers vs. FLIR profiles

Logger date	SFJD Reach 12 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	14:40	21.63			
8/10/03	14:40	21.8			
8/11/03	14:40	21.97			
8/12/03	14:40	20.81			
8/13/03	14:40	20.97			
8/14/03	14:40	21.13			
8/15/03	14:40	22.22	21.4	21.1	21.7
Average		21.5			
St dev		0.1			
logger date	BC Reach 1 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	15:10	18.73			
8/10/03	15:10	18.9			
8/11/03	15:10	19.06			
8/12/03	15:10	19.22			
8/13/03	15:10	19.38			
8/14/03	15:10	19.71			
8/15/03	15:10	19.8	18.1	17.7	18.7
Average		19.3			
St dev		0.4			
logger date	MC Reach 1 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	13:45	22.61			
8/10/03	13:45	22.61			
8/11/03	13:45	22.77			
8/12/03	13:45	22.77			
8/13/03	13:45	22.94			
8/14/03	13:45	22.94			
8/15/03	13:45	23.11	22.9	21.9	23.9
Average		22.8			
St dev		0.7			
logger date	MC Reach 2 time	temperature ºC	FLIR average	Min temp	Max temp
8/9/03	13:52	22.7			
8/10/03	13:52	22.81			
8/11/03	13:52	22.77			
8/12/03	13:52	22.65			
8/13/03	13:52	22.8			
8/14/03	13:52	22.9			
8/15/03	13:52	22.8	22.6	22.2	23.0
Average		22.8			
St dev		0.2			

Appendix table A2: Maximum temperature of temperature loggers vs. FLIR profiles

	Max temp (FLIR)	Pool area (m2)	Biomass (g/m2)	Total Biomass (kg)	Biomass g/m2
BC3	13	152.2	3744	569.8	24.60
BC2	17	203.8	4858	990.1	23.84
SFJD5	19	500.4	410	205.2	0.82
BC1	20	254.9	5066	1291.3	19.87
MC3	20	542	3254	1763.7	6.00
SFJD10	21	569.3	449	255.6	0.79
SFJD2	22	441.8	250	110.5	0.57
SFJD3	22	305.8	351	107.3	1.15
SFJD6	22	1337.1	828	1107.1	0.62
SFJD11	22	134.4	493	66.3	3.67
SFJD16	22	174.2	977	170.2	5.61
SFJD17	22	88.9	1771	157.4	19.92
MC2	23	1704	3554	6056.0	2.09
SFJD4	23	681.1	54	36.8	0.08
SFJD9	23	117.4	86	10.1	0.73
SFJD12	23	575.1	755	434.2	1.31
SFJD15	23	398.7	993	395.9	2.49
MC1	24	322.5	1333	429.9	4.13
SFJD7	24	587.2	802	470.9	1.37
SFJD8	24	103.7	7	0.7	0.07
SFJD13	25	407	991	403.3	2.43
SFJD14	25	186.1	486	90.4	2.61

Appendix table A3: Water temperature, pool area and trout biomass per reach. BC = Black Canyon Creek, SFJD = Mainstem South Fork John Day and MC = Murderers Creek