Modeling Effective Shade to Prioritize Riparian Restoration Efforts in the Johnson Creek Watershed

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Abstract

The influence of stream temperature on the survival and reproductive success of anadromous salmonid populations has become an increasingly concerning issue in the Pacific Northwest. Enhancing the height, density and extent of riparian vegetation is widely accepted as one of the most effective strategies for reducing stream temperatures, while also providing numerous ancillary benefits. Effective shade is defined as the percentage of direct beam solar radiation attenuated and scattered by riparian vegetation before reaching the stream surface and is a commonly used criterion for choosing where to restore riparian vegetation. This project aims to prioritize sites for riparian restoration through effective shade modeling within the geographic extent of the Johnson Creek watershed. Model inputs included a limited set of channel morphology and near stream vegetation attributes and were sampled from high spatial resolution LiDAR derived raster datasets (6 ft.) using Python script programming tools. A separate raster was created to depict restored conditions, in which the maximum height of near stream vegetation is set equal to 27 meters. Using a data intensive stream temperature model, Heat Source, effective shade simulations were performed along the mainstem Johnson Creek and all tributary streams over the duration of a single day in August. Model outputs provided average solar flux attenuation rates for near stream vegetation under current and restored conditions, the difference of which represented the potential increase in solar flux attenuation that would result from restoration. Model outputs were used to prioritize restoration efforts at the taxlot and subwatershed scale. Under a restoration scenario, 544.9 acres would be restored resulting in the additional solar flux attenuation of 209,118.9 watts/m^2*d^{-1}. Restoring only 22% of all taxlots, 50% of all subwatersheds, or 21% of all restorable acres would accomplish 50% of the solar reduction target. Restoring 38% of all taxlots, 69% of all subwatersheds or 55% of all restorable acres would accomplish 90% of the solar reduction target. A large portion of taxlots (40%) exhibited no difference in solar flux attenuation between current and restored conditions. Prioritizing at the taxlot scale, as opposed to subwatersheds, promotes a higher level of efficiency in the prioritization of restoration efforts. All taxlots should be further screened prior to final prioritization for opportunistic prospects such as landowner willingness, community support or proximity to existing restoration projects, and fundraising opportunities.

1.0 Introduction

1.1 Salmon in the Pacific Northwest

Salmonid populations in the Pacific Northwest have dramatically declined since European settlement, primarily due to the degradation of coldwater habitat (Allen et al. 2007). Currently, six salmonid species are listed under the Endangered Species Act as threatened or endangered in Oregon alone (NMFS 2013; USFWS 2013). Above all other water quality attributes, elevated water temperatures are particularly harmful to all life stages of salmonid species, causing weight loss, disease, competitive displacement or death (Beschta 1997; Richter & Kolmes 2005; ODEQ 2006). As water quality continues to degrade, the influence of stream temperature on the survival and reproductive success of anadromous salmonid populations has become an increasingly concerning issue in the Pacific Northwest (Chen et al. 1998; ODEQ 2006; Allen et al. 2007). As such, restoring thermal regimes is a major component of salmonid conservation and management (Richter & Kolmes 2005).

Every year, millions of dollars are spent on watershed restoration efforts aimed at increasing the abundance and resiliency of native salmonid populations in this region, yet many wild populations continue to decline causing policy makers, natural resource managers, and stakeholders question the effectiveness of these efforts (Beschta 1997; Beechie & Bolton 1999; Watanabe et al. 2005; Roni et al. 2002, 2008, 2010). By nature, salmonid populations are highly adapted to unique local conditions composed of spatially and temporally variable ecological processes and are known to exhibit large inter-annual fluctuations in abundance (Beechie & Bolton 1999; Richter & Kolmes 2005; Roni et al. 2002, 2010). When combined, these distinguishing features tend to confound management efforts and impede attainment of restoration goals. The cumulative effects of human population growth, competing societal priorities, and climate change are expected to further exacerbate the challenges associated with restoring salmon runs in the Pacific Northwest (Richter & Kolmes 2005). In sum, the quest for effective restoration strategies that will promote and sustain salmonid populations in the Pacific Northwest is a work in progress.

1.2 Stream Temperature Regulations

Water quality standards are established to protect the beneficial uses of state waters such as irrigation, recreation, hydropower or fish and aquatic life (ODEQ 2011). In the Pacific Northwest, water quality policy is largely driven by the need to protect the beneficial use of fish and aquatic life from the effects of water quality degradation. Fish and aquatic life are typically the most sensitive beneficial use to water temperature, with anadromous salmonid species being particularly vulnerable to temperature changes. The distribution, health, and survival of salmonid species is greatly influenced by stream temperature largely due to their cold-blooded, or ectothermic, nature (ODEQ 2006, 2008). Temperature standards are designed to accommodate the temperature needs of all fish and aquatic life, including specific salmonid life stages. (Nehlsen 1997; ODEQ 2008; Palmer 2009; Roni et al. 2010).

Numeric stream temperature criteria, expressed as a 7-day moving average of daily maximum temperatures, are determined by the Environmental Protection Agency (EPA) from the upper optimal physiological temperature preferences known to support the biological processes required in salmonid spawning, rearing, and migration life stages (Richter & Kolmes 2005; ODEQ 2008). In general, stream temperatures between 18-25 °C that last anywhere from hours to months can cause thermal stress, leading to weight loss, disease or competitive displacement. Given sufficient time, these same temperatures can also cause thermally induced fish mortality for species that are poorly adapted to the prevailing conditions (Richter & Kolmes 2005).

Streams that are found to violate water quality standards will be listed on the 303(d) list as water quality impaired and the formation of total maximum daily load (TMDL) allowances for pollutants of concern will be required (ODEQ 2008). TMDL's are developed by the Oregon Department of Environmental Quality (ODEQ) and submitted to the Environmental Protection Agency (EPA) for approval. TMDL's generally serve to identify the pollutant of concern, develop a loading capacity, identify pollutant sources and determine waste load allocations (ODEQ 2011). ODEQ will then work with implicated local or state agencies to implement the TMDL and attain the objectives.

With respect to water temperature, heat is the pollutant of concern which can enter the stream as direct solar radiation (non-point sources) or heated effluent from point sources. A temperature TMDL defines the amount of thermal energy that can be discharged into a water body without exceeding water temperature standards, and distributes waste load allocations to point and nonpoint sources (ODEQ 2011; Niemi et al. 2006).

1.3 Riparian Shade Restoration

Although direct solar radiation is just a part of the heat budget for any given stream, it is the most important source of radiation in terms of temperature regulation, particularly in mid latitude regions during the summer months (Beschta 1997; Johnson 2003; Allen et al. 2007; Li et al. 2012). Riparian vegetation provides a physical barrier between the stream and the sun that can attenuate and deflect this incoming solar radiation. As such, enhancing riparian vegetation (canopy height, density, and buffer extent) is widely accepted as one of the most effective strategies for reducing stream temperatures, while also providing numerous ancillary benefits including erosion control, flood mitigation, water purification, improved channel complexity, formation of instream and riparian habitat and general ecosystem resilience (Chen et al. 1998; Gebhardt & Fischer 1999; Holmes et al. 2004; Niemi et al. 2006; ODEQ 2006; Teels et al. 2006; Johnson et al. 2007; Kentula 2007; Li et al. 2012). More specifically, riparian vegetation promotes the formation of habitat through large woody debris (LWD) recruitment, by creating narrower, more complex stream channels with reduced width to depth ratios, and by providing a microclimate along the streambank characterized by cooler air temperature, reduced wind speed, and higher relative humidity (Opperman & Merenlender 2004; Gergel et al. 2007).

Effective shade is defined as the percentage of direct beam solar radiation attenuated and scattered by riparian vegetation before reaching the ground or stream surface (ODEQ 2006). In simple terms, effective shade is a function of near stream vegetation and channel morphology. The height of near stream vegetation controls the shadow length cast across the stream surface and timing of the shadow, whereas the channel width determines the length of shadow necessary to shade the stream surface (Boyd & Kasper 2007). In addition, changes in solar position based on the season, time of day, and geographic location will also greatly influence effective shade.

A strong predictive relationship has been observed between shade provided by riparian vegetation and stream temperature and, as such, it was selected by the Environmental Protection Agency (EPA) as a surrogate measure for stream temperature (Gebhardt & Fischer 1999; ODEQ 2006; Li et al. 2012). In general, surrogate measures are intended to provide managers with a cost-effective and workable tool for pollutant loading assessment and allocations (Gebhardt & Fischer 1999). When compared to stream temperature, effective shade is more stable over short periods of time, can be sampled and derived from widely available remotely sensed data sources, is easily translated into quantifiable management objectives and is more sensitive and responsive to management changes (Chen et al. 1998; Gebhardt & Fischer 1999; ODEQ 2006). Attainment of effective shade targets is equivalent to attainment of non-point source (NPS) load allocations (ODEQ 2006). A common approach to prioritizing restoration efforts aimed at stream temperature reduction uses riparian vegetation, valuated in terms of effective shade, as the site suitability criteria.

1.4 Prioritization Schemes

Prioritizing riparian restoration efforts can be done in many ways, but most approaches tend to share a few elemental components (Landers 1997). In general, most approaches tend to involve a determination of reference conditions, or the "system potential", and current conditions in terms of the site suitability criteria (Landers 1997; Tompkins & Kondolf 2000). Once determined, current conditions are compared to reference conditions to identify and prioritize areas performing below their ecological potential using a number of systematic approaches (Landers 1997). As described by Landers (1997), reference conditions, or system potential conditions, "...should represent a range of values that reflect local climatic, hydrologic, and geologic conditions." Developing reference conditions typically requires an interdisciplinary approach that examines aspects of regional geomorphology, hydrology, geography, ecology, and/or socio-economics as they relate to the site suitability criteria (Landers 1997). Reference conditions can be derived from historic and current data sources (aerial photos, visual assessments, water quality data and flow measurements, etc.) concerning aspects of either the system in question, or a functionally equivalent system (Harris & Olson 1997; Landers 1997; Palmer et al. 2005; USGS 2007).

Prioritizing riparian areas using effective shade criterion can be accomplished through a variety of prioritization schemes, including systematic ranking systems, hierarchical decision trees, mechanistic modeling techniques or any combination of the above. In general, techniques involving high resolution data sources and quantitative outputs will produce the most accurate and reliable results (Harris & Olson 1997; Fullerton et al. 2006). Effective shade can be estimated from aerial photos and remotely sensed vegetation data or directly measured using a solar pathfinder or gap light analyzer of hemispheric photos. While it is unreasonable to rely on direct measurements when dealing with large spatial extents, estimates derived from high resolution data sources are far more convenient and practical. Consequently, modeling effective shade using data derived from high resolution spatial data sources has become a popular tool for prioritizing riparian restoration projects aimed at reducing stream temperature.

1.5 Modeling Effective Shade

Various GIS based models have been developed over the past few decades to estimate effective shade, or some contingent parameter, as a function of the structure and orientation of riparian vegetation, channel width, directional flow of the stream, global position, time of day and time of year (Larson & Larson 1996; Chen et al. 1998; Li et al. 2012). The major difference between individual shade models is largely contained in the underlying set of algorithms used to calculate the heat energy balance. Shade models also vary in terms of their output and overall utility. Quigley (1981) developed the first algorithm to solve the temporally variable problem of shade cast by riparian vegetation as the sun travels along its daily arc (Li et al. 2012). Today, various similar algorithms exist that build upon this basic concept ranging from very simple to very complex (Li et al. 2012). More complex models incorporate additional variables, the data for which can be difficult and time consuming to collect, such as tree overhang, channel insulation and localized meteorological conditions (Johnson 2003; Li et al. 2012).

1.6 Johnson Creek Watershed

Johnson Creek and its tributaries experience annual warming beginning in late spring and lasting though the fall, largely due to anthropogenic non-point sources of heat loading. During this period, stream temperatures often exceed the criteria established to protect salmon and trout habitat during discrete life stages. Johnson Creek was 303(d) listed for temperature in 1998 due to observed exceedances of the biologically based numeric criteria for salmon and trout rearing (17.8 C) in the summertime of 1992. The Willamette Basin TMDL which was completed in 2006 further modified the listing for Johnson Creek. Two numeric criteria currently apply to Johnson Creek: salmon and trout rearing and migration (17.9° C) applies year round for most of the mainstem (river mile 0-23.7) while the criteria for salmon and steelhead spawning (13° C) applies October 15-May 15 from river mile 0.2-10.5.

During TMDL development, natural background radiation under the system potential condition was found to consume all assimilative capacity in Johnson Creek and, as such, received 100% of the waste load allocation. This meant that all anthropogenic sources of heat loading would need to be attenuated. While the tributaries of Johnson Creek are not 303(d) listed, the TMDL states that the temperature targets apply to all streams in the watershed since tributaries are known to contribute heat loading to the mainstem.

In 2012 and 2013, temperature loggers were placed throughout the Johnson Creek watershed to determine the location, magnitude, and duration of temperature standard exceedances still occurring. Results of these efforts suggest that the mainstem and many tributaries continue to exceed temperature standards for salmon and trout rearing and migration (17.9° C) with the exception of a few well-shaded tributaries. As of 2013, the duration of temperature exceedances at each logger ranged from 2-113 days per year, with maximum recorded temperatures between 20-19.7° C. Only two locations (out of 41 total) remained in compliance year round.

Existing riparian vegetation in the watershed generally consists of mixed forest with some coniferous forest and shrub areas. Many areas are dominated by blackberry, or young native plants and large mature trees. While some of the smaller headwater creeks have extensive riparian vegetation, all other riparian areas are either narrow, minimal, or lacking (JCWC 2002). As of 2013, over 100 restoration projects involving the enhancement of riparian vegetation to some extent have occurred or are currently underway in the watershed (JCWC 2013). The earliest projects date back to 1995; however most projects are relatively young and were not initiated until after 2000. Generally, planted trees will establish themselves within the first 5-10 years, depending on the species, but will not greatly increase shade until significant growth has occurred. Depending on the tree species, stream width, and other environmental variables, this could take 20-60 years. As such, the effectiveness of more recent restoration efforts may not exhibit significant increases in stream shading for decades to come. While some of the older projects have been monitored for their effectiveness and appear to be progressing with limited maintenance and human aid, many smaller projects are not actively monitored at this time and may take decades to produce significant results and benefits.

While numerous riparian restoration efforts have taken place in the watershed, temperatures continue to exceed the numeric criteria for salmon spawning and rearing. Additional riparian efforts are needed to achieve effective shade targets established in the TMDL and reduce stream temperatures. Confounding this issue is the fact that financial resources are limited, the effectiveness of past restoration efforts are difficult to evaluate given limited long term monitoring data, and effective shade data are lacking for the tributaries of Johnson Creek. Combined, these factors make it difficult to prioritize areas for riparian restoration and allocate resources effectively and economically.

1.7 Purpose of Project

The purpose of this project is to assist the Johnson Creek Watershed Council (JCWC) in prioritizing areas for riparian restoration within the geographic extent of the Johnson Creek Watershed. Modeling effective shade along Johnson Creek and its tributaries, under current and restored conditions, will help to identify areas that produce the greatest benefit in terms of shade per unit restored.

There are two main objectives of the project: modeling effective shade under current and restored conditions and prioritizing areas for riparian restoration based on the modeling outcomes. The first objective involves modeling effective shade for all Johnson Creek tributaries and mainstem using Heat Source, a model developed to accommodate the spatial variability inherent in hydrological systems. Physical and biological model input parameters are derived from high spatial resolution light detection and ranging (LiDAR) data sets and processed using GIS and processing tools programmed using python scripts. The model will calculate solar flux at the stream surface and percent effective shade under both current and restored conditions, the latter of which will depict the height of restored vegetation at maturity. For the second objective, modeling results will be used to prioritize restoration efforts at the taxlot and subwatershed scale, based on the potential for solar flux attenuation to increase under restored conditions. The spatial extent of this study includes both the mainstem and all tributaries of Johnson Creek while, temporally, restoration objectives project out approximately 60 years.

2.0 Methods

2.1 Study Area

2.1.1 Geography

The study area for this project includes all streams and near-stream vegetation within the Johnson Creek watershed, which encompasses two USGS 12-digit Hydrologic Units, Lower

Johnson Creek (170900120103) and Upper Johnson Creek (170900120101). The Johnson Creek watershed occupies a relatively small but densely populated area of 54 square miles within the Willamette River Basin in Oregon. The watershed is home to 180,000 people and includes portions of the cities of Milwaukie, Portland, Gresham, Happy Valley and Damascus and Multnomah and Clackamas counties (see Figure 1). The creek itself travels 26 miles west from its headwaters at the foothills of the Cascade Range, near Boring, to its confluence with the Willamette River in Milwaukie. The creek is fed by numerous springs, surface runoff, and 50 inches of annual precipitation. Major tributaries include Badger, Kelley, Mitchell, Sunshine, Veterans and Crystal Spring creeks. A total of 40 subwatersheds, ranging from <1 to 7 mi^2 are recognized by the Johnson Creek Watershed Council (see Figure 2).

The geology of the watershed traces back to the Missoula floods and the Columbia River basalt group, which collectively deposited a thick layer of sediment underlain by thick basalt lavas. Large, flat, floodplains dominate the northern part of the watershed as a result of these historic floods (BES 2001). Most of the watershed's tributaries are located in the southern part of the watershed, where the topography is steep and varied (BES 2001). Elevation varies between 26-1100 feet above sea level and slopes generally range between 1-25%, with a few localized exceptions such as Mt. Scott and Powell Butte (10-30% slope).

Johnson Creek passes through heavily developed residential, commercial, and industrial areas before emptying into the Willamette River (Niemi et al. 2006). In general, the upper portion of the watershed is dominated by agricultural and rural residential land uses while the lower portion contains heavily developed urban areas (JCWC 2002).

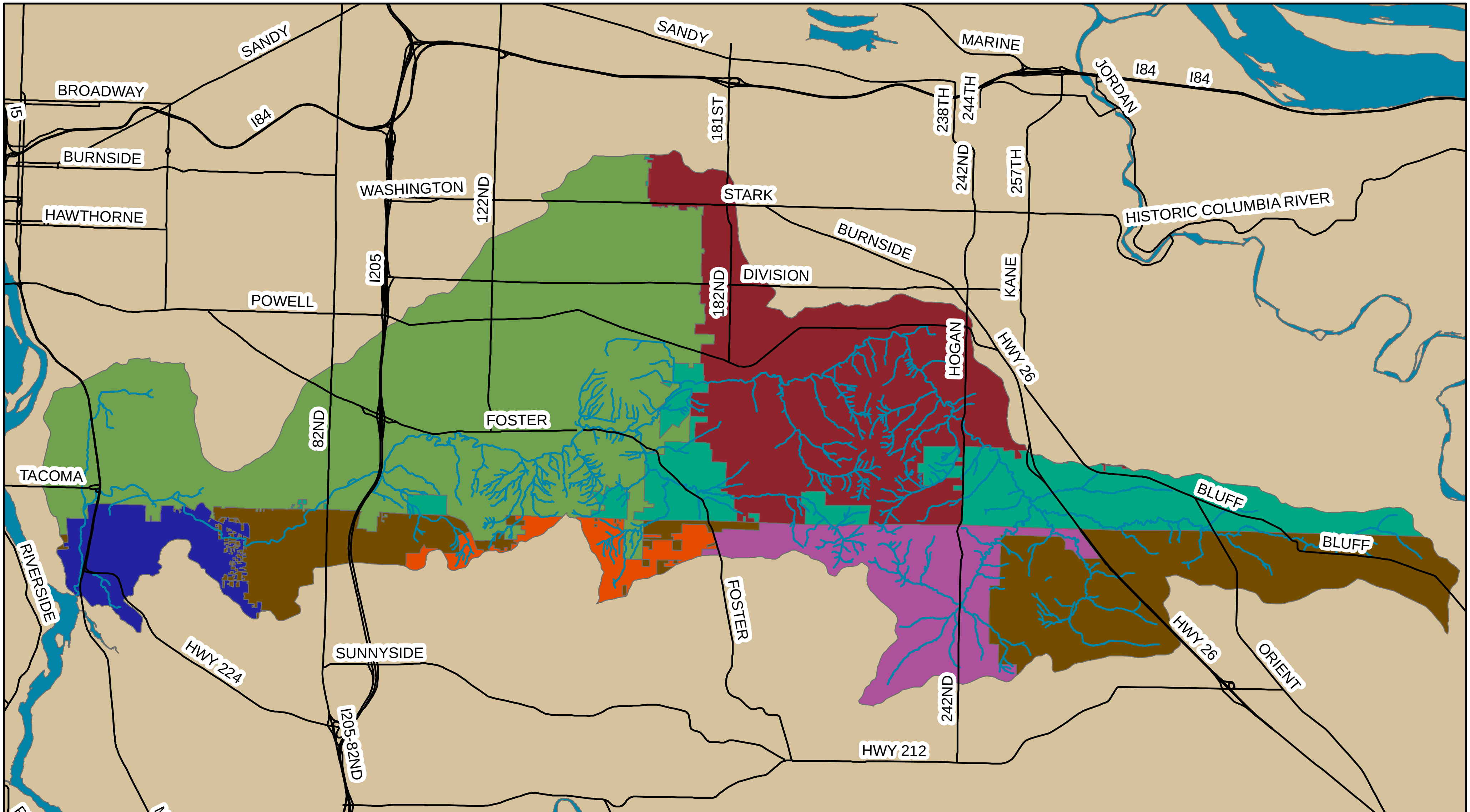


Figure 1: Jurisdictional Boundaries in the Johnson Creek Watershed

November, 2013

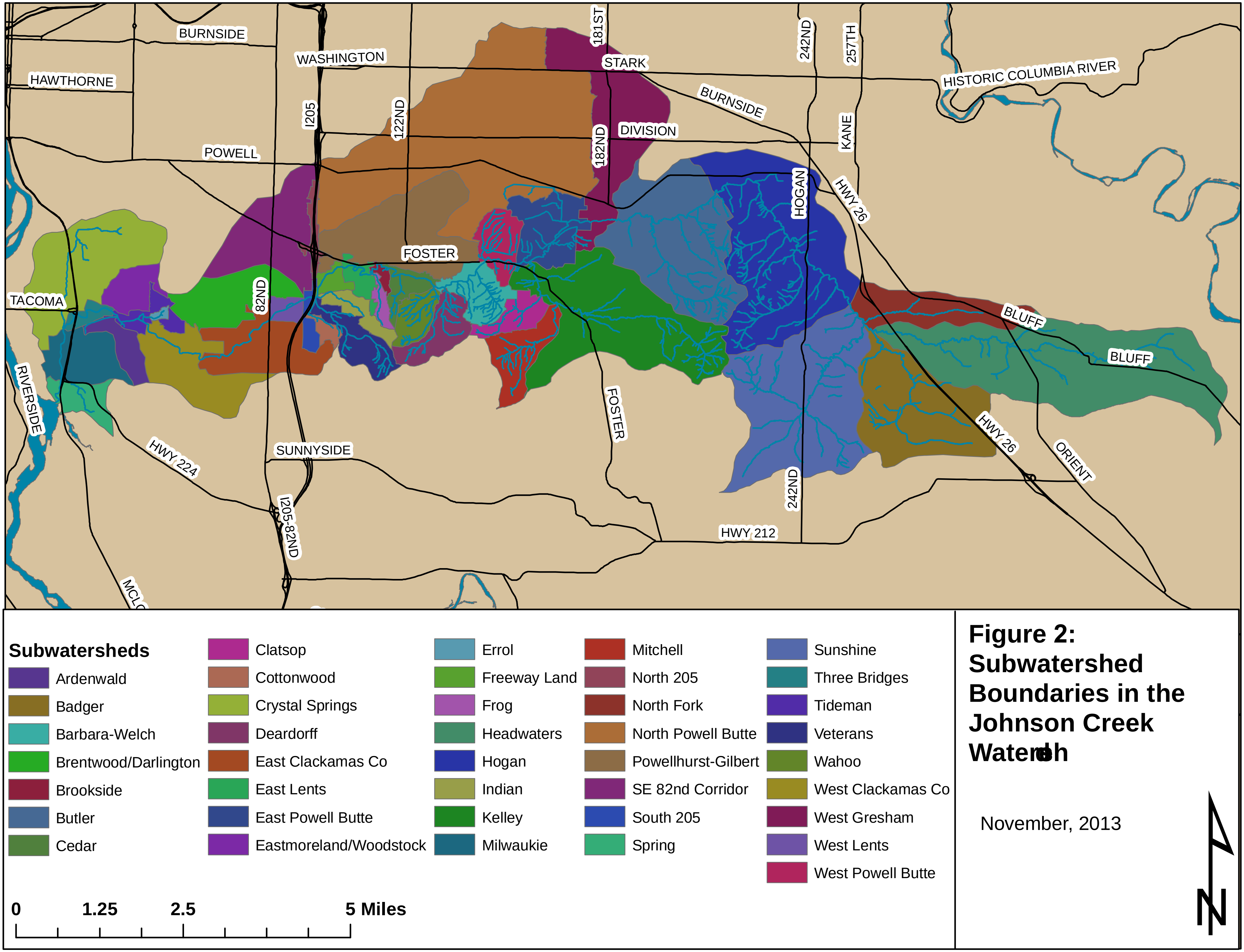


Figure 2: Subwatershed Boundaries in the Johnson Creek Watershed

November, 2013

2.1.2 Disturbance History/ Ecological Integrity

Gradual development of the watershed has adversely impacted the ecological integrity of the watershed. Before urbanization, the Johnson Creek watershed hosted a diverse array of habitats including forests, marshes and wetlands (BES 2001). As settlers arrived, the emergence of sawmills, agriculture, ranching and general industrial, commercial or residential development gradually began to diminish natural resources and degrade ecological functioning within the watershed (BES 2001). In the 1930's the Works Progress Administration (WPA) straightened, deepened, and lined the mainstem with rock in an effort to control flooding (BES 2001). Unfortunately, these and other flood control strategies have accomplished very little in terms of flood control, and have instead contributed to degraded streambank and wetland conditions (BES 2001). Native species of salmon and trout, once plentiful in Johnson Creek, were severely depleted by the 1980's; many of these native populations were eventually listed as threatened under the Endangered Species Act (ESA) during the late 1990's (BES 2001).

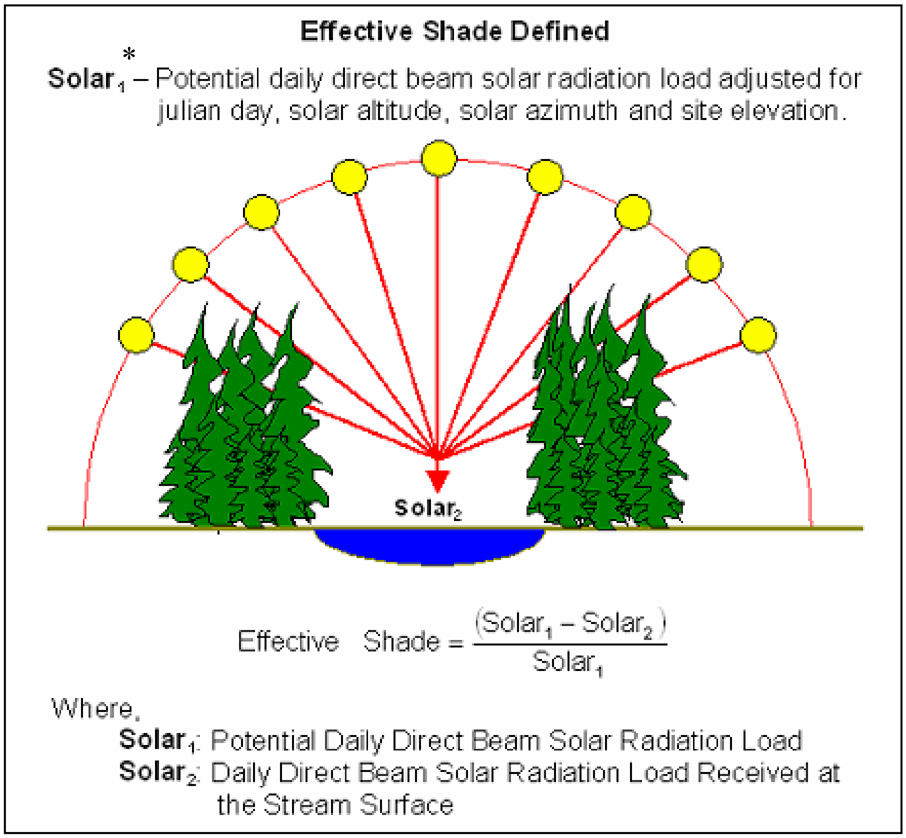
Beginning in the 1990's, fish surveys have periodically been performed to determine the species and extent of fish presence in the watershed (JCWC 2002; 2012). While salmon and trout species still inhabit Johnson Creek, their abundance has been reduced to a fraction of historic levels (JCWC 2012). There are three salmonid species listed as threatened under the ESA that are known to occur within the Johnson creek watershed: the Lower Columbia River Chinook Salmon Evolutionarily Significant Unit (ESU), Lower Columbia River Coho Salmon ESU, and Lower Columbia River Steelhead Distinct Population Segment (DPS). In addition, coastal cutthroat occurs within the watershed but is not listed under the ESA within the extent of the watershed. Recent fish surveys (2011) found native salmonid species occurring in nearly every tributary surveyed, even small intermittent streams.

There is a clear need for riparian restoration in the Johnson Creek Watershed to protect salmon populations and meet TMDL requirements for stream temperature. Disturbance or removal of riparian vegetation, channel modification, and alteration of the hydrologic regime resulting from historical development has greatly compromised ecological functioning within the watershed. Overall water quality and habitat conditions in the Johnson creek watershed are generally rated as poor, with problems related to sediment, bacteria, water temperature, streamflow, flooding and chemical contamination currently present and considered in management activities (BES 2001; ODEQ 2005). Current in-stream and near stream conditions are characterized by extensive bank erosion, few pools, little to no LWD, homogenous channel bedform, substrate dominated by fine sediments, high levels of channel incision, all of which provide very little benefit to native salmonid populations in terms of habitat (BES 2001). Of particular relevance to this study, optimum salmon and trout habitat requires an average of 80% effective shade (JCWC 2012), yet as of 2002, effective shade on the mainstem of Johnson Creek averaged only 40% leaving ample room for improvement.

2.2 Modeling

Modeling was accomplished using Heat Source (version 7.0), a temperature model utilized by ODEQ to estimate stream network thermodynamics and hydrology. It was developed by graduate students (Mathew Boyd and Brian Kasper) in 1996, as a Masters Thesis at Oregon State University in the Bioresource Engineering and Civil Engineering Departments and has been regularly updated through 2007 (ODEQ 2006, Boyd & Kasper 2007). Heat Source is recognized as a relatively data intensive stream temperature model utilizing high resolution inputs and producing equally refined outputs (Watanabe et al. 2005; Boyd & Kasper 2007). Heat Source uses multiple Microsoft Excel worksheets to store and configure model inputs and to chart and store model outputs. Using Visual Basic programming to calculate simulation algorithms, the model is capable of executing various modules including simulation of effective shade, comprehensive heat and mass transfer, and water column temperature. The module utilized for this study, referred to as Shade-a-lator, is a solar routing routine from the sun to the stream surface used to simulate effective shade and stream surface solar exposure. More specifically, Shade-a-lator calculates the potential and received solar radiation flux at the stream surface while also providing percent effective shade output data. For the purposes of this study, effective shade simulations were calculated as a function of geographic positioning and limited near stream vegetation and channel morphology attributes only.

Effective shade estimates are calculated using a relatively simple and straightforward algorithm (Figure 3). Heat Source simulates the sun's daily path across the sky based on user defined parameters (geographic position and Julian day) to determine the potential amount of incoming solar radiation. The amount of incoming solar radiation actually received at the stream surface is estimated as a function of potential solar insolation (see glossary for definition), near stream vegetation (height, density and extent), elevation, gradient and topographic shade. For the purposes of this study, the aforementioned subset of near stream vegetation and physical attribute data was sampled from LiDAR derived raster data, the methods of which are further discussed in the following sections. Please refer to the Heat Source Methodology in Appendix A for further details (Boyd & Kasper 2003).



Source: Heat Source Methodology (Boyd & Kasper 2003)

* Does not account for near stream vegetation; represents potential solar insolation without any interference from vegetation.

Figure 3: Visual representation of effective shade as it changes throughout the course of a day, in conjunction with the path of the sun. Equation used to calculate effective shade using Heat Source is presented.

2.3 Base Data

A digitized stream layer, including the Johnson Creek mainstem and all tributaries, was developed by the Johnson Creek Watershed Council (JCWC) in 2007 using a combination of LiDAR raster data (6 ft. resolution) and aerial photographs (insert resolution), and subsequently modified in 2009 to include additional data provided by the City of Gresham. This pre-existing polyline stream layer was digitized using high spatial resolution imagery and, as a result, exhibited a high level of accuracy when overlain with current aerial photographs and LiDAR derived raster data (2007). Subwatershed boundaries were delineated by the JCWC using this same digitized stream layer. Both the polyline stream layer and subwatershed boundary layer were acquired with the help of various members from the Inter-jurisdictional Committee (IJC) for the Johnson Creek watershed. Once acquired, the polyline stream layer was subdivided into many separate streams in ArcGIS, such that each stream was contained within a separate shapefile, and could be sampled and modeled separately. All streams less than 50 meters in length fell below the minimum length required for sampling and, as such, were excluded from the study. A total of 461 streams were delineated, 14 of which fell below the minimum length requirement resulting in a final count of 448 streams to be sampled and modeled.

LiDAR derived raster datasets for bare earth (DEM) and vegetation height within the boundary of the watershed were provided by Ryan Michie (ODEQ 2012) and were pieced together from three separate data sources. The majority (~90%) of LiDAR data came from the Portland/Mt. Hood data acquisition project, flown between March 16th -April 15th of 2007 (3 ft. resolution). A small portion of the watershed in the Milwaukie area came from the Portland Pilot study flown in March of 2004 (6 ft. resolution). Another small portion of the watershed in the Crystal Springs area came from the Lower Columbia Study, flown between January 10th and February 12th of 2005 (6 ft. resolution). Once combined, the final resolution of the raster data for bare earth (DEM) and vegetation defaulted to the coarsest of all three sources, 6 ft.

The Datum used for all spatial data analysis was D_North _American_1983_HARN with a geographic coordinate system of GCS_North_American_1983_HARN and projected coordinate system of NAD_1983_HARN_Lambert_Conformal_Conic. Jurisdictional (city, county, and metro) and 12th field Hydrologic Unit (HU) boundaries were derived from public RLIS data dated August 2013 (RLIS 2013). Additional base data concerning taxlot attributes (such as land ownership and land use) and subbasin boundaries were provided by members of the IJC and used for post-modeling data analysis purposes.

2.3.1 Restored Conditions

The maximum near stream vegetation height under restored conditions was determined using the average height at maturity for six of the most common riparian tree species planted for restoration purposes in the Johnson Creek watershed. For this study, trees are considered mature when they reach 90 percent or more of their maximum height (Niemiec et al. 1995); the age at maturity for all six tree species was averaged to determine the length of time elapsed between current and restored conditions. The most common riparian tree species were identified using the Portland Plant List of Native Plant Communities: Mixed coniferous/deciduous riparian forest (ODOT 2011). They include: big leaf maple (*Acer macrophyllum*), red alder (*Alnus rubra*), Oregon ash (*Fraxinus latifolia*), black cottonwood (*Populus balsamifera var. trichocarpa*), Pacific willow (*Salix lucida ssp lasiandra*) and Western red cedar (*Thuja plicata*). Two additional tree species, black hawthorn (*Crataegus suksdorfii*) and quaking aspen (*Populus tremuloides*), were included in the Portland Plant list for this community but are not commonly planted for restoration purposes and as such, were excluded from the maximum restored height calculation (Jenkinson, personal correspondence, February 19, 2013).

For each tree species, the height at maturity was derived from the USDA PLANTS database and the average of all values came to 26.6 meters. The maximum height of vegetation under restored conditions was rounded up to 27 meters to account for the occasional presence of Douglas Fir trees (*Pseudotsuga menziesii*), which reach heights of 200 ft. (61 m) at maturity. Douglas Fir trees were not included in calculating the maximum height due to the infrequency of their being planted for restoration purposes (Jenkinson, personal correspondence, February 19, 2013) and their exclusion from the "most common" category in the Portland Plant List. However, they are known to frequently occur naturally and there is some debate over whether or not they should continue to be excluded from riparian restoration projects and to what extent they currently are excluded. The average age at maturity for each species was derived from a few different sources and estimated at 55 years old (Niemic et al. 1995, Michie 2013); see Table 1 for further details.

Table 1: Average height and age at maturity for six of the most common riparian tree species planted in riparian restoration projects.

Species	Age at maturity	[4]Height at maturity (m)
Big leaf maple (*Acer macrophyllum*)	[1]60	18
Red alder (*Alnus rubra*)	[1]65	27
Oregon ash (*Fraxinus latifolia*)	[1]60	21
Black cottonwood (*Populus balsamifera var. trichocarpa)*	[1]60	30
Pacific willow (*Salix lucida ssp lasiandra*)	[3]30	16
Western red cedar (*Thuja plicata)*	[2]55	45

[1]*Source: Niemic et al. 1995*
[2]*Source: Site Index Growth Curve provide by Ryan Michie (2013)*
[3]*Source: Professional judgment/correspondence with JCWC*
Source: USDA Plants Database (accessed online 2013)

Using LiDAR derived sampling data, current day vegetation was divided into two categories: vegetation greater than or equal to 4m in height and vegetation less than 4m in height. These two categories were used to classify vegetation as "restorable" or "un-restorable" based on the rationale described below.

Vegetation that is currently greater than or equal to 4m in height is likely comprised of trees and/or large shrubs that provide some level of shade to the stream. As such, these areas are unlikely to be prioritized for restoration unless they happen to be invasive, in which case restoration would, indeed, be desirable, but still unlikely to occur due to resource constraints. Where buildings and roads occurred within the restoration buffer, vegetation height also remained unchanged, since restoration is not likely to be feasible in these areas (see Figure 4). All areas with current vegetation greater than or equal to 4m in height, or occupied by buildings and/or roads are collectively referred to as the "un-restorable" area.

Vegetation that is currently less than 4m in height is likely comprised of a mixture of native and invasive shrubs, herbaceous grasses and sedges that contribute very little to stream shading or contains no vegetation at all (Portland Plant List 2010). While native understory vegetation is not typically targeted for restoration, these areas would still have the largest likelihood of receiving restoration efforts due to their lack of shade producing structure, higher likelihood of containing invasive species, or a lack of any vegetation at all. The total area within the restoration buffer occupied by vegetation <4 meters in height is collectively referred to as the total "restorable" area in the watershed (Figure 10).

A separate restored conditions raster was created by modifying the current-day LiDAR derived raster dataset (6 ft.). The restored conditions raster was created by delineating a restoration buffer along all streams within the watershed, extending 15 meters to either side of the stream channel, which represents the furthest distance from the stream in which restoration is likely occur. This buffer width has also been shown to provide an adequate level of shade to small streams in various studies (WSDOE 2007). Within the restoration buffer, vegetation greater than or equal to 4 meters in height (un-restorable area) remained unchanged, whereas vegetation less than 4 meters in height (restorable area) was set to equal the maximum height under restored conditions (27m). All un-restorable acres remained unchanged to control for differences between sites and evaluate the solar flux reduction resulting from restoration efforts alone. In sum, restored conditions represent the condition of the watershed after all restorable acres have been restored, and the vegetation therein has been allowed to reach its maximum height at maturity (~55 years later) while holding all un-restorable area constant.

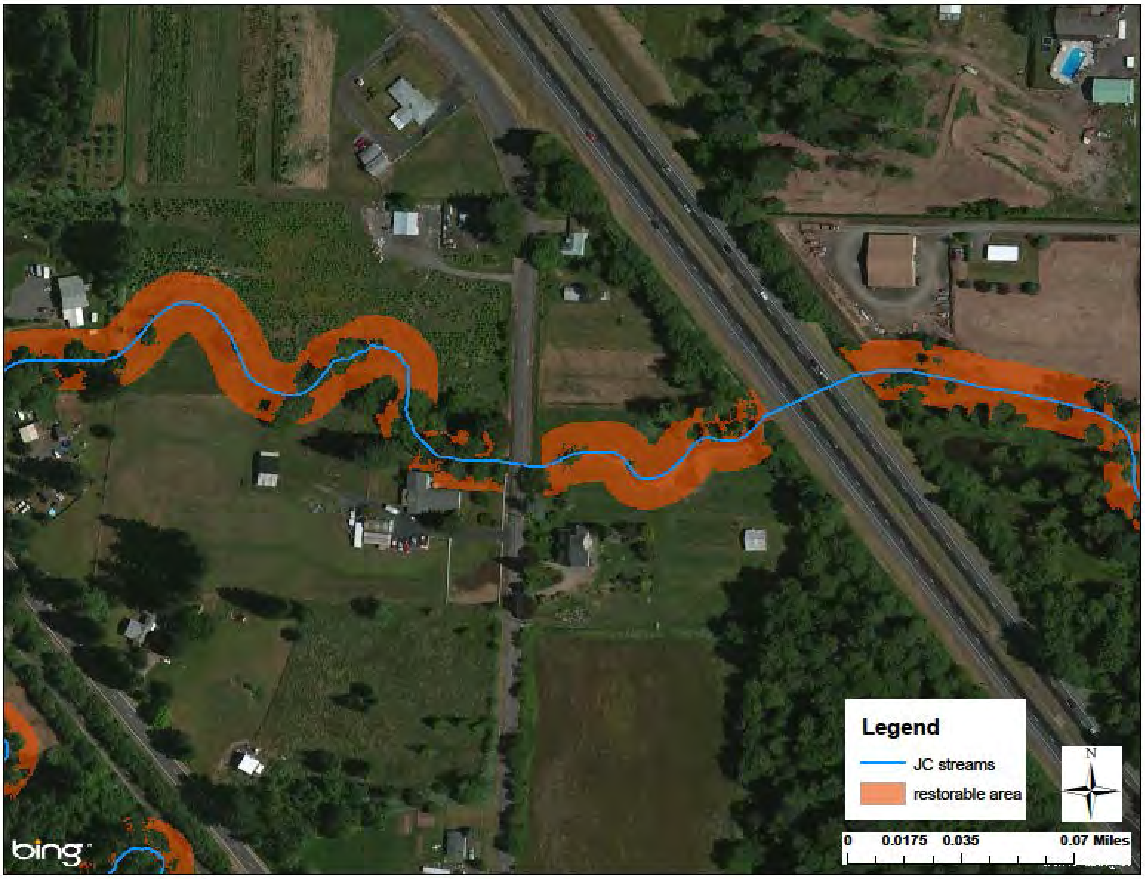


Figure 4: Example of restored conditions along streams in the Johnson Creek watershed. Area in orange corresponds to restorable area, or area within 15m of stream channel containing vegetation <4m in height.

2.4 Spatial Data Derivation

All physical attribute and near stream vegetation data were sampled from LiDAR derived raster datasets (6 ft. resolution) using Ttools, an ArcGIS extension developed by the Oregon Department of Environmental Quality (ODEQ) for use in conjunction with Heat Source, and the LiDAR Landcover Sampler, a python script programming tool designed by Ryan Michie (ODEQ 2011). All of the above programming tools were pre-existing and previously utilized for other projects; Ttools is publicly available for downloading from ODEQ's website while the Landcover sampler is personal property of Ryan Michie.

2.4.1 Sampling Units

Each stream was sampled for physical attribute information and near stream vegetation at a longitudinal sampling rate of 50 meters using a systematic area sampling approach. Two different sampling units were used; one primarily for sampling physical attributes and one primarily for sampling near stream vegetation. Longitudinal sampling nodes occurring at 50m intervals were used to sample physical attribute data including elevation, gradient, geographic coordinates and topographic shade. At each of these longitudinal sampling nodes, near stream vegetation height and bare earth elevation were sampled at a higher spatial resolution using a radial sampling pattern approach. The radial sampling approach involved multiple polygon-type sampling units. The following section describes the radial sampling pattern used for deriving data within polygons only.

2.4.2 Vegetation Height and Ground Elevation Sampling

In order to evaluate the difference in solar flux attenuation provided by near stream vegetation under current and restored conditions, the following sampling pattern was used to sample near stream vegetation height and bare earth elevation from both current and restored condition raster datasets. At each longitudinal sampling node, radial sampling extended 30 meters out in every cardinal direction (8 total) at 2 meter intervals. The resultant radial sampling pattern is made up of a circle with eight "wedges", or directional zones, and 15 concentric circles radiating out from the sampling node at every 2 meters. Within each wedge, area samples were taken every 2 meters out from the stream channel, up to a distance of 30 meters, resulting in a total of 15 polygons sampled in each cardinal direction (see Figure 6). Samples that occurred within the North wedges were not included in the final model since the sun does not shine from that direction in the Northern Hemisphere and consequently, shadows will not be cast in a southerly direction (Boyd & Kasper 2003). Therefore, 105 polygons were individually sampled (excluding the North wedges) for near-stream vegetation height and bare earth elevation, at every 50 meters of stream length (see Figures 5 & 6).

Each individual polygon sampled was assigned an identifying code, LWV, which is a function of:

- *Stream km*: the stream kilometer, or distance from stream mouth, for sampling node
- *WedgeZone:* number associated with cardinal direction of wedge

Cardinal Direction	Wedge Zone
NE	1
E	2
SE	3
S	4
SW	5
W	6
NW	7

- *VegZone*: number associated with the distance of each polygon from sampling node, or stream channel (see Fig. 7 below)

$$LWV = (stream\ km * 10{,}000) + (WedgeZone * 100) + (VegZone)$$

While LWV codes are unique to the stream they are associated with, they are not unique across streams (i.e. many streams will have LWV codes in common but no stream will have duplicate LWV codes occurring in their own polygons).

Within each polygon sampling unit, current near stream vegetation height was sampled from LiDAR derived raster data (6 ft resolution) using the LiDAR Landcover Sampler programming tool. Summary statistics for near stream vegetation height were generated for each polygon including: minimum, maximum, range, mean, standard deviation, and sum. The same summary statistics were generated for bare earth elevation within each polygon, as sampled from the same DEM raster dataset used in Ttools (6 ft. resolution).

Near stream vegetation height under restored conditions was sampled from the restored conditions raster dataset using the LiDAR Landcover Sampler (Michie 2011), following the same radial sampling procedure used to sample current vegetation.

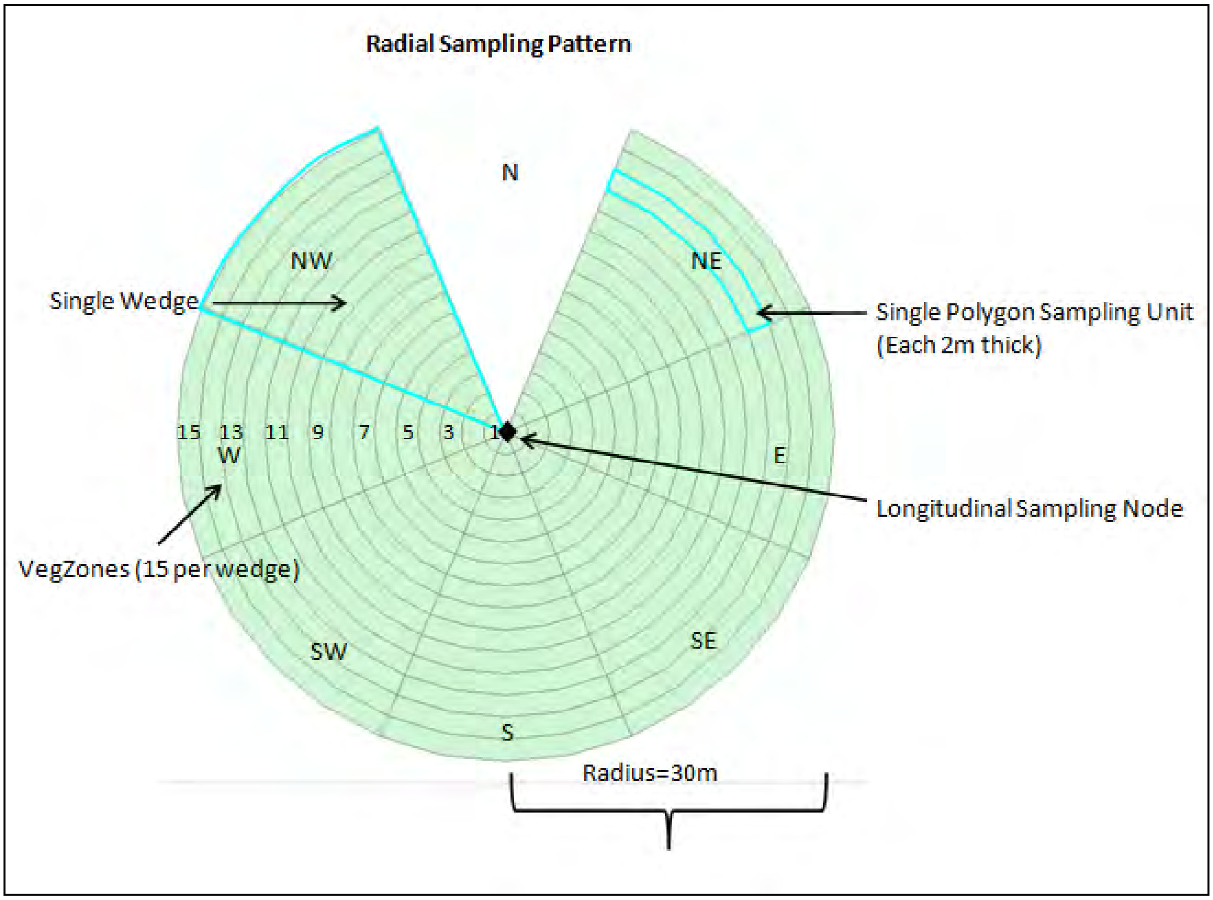


Figure 5: Radial sampling pattern occurring at each longitudinal sampling node (every 50 meters of stream length). Sampling occurs 30 meters out from each sampling node at 2m increments, in seven cardinal directions. Each single polygon is assigned a unique identifying code, referred to as LWV, based on its location both within the radial sample and along the stream (distance from mouth). Each polygon is sampled for vegetation height (under current and restored conditions) and bare earth elevation. Northernmost wedges are excluded from modeling since the sun does not shine from that direction in the Northern hemisphere. Sampling of basic physical attribute data (geographic coordinates, elevation, gradient, and topographic shade) employed a coarser sampling pattern described in section 2.4.3.

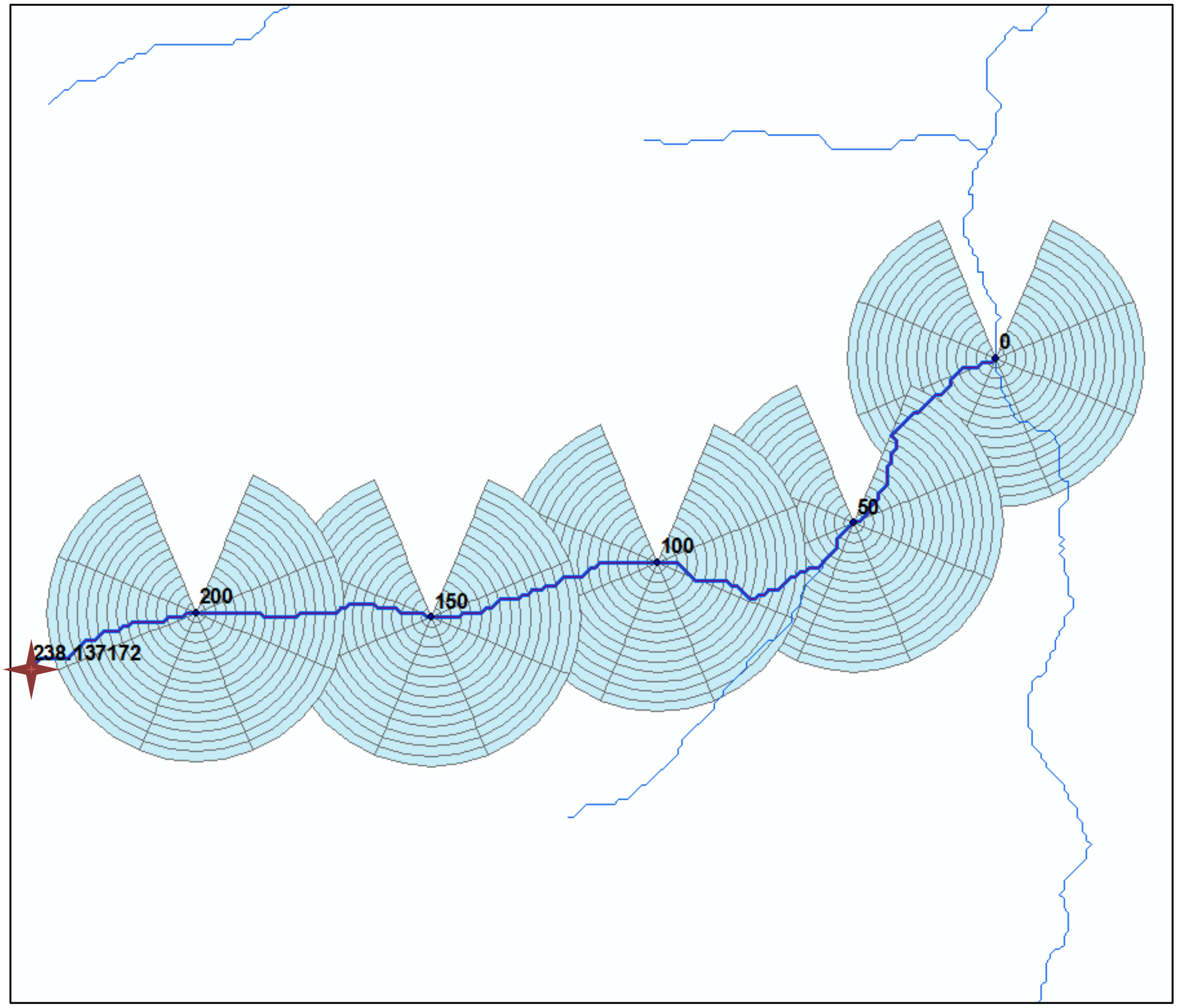


Figure 6: Series of radial sampling patterns distributed along a single stream. Sampling occurs at a longitudinal sampling rate of 50 meters. Each longitudinal sampling node is labeled according to its stream length (m), with length 0 starting at the mouth of the stream. The last sample at the upper end of the stream (length=238.14m), as indicated by a red star, falls short of 50 meters from the previous sample and is not included in the model. Radial sampling pattern is not used for all spatial data derivation; a coarser sampling pattern occurs at each longitudinal sampling node to derive basic physical attribute data. See section 2.5, page 29 for an explanation of how overlapping polygons will not result in double-counting.

2.4.3 Elevation, Gradient, and Topographic Shade Sampling

Additional physical attribute data was sampled at a coarser scale using longitudinal sampling node as the sampling units (see Figure 6). At each longitudinal sampling node (every 50 meters of stream length), Ttools was used to derive the following physical attribute data from DEM raster data: geographic coordinates, maximum topographic shade angle, elevation and gradient. Ttools calculated elevation by sampling 25 pixels surrounding each node and defaulting to the lowest elevation found. Stream gradient was calculated from the elevation of each sampling node and the distance between nodes. Topographic shade angles were calculated at every 50 meter sampling node in three directions: east, south, and west. For each angle, Ttools sampled DEM pixels for elevation up to 10 km away from each longitudinal sampling node and recorded the maximum topographic shade angle found within this zone.

Longitudinal sampling of physical attribute data (i.e. elevation, gradient, topographic shade) was not repeated for restored conditions since these values remained the same under both current and restored conditions; the only difference between current and restored input parameters was the near stream vegetation height and density, the latter of which was calculated and not sampled (see Section 2.5 for density calculation details).

2.5 Input Parameters and Modeling Outputs

Almost all input parameters for Heat Source modeling were derived from raster data using Ttools and LiDAR Landcover Sampler programming. See Table 1 for detailed information on the data sources and resolution of all modeling inputs. In addition to these derived input parameters, vegetation density values were estimated for each polygon. Density was estimated as a function of the spread, or dispersion, of height values from the mean using the equation provided below.

$$\rho = -80/7 \times [(max - mean)/stdev] + 90$$

Using LiDAR derived sampling data for near stream vegetation height, the difference between maximum and mean was divided by the standard deviation for each polygon sampled; the resulting ratios ranged from 0 to 7 (see red-colored portion of equation above). Higher ratios indicate low density vegetation; while the standard deviation is low, the difference between the max and mean is high due to the presence of outliers (ex: a single large tree surrounded by shrubs). Conversely, a lower ratio indicates higher density vegetation; the difference between max and mean is almost the same as the standard deviation and both values are relatively low indicating a relatively robust canopy of uniform height (ex: stand of trees all generally the same height). If there is no deviation from the mean at all, the ratio goes to 0 and density is going to be very high (maximum possible = 90%).

After calculating the ratios for each polygon, the density equation was derived using the point-slope formula for a linear line with two known coordinates. The two known coordinates were determined by choosing two polygons that represented opposite extremes in terms of spread (one with a high ratio and one with a low ratio) and assigning density values to them. The lowest density was assigned a value of 10% whereas the highest density was assigned a value of 90%. For comparison, other studies were identified that used similar maximum or fixed density values (~85%) for effective shade modeling (WSDOT 2007). The resulting coordinates were: *(0, 90)* and *(7, 10)* where x is equal to the ratio (difference maximum and mean divided by standard deviation) and y is equal to the density. The following formulas were used to derive the density equation using these two known coordinates:

$$m = (y_1 - y_2)/(x_1 - x_2)$$

Where m equals the slope of the line, and the point-slope formula:

$$(y - y_1) = m(x - x_1)$$

Shade simulations were set to occur over the defined stream network for the duration of a single day, August 1, 2012, to capture the environmental conditions present when stream temperatures are expected to reach their maximum values, and where the potential to exceed stream temperature regulations is at its greatest. At each longitudinal node, the model calculated the amount of incoming solar radiation attenuated by near stream vegetation in each polygon once every minute during the specified 24 hour period. The final output for each polygon is provided as an average of all values within the 24 hour period. In sum, the final output provides the daily average of incoming solar radiation that is attenuated by the vegetation within each polygon (henceforth referred to as solar flux attenuation). Based on the net incoming solar radiation at each longitudinal sampling node, the model also calculates the daily average of percent effective shade at each longitudinal sampling node. Model outputs for the average daily solar flux attenuation (watts/m^2/d^{-1}) in each polygon were ultimately used in the prioritization scheme, whereas effective shade estimates were not. Effective shade estimates were, however, used for quality control purposes, which is further discussed in Section 2.8.

It should be noted that the solar flux attenuation estimates associated with each polygon represent the amount of incoming solar radiation prevented from reaching the stream surface at a specific location, which is determined by the location of the longitudinal sampling node the polygon corresponds to. In other words, the model is not estimating the overall solar flux attenuation provided by the vegetation within a polygon; it only estimates the solar flux attenuation provided to a discrete point along the stream. In this way, the overlap that occurs between neighboring polygons (see Figure 7) will not result in certain riparian areas being double-counted; overlapping polygons will have completely different solar flux estimates since they will each correspond to two completely different points along the stream.

Each stream was modeled twice; once under current conditions and once under restored conditions. Current and restored models differed only with respect to near stream vegetation height and density; all other inputs were the same between both current and restored scenarios. The following table (Table 2) provides information on the sources and resolution of raster datasets used to derive spatial data concerning near stream vegetation height and physical attribute under both current and restored scenarios.

Table 2: Shade-a lator input parameters derived from geospatial data (except for density). Where applicable, information concerning the resolution of data source is provided.

Input Parameters	Data Source	Resolution
Elevation, Gradient, and Topographic Shade Sampling		
Stream length (km)	Derived from digitized stream channel-shapefile using Ttools; stream channel digitized using LiDAR derived raster data	6 ft.
Coordinates (lat/lon)	Derived from DEM raster data using Ttools	6 ft.
Gradient	Derived from DEM raster data using Ttools	6 ft.
Elevation (meters)	Derived from DEM raster data using Ttools	6 ft.
Topographic shade (in 3 directions)	Derived from DEM raster data using Ttools	6 ft.
Vegetation Height and Ground ElevationSampling		
LWV codes	Generated by Ttools	N/A
Bare earth elevation (mean)	Derived from DEM raster data using LiDAR Landcover Sampler	6 ft.
Vegetation height (mean)	Derived from LiDAR raster data using LiDAR Landcover Sampler	6 ft.
Density	Estimated from linear equation (see Section 2.5)	N/A

2.6 Priority Ranking

Solar flux attenuation estimates from current conditions were subtracted from restored condition estimates to determine the net increase in solar flux attenuation per polygon under restored conditions. This is essentially the amount of solar insolation prevented from reaching the stream surface that is a direct result of restoring all restorable area within that polygon. The net increase in solar flux attenuation under restored conditions will henceforth be referred to as potential solar flux attenuation (see Glossary for further clarification). Post processing of model outputs involved the use of additional programming tools (using python scripts) to rearrange, or sort, the simulation data results into a table format with the net increase in solar flux attenuation (under restored conditions) listed per polygon. Potential solar flux attenuation estimates were assigned to individual taxlots and subwatersheds by aggregating all streams (and the polygons therein) within their boundaries and taking the sum of the potential solar flux attenuation for those streams. The processes used for prioritizing both taxlots and subwatersheds are discussed in further detail below.

2.6.1 Prioritizing Taxlots

Modeling results for all streams were spatially joined to taxlot data and incorporated into a single taxlot shapefile in ArcGIS using the following procedure. Polygons containing potential solar flux attenuation data were converted to points in ArcGIS (see Figure 7) and all points within each taxlot were aggregated resulting in a total sum of potential solar flux attenuation (watts/m^2/d^{-1}) for each taxlot. Additionally, the amount of restorable area within each taxlot (vegetation <4m in height and within 15m or stream channel) was calculated using built-in geometry calculation functions in ArcGIS. GIS derived taxlot data was then transferred to an Excel spreadsheet to calculate priority rankings.

Dividing the potential solar flux attenuation by the acreage restored for each taxlot gave a normalized measure of restoration efficiency within each taxlot that was then used to sort the taxlots from most efficient (greatest potential solar flux attenuation per are) to least efficient (least potential solar flux attenuation per acre) (see glossary for further clarification of terms). Once sorted, the cumulative potential solar flux attenuation was calculated for the entire watershed to determine the restoration goal, or solar reduction target, for the watershed. A running total of the percent of the reduction goal having been met was tabulated, beginning with the most efficient taxlots at the top of the list and down to the least efficient at the bottom. Priority rankings were assigned based on the following criteria: taxlots that collectively attain the first 50% of the watershed reduction goal are classified as high priority; taxlots that collectively attain the next 40% (from 50-90%) of the reduction goal are classified as medium priority; taxlots that make up the last 10% (from 90-100%) of the reduction goal are classified as low priority and finally, taxlots that do not contribute to the restoration goal (potential increase in solar flux attenuation =0) are classified as "maintain". Refer to Appendix B to view the priority ranking spreadsheet for the watershed.

2.6.2 Prioritizing Subwatersheds

Subwatersheds were prioritized almost exactly the same way as with taxlots. After solar flux attenuation estimates were aggregated within taxlots, each taxlot was assigned to a subwatershed through a spatial join process in ArcGIS; taxlots that fell within more than one subwatershed were assigned to the subwatershed that contained the taxlot centroid such that each taxlot was associated with only one subwatershed. The total solar flux attenuation from all taxlots within each subwatershed was aggregated, resulting in a total sum of potential solar flux attenuation for each subwatershed. The amount of restorable area in each subwatershed was calculated using built-in geometry calculation functions in ArcGIS and the data was transferred to an Excel spreadsheet to calculate priority rankings. In Excel, the potential solar flux attenuation per acre of restored area within each subwatershed was calculated and used to sort the subwatersheds from highest restoration efficiency to least efficient. The total solar reduction target was the same as with taxlots and a running total of the percentage of the solar reduction target goal being met was calculated similarly. Priority rankings were assigned using the same solar reduction thresholds as criteria.

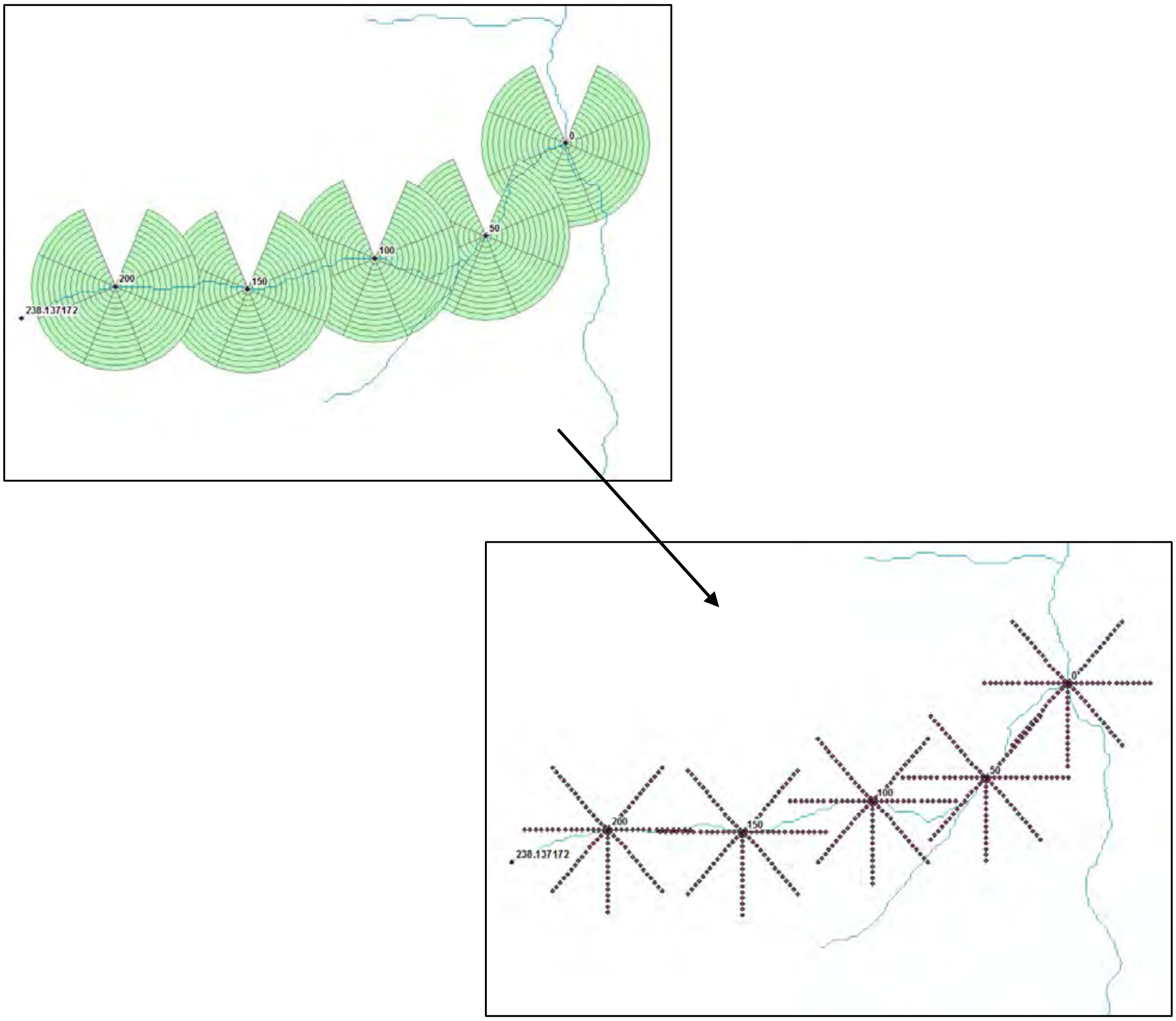


Figure 7: Polygons were converted to points prior to spatially correlating to taxlots. Each point contains a value for total daily solar flux reduction (watts/m^2/d^{-1}) which were ultimately aggregated within each taxlot's boundaries. See section 2.5, page 29 for an explanation of how overlapping polygons or points will not result in double counting.

2.7 Summary Statistics

The number of taxlots, restorable acres, and subwatersheds that fall within each priority ranking were calculated to identify which areas in the watershed will maximize the ecological returns of restoration efforts. Additionally, priority allocations for taxlots were used to evaluate restoration prospects within each jurisdiction in an attempt to help jurisdictional management agencies evaluate their standing relative to others. Furthermore, summary statistics were used to evaluate the relationships between priority rankings and certain taxlot or subwatershed attributes, such as the size of the taxlot or subwatershed, or the percent of the restoration buffer that is restorable. All summary statistics were calculated in an Excel spreadsheet or using ArcGIS data summary tools. All the original data used in the formation of summary statistics are provided in Appendix B.

2.8 Quality Control

2.8.1 Testing an Alternative Approach

In an effort to evaluate the potential impact of assuming a fixed height for unrestored vegetation, 14 streams were re-modeled using an alternative set of assumptions to define restored conditions. The 14 streams chosen for re-modeling occupy the north-western portion of the Sunshine Creek subwatershed and comprise a cluster of tributary streams that eventually converge with the mainstem of Sunshine Creek; they are not randomly scattered throughout the watershed but rather clustered together. Restored conditions were modified to reflect the height of all vegetation, whether restored or un-restored, at maturity. Un-restored vegetation was assumed to reach the same height at maturity as restored vegetation and, as such, the maximum height of all un-restored vegetation currently less than 27m was set equal to 27m. In sum, the restored conditions assumed that the height of all vegetation was equal to or greater than 27m; only vegetation that is currently over 27m tall was fixed and did not receive additional growth.

Restored conditions were re-modeled for the streams and compared to current conditions to determine the net change in solar flux attenuation as a result of both restoration *and* the natural growth of vegetation. Spatially assigning solar flux attenuation estimates to taxlots was done exactly the same way as previously described in Section 2.6. A total of 51 taxlots intersected the subset of re-modeled streams.

Priority rankings were assigned to each taxlot using the same general approach outlined in Section 2.6.1, however, only the subset of taxlots that intersected the re-modeled streams were included in the prioritization scheme (i.e. the priority rankings did not reflect their ranking in the entire watershed, but only within the streams that were re-modeled). The total solar reduction target was determined by summing up the potential solar flux attenuation for just the 51 taxlots being evaluated. Then, the taxlots were sorted from most efficient (most watts/acre) to least efficient (least watts/acre) and prioritized according to their contribution to the solar reduction target. For each taxlot, two priority rankings were determined: the first using the old solar flux estimates, and the second using the new solar flux estimates.

The majority of priority rankings were either the same or only a single ranking removed (i.e. maintain instead of low, or medium instead of high). Over half of the priority rankings (52%) were the same for both model runs. Almost all of the rankings that differed (43%) between model runs were only a single ranking removed. There were 2 taxlots that had very different rankings resulting from each model run; one went from a maintain ranking (original approach) to medium ranking (alternative approach) and another went from a maintain ranking (original approach) to a high ranking (alternative approach).

The taxlot that changed from maintain (using original approach) to medium (using alternative approach) had restorable area within it, but did not contribute any increase (increase was equal to 0 watts/acre) in solar flux attenuation as a result of restoration; thus the maintain ranking from the original approach. Once the un-restorable area was allowed to grow, the observed increase in solar flux attenuation under restored conditions significantly increased. When this new solar flux estimate was divided by the restorable area, it gave the false impression that there would be an increase in solar flux attenuation as a result of restoration; this increase was actually a result of un-restored vegetation growing taller.

A similar circumstance can explain how the second taxlot went from maintain (using original approach) to high priority (using alternative approach) as well. While there was restorable area in this taxlot, the increase in solar lux attenuation as a result of restoration was extremely low (~1watt/acre); thus the maintain ranking from original approach. When the un-restorable area was allowed to grow, the observed increase in solar flux attenuation significantly increased while the restorable acres remained the same; as a result, this gave the false impression that the restoration efficiency (measured in watts/acre) for this taxlot was very high.

In order to identify taxlots with a high level of restoration efficiency, the effect of un-restored vegetation must be controlled for by keeping it fixed. Furthermore, a major assumption of the alternative approach is that all vegetation is comprised of trees and that the tree species are the same as those planted in restorable areas (height and age at maturity are the same as in restored areas).

2.8.2 Re-modeling

To ensure accuracy of modeling results, ~10% of the streams (43 streams) were randomly chosen (using the RANDBETWEEN function in Microsoft Excel) to be re-sampled and re-modeled, using exactly the same sampling and modeling procedures from the original run. Results from second models were compared to the first model results in an attempt to identify recurring errors and evaluate model precision. Results from the second set of model runs exhibited a 4.6% margin of error when compared to original model outputs. In particular, 2 streams out of the 43 total (i.e. 4.6%) that were randomly chosen to be re-sampled and modeled had output values that differed from their original counterparts. For the remaining 41 streams, model results from first and second runs were 100% identical.

For one of the streams that exhibited modeling errors, the source of the error was determined to be improperly formatted model inputs, which could easily be detected from the spreadsheet containing model input parameters for said stream. This particular stream was one of the first streams modeled during the earlier phases of the project and, as such, was subject to a higher probability of operator error. To ensure that this error was not widespread, the datasheets containing input parameters for all streams were double-checked for similar formatting errors. No additional formatting errors were found as a result of these efforts and the pervasiveness of this specific error is assumed to be low.

The second stream exhibiting modeling errors was also determined to be a result of operator error. During the second model run for this stream, data concerning current vegetation was mistakenly used when modeling both current and restored scenarios and, as a result, when comparing results for both scenarios the apparent difference in solar flux attenuation was zero watts/m^2/d^{-1} for all polygons sampled. This error was also very easily detectable from modeling results (i.e the difference between current and restored conditions is 0 across the board which, visually, is very obvious) and was not apparent in any of the other streams modeled. As such, this particular operator error is not likely to be prevalent; however, operator errors in general are likely to remain largely undetected and a 4.6% margin of error is assumed to appropriately reflect the level of operator error to be expected within the modeling results presented in this paper.

2.8.3 Field Measurements

In order to evaluate the accuracy of model estimates, 24 field measurements of effective shade were collected for comparison; over half (14) were collected in July 2012 and the remaining 10 were collected in November, 2013. Collection of field measurements was originally scheduled to occur during the month of August, in order to match up with the date used for shade simulations. Additional measurements were taken in November to increase the sample size of field measurements and provide a more robust measurement of error.

Using a solar pathfinder adjusted for the appropriate latitude band (45°) and magnetic declination (15°), the sunpath arc for August was used to measure effective shade at these locations during both field surveys. GPS coordinates (UTM) were recorded using a Samsung Galaxy cell phone with the Backcountry Navigator PRO application. Modeling estimates for percent effective shade generally agreed with field measurements plus or minus 19%. However, the average difference between measured and modeled effective shade estimates was only ~4% (R^2=0.73). Possible causes for disagreement stem from outdated LiDAR raster data (2007), any restoration activities or general growth of vegetation that has occurred after 2007 in the areas sampled, and because the measurements were taken in November after abscission of deciduous trees had begun.

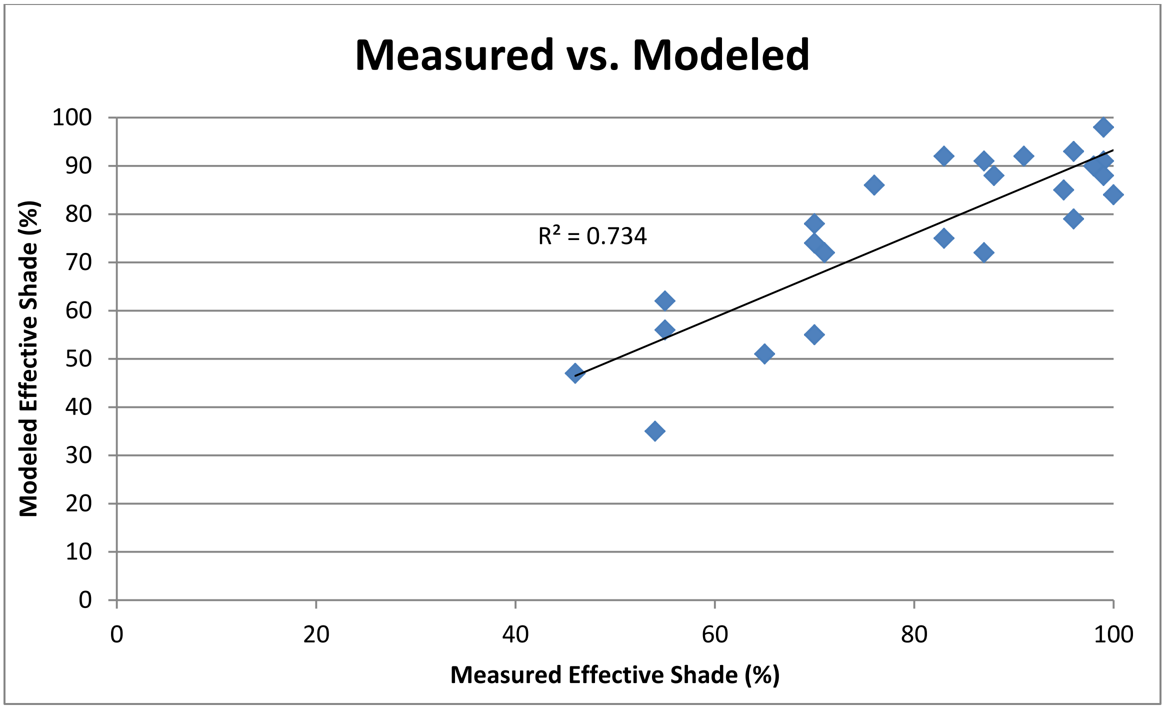


Figure 8: Agreement between field measurements and modeling estimates of percent effective shade is generally high. Model estimates can explain about 73% of the variation in shade, with the remaining 27% explained by changes in riparian vegetation since LiDAR data was collected or measurement error.

3.0 Results

3.1 Restored Conditions

The total solar reduction target, or total increase in solar flux attenuation as a result of restoration, was estimated at 209,118.9 (watts/m^2 /d^{-1}). The entire restoration buffer, or area extending 15m to either side of the stream channel where restoration activities are likely to occur, encompassed a total area of 8,841.4 acres. The total restorable area, or area with current vegetation < 4m in height within the restoration buffer that *would* be restored under a restored scenario, was estimated at 544.9 acres (6% of the total restoration buffer). The remaining 94% of the restoration buffer either currently supports vegetation ≥4m in height, or is occupied by buildings or roads and *would not* be restored under a restoration scenario. Figure 10 shows the extent and geographic distribution of the total restorable area within the study area.

3.2 Priority Rankings by Taxlots

A total of 3,722 taxlots of varying sizes and land uses were found to intersect the restoration buffer within the study area. According to RLIS taxlot data, the primary land uses in these taxlots include: single family residential (54.7% of all taxlots), undeveloped (24.3%), rural (8.1%), agriculture (3.9%), forest (2.6%), commercial (2.4%) and multi-family residential (1.0%). The average area for each taxlot was 2.78 acres, with values ranging between $8.72*10^{-4}$ to 153.77 acres. The restorable area within each taxlot was, on average, only 9.8% of the entire restoration buffer within each taxlot, yet these values were highly variable ranging between 0 and 100%.

As shown in Figure 9, high priority taxlots collectively achieved 50% of the total solar reduction target for the watershed. Medium priority taxlots collectively made up another 40% of the total solar reduction target, bringing the watershed up to 90% of its goal. Low priority taxlots collectively made up 10% of the total solar reduction target and taxlots categorized as “maintain” did not contribute at all to the attainment of the solar reduction target.

High priority taxlots had the largest gain in solar flux attenuation rates as a result of restoration (1719 watts/acre/d^{-1} on average), medium priority taxlots gained an intermediate amount (438 watts/acre/d^{-1} on average), low priority taxlots gained even less (102 watts/acre/d^{-1} on average) and taxlots classified as “maintain” did not exhibit any change in solar attenuation between current and restored conditions (increase of 0 watts/acre/d^{-1}).

3.2.1 Number of Taxlots in Each Ranking

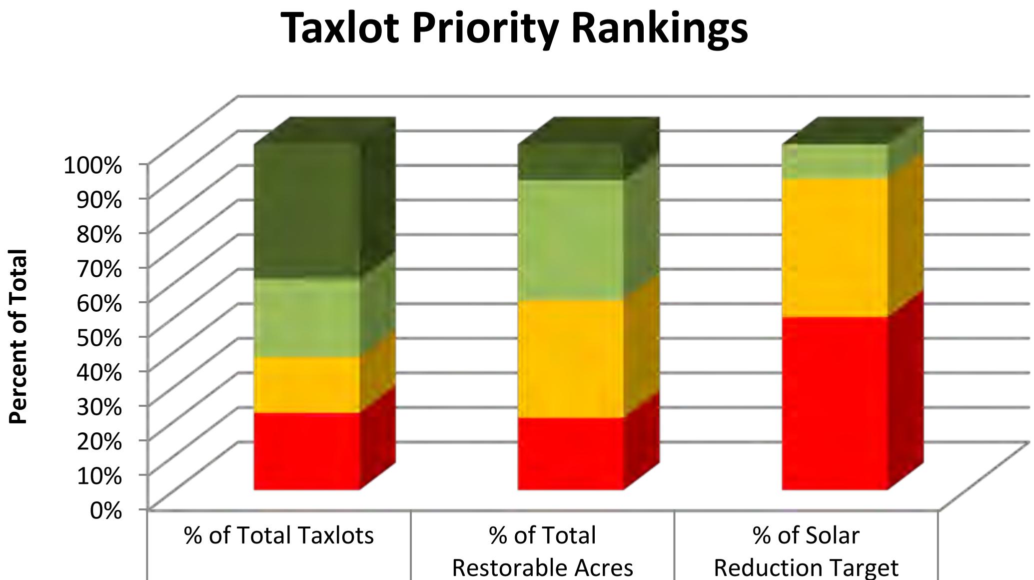
Of the 3,722 taxlots that were found to intersect the restoration buffer, 831 (22% of all taxlots) were categorized as high priority, 601 (16%) were categorized as medium priority 837 (22%) were categorize as low priority and 1453 (39%) were categorized as “maintain”. Table 3 provides summary statistics for each priority ranking group. In addition, Figure 9 illustrates the percentage of all taxlots that fall within each prioritization ranking group. Figures 11 and 12 provide detailed maps of taxlot rankings throughout the watershed.

3.2.2 Restorable Acres in each Ranking

Based on prioritization rankings made at the taxlot scale, 113.7 acres of the total 544.9 restorable acres within the study area (21% of total restorable acres) fell within high priority taxlots, 184.8 acres (34%) fell within the medium priority taxlots, 189.2 acres (35%) fell within low priority taxlots and 57.0 (10%) occurred in taxlots categorized as “maintain” (Table 3 and Figure 9).

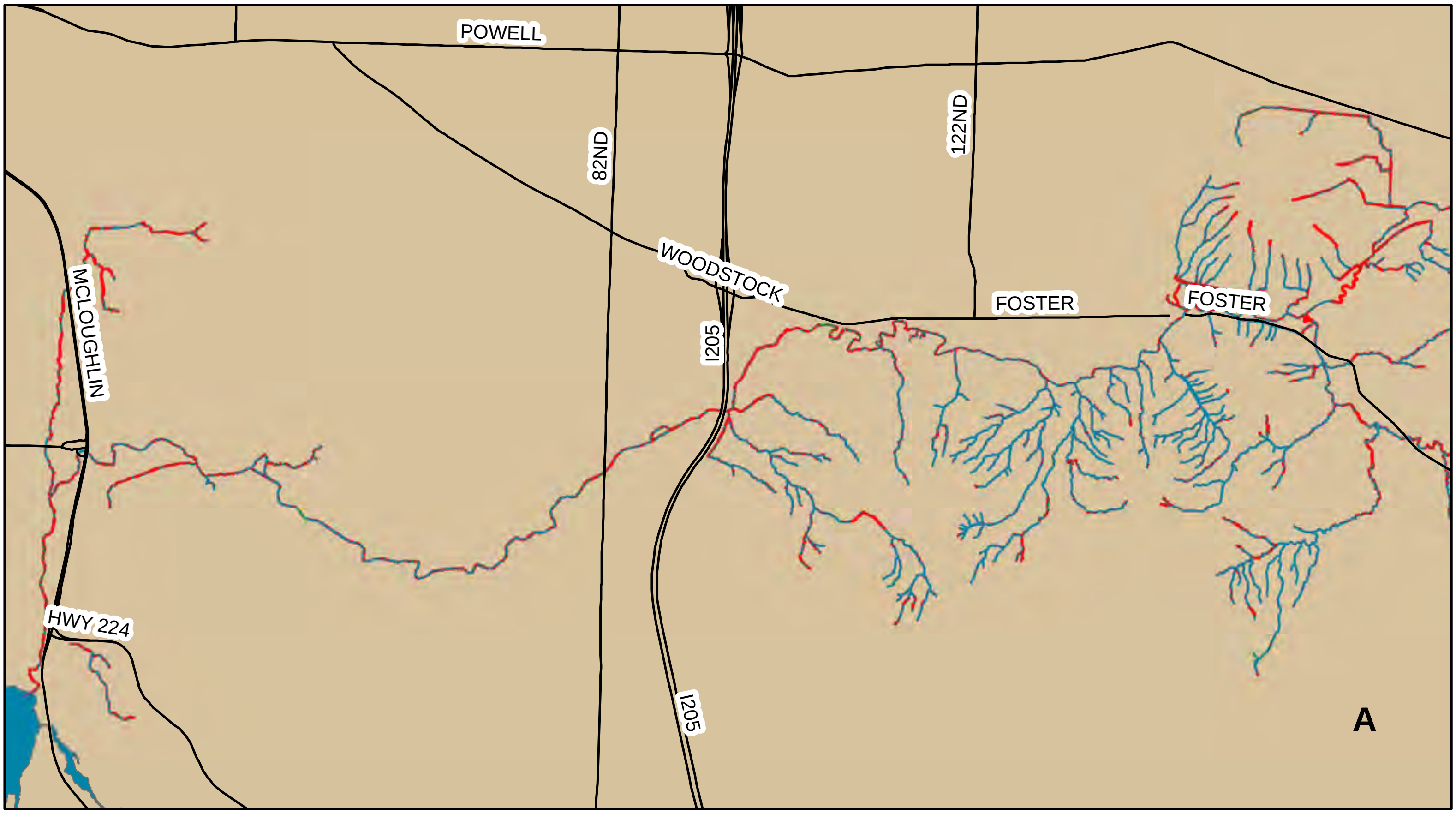
Table 3: Summary statistics for taxlot priority rankings within the Johnson Creek watershed. All taxlots are included in this table. Restorable acres represent the sum of all restorable acres for all taxlots within each ranking. Average taxlot area represents the average size of taxlots (acres) within each ranking. Percent of taxlot restorable represents the average proportion of each taxlot’s restoration buffer that is deemed restorable.

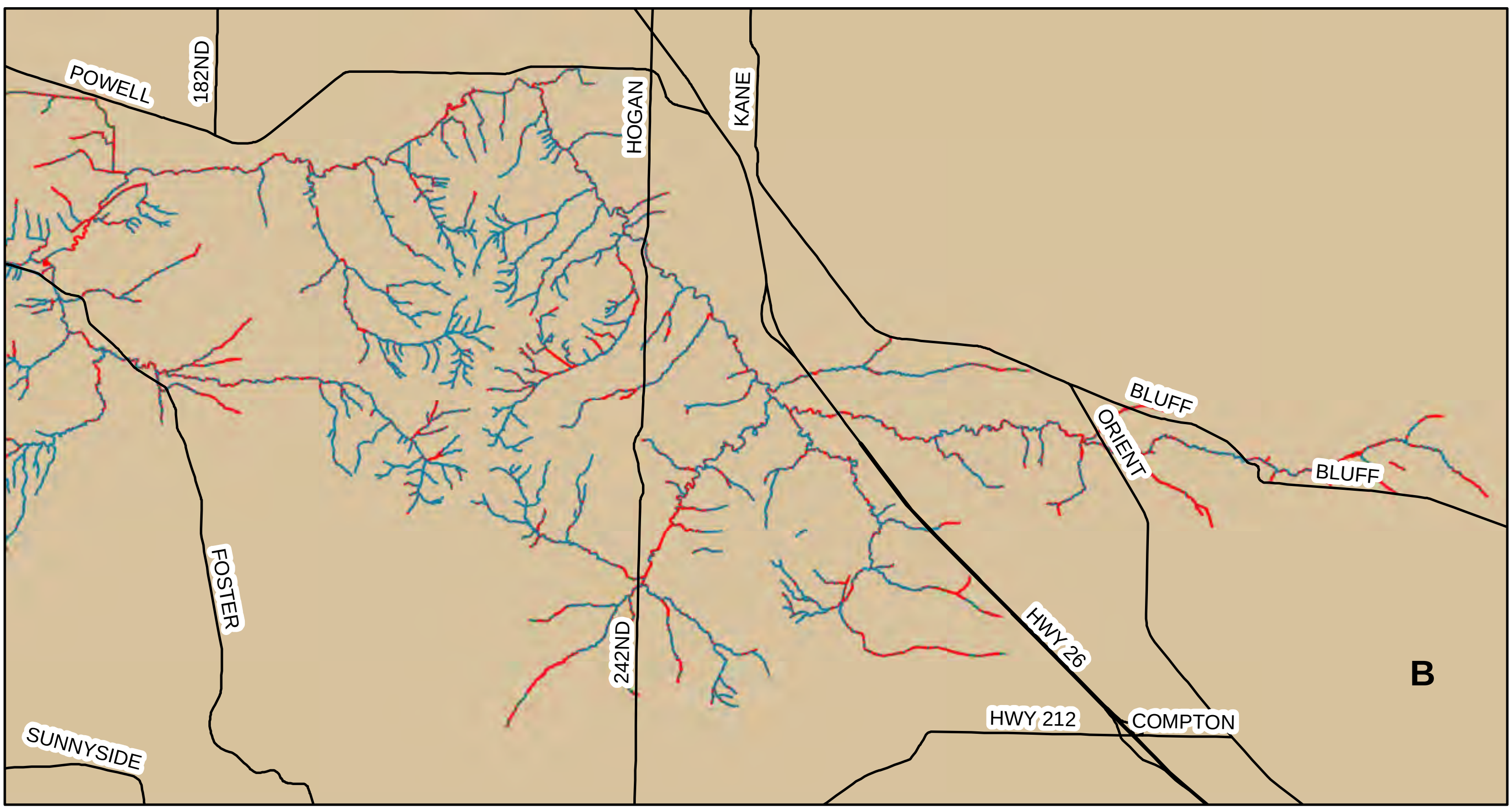
Priority	Av. Watts/Acre/d^{-1}	# Taxlots	Restorable Acres	Av. Taxlot Area (acres)	Av. % of Restoration Buffer Deemed Restorable
High	1719	831	113.7	1.6	15%
Medium	438	601	184.8	4.0	14%
Low	102	837	189.2	5.2	10%
Maintain	0	1,453	57.0	1.5	5%



	% of Total Taxlots	% of Total Restorable Acres	% of Solar Reduction Target
maintain	39%	10%	0%
low	22%	35%	10%
medium	16%	34%	40%
high	22%	21%	50%

Figure 9: Taxlot priority rankings evaluated in terms of various spatial metrics. Total solar reduction target is the net increase in solar flux attenuation resulting from restoration. The total amount of restorable acres is the total acreage within the restoration buffer (15m from stream channel) that would be restored under a restoration scenario (current vegetation is <4m in height). The total number of taxlots in the watershed that intersected the restoration buffer was 3,722.





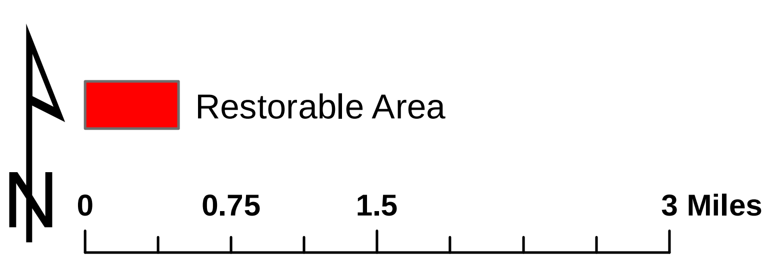


Figure 10: Total Restorable Area

A: Western Half of Watershed

B: Eastern Half of Watershed

November, 2013

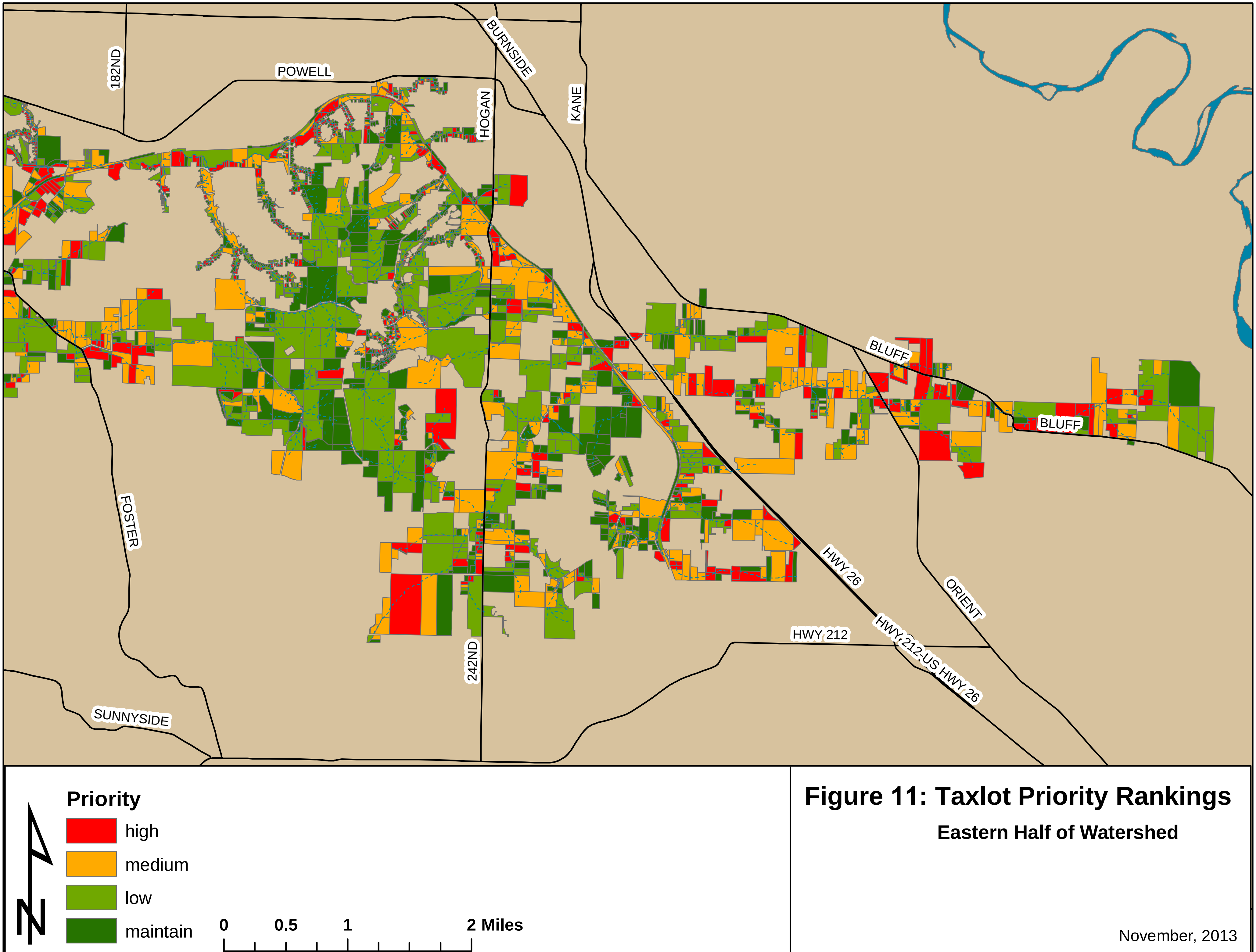


Figure 11: Taxlot Priority Rankings

Eastern Half of Watershed

November, 2013

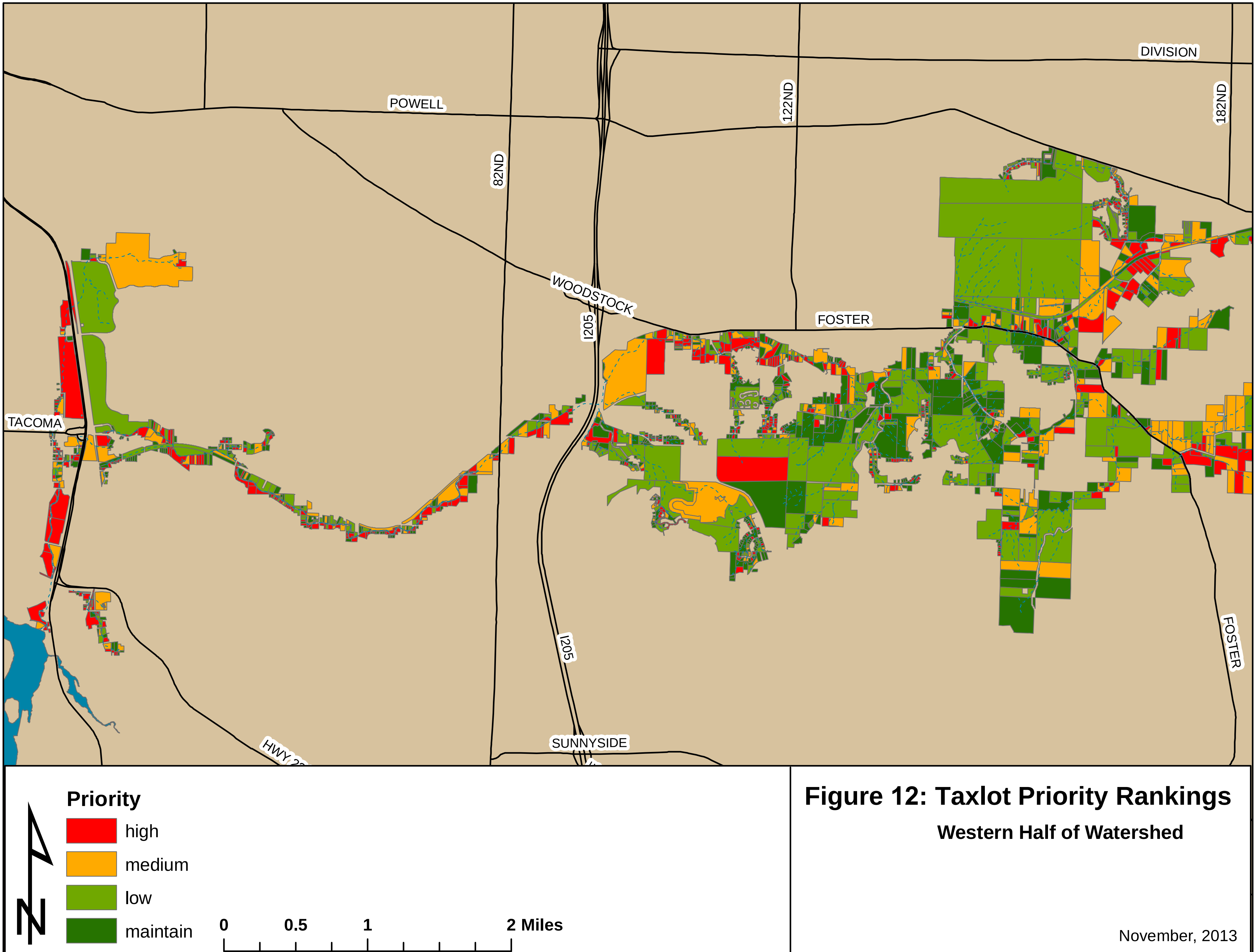


Figure 12: Taxlot Priority Rankings

Western Half of Watershed

November, 2013

3.3 Priority Rankings by Subwatersheds

A total of 36 subwatersheds intersected the restoration buffer and were considered in the prioritization scheme. The same prioritization scheme used for taxlots was applied at the subwatershed scale, where subwatersheds that collectively attain the first 50% of the total solar reduction target are high priority, the next 40% are medium priority, the last 10% are low priority, and those that do not contribute at all are classified as "maintain". Table 3 provides summary statistics for each priority ranking group in terms of subwatershed allocations.

3.3.1 Number of Subwatersheds in each Ranking

Of the 36 subwatersheds, 18 (50% of all subwatersheds considered) were categorized as high priority, 7 (19%) were categorized as medium priority 9 (25%) were categorize as low priority and 2 (6%) were categorized as “maintain”. Figure 13 illustrates the percentage of all subwatersheds that fall within each prioritization ranking group. In addition, Figure 14 depicts the priority ranking assigned to each subwatershed in the study area.

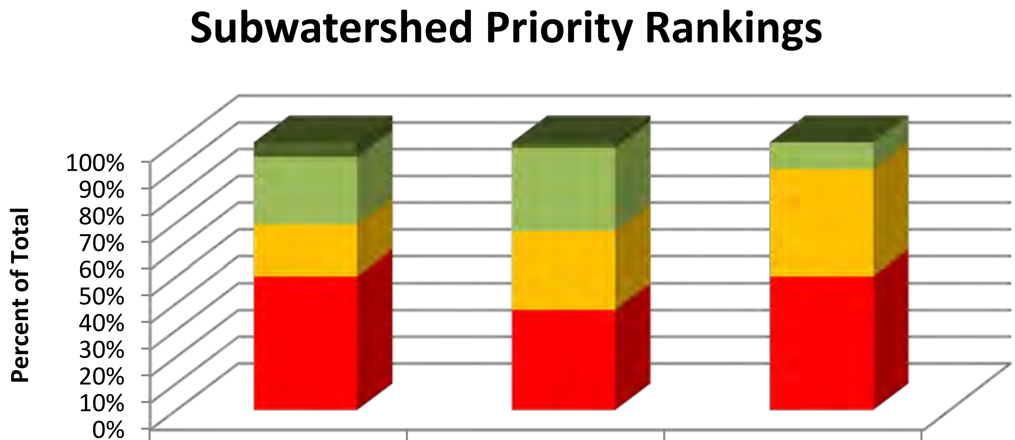
3.3.2 Restorable Acres in each Ranking

In terms of restorable acres, high priority subwatersheds collectively comprised 38% of all restorable acres in the study area, medium priority subwatersheds comprised 29%, low priority subwatersheds comprised 31% and subwatersheds classified as "maintain" comprised 2% of all restorable acres (Figure 13).

Due to differences in the size of each subwatershed, the amount of restorable area within them was highly variable, ranging from 0 to 110 acres (Figure 15). The percentage of restorable area within each subwatershed's entire restoration buffer is variable, ranging between 0-10% (Table 3 and Figure 16). Additional data concerning subwatershed solar flux attenuation and prioritization calculations is included in Appendix B.

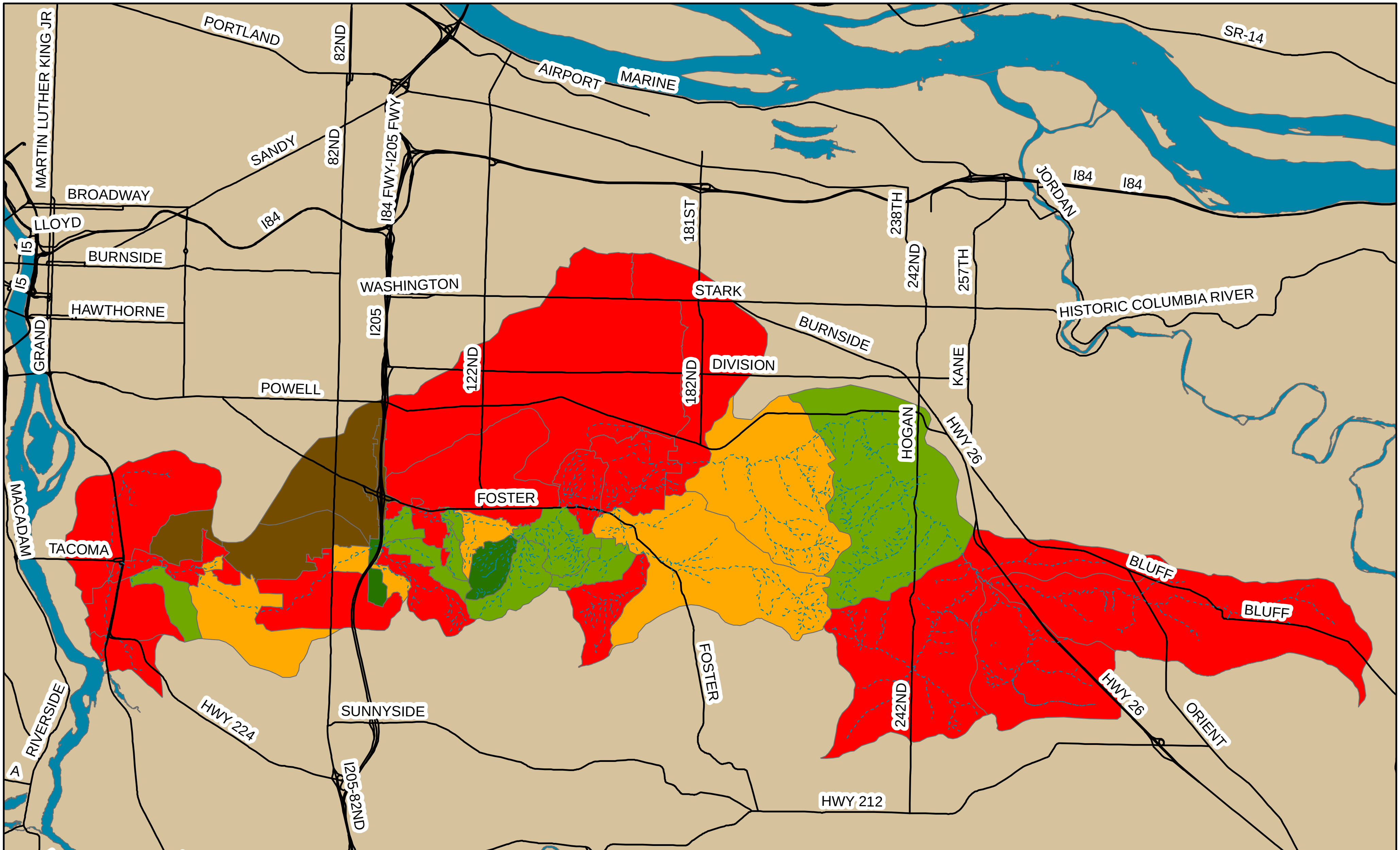
Table 4: Summary statistics for subwatershed priority rankings. Please refer to the glossary (pg. 63) for clarification of any terminology used in this Table. The average percent of restoration buffer deemed restorable is essentially the number of restorable acres, divided by the un-restorable acres within each subwatsershed's restoration buffer (15m from stream channel) (converted to a percentage).

Priority Ranking	# of subwatersheds	% of all subwatersheds considered	Restorable Acres	% of total restorable acres	Av. % of restoration buffer that is deemed restorable	Av. Increase in solar flux attenuation (watts/acre /d^{-1})	% of total solar reduction target
high	18	50%	204.7	38%	7%	542.0	50%
medium	7	19%	158.8	29%	6%	362.3	40%
low	9	25%	169.7	31%	7%	263.1	10%
maintain	2	6%	11.6	2%	2%	75.7	0%
Total	**36**	**100%**	**544.9**	**100%**			**100%**



	% of Total Subwatersheds	% of Total Restorable Acres	% of Solar Reduction Target
maintain	6%	2%	0%
low	25%	31%	10%
medium	19%	29%	40%
high	50%	38%	50%

Figure 13: Subwatershed priority rankings evaluated using various forms of measurement. The percent of all subwatersheds considered in this study (36 total intersecting restoration buffer), total restorable area (544.9 acres total) and the total solar reduction target (209,118.9 watts/acre/d^{-1}) fulfilled by each priority ranking is presented.



Priority

- high
- medium
- low
- maintain
- does not intersect restoration buffer

0 1 2 4 Miles

N

Figure 14: Subwatershed Priority Rankings

November, 2013

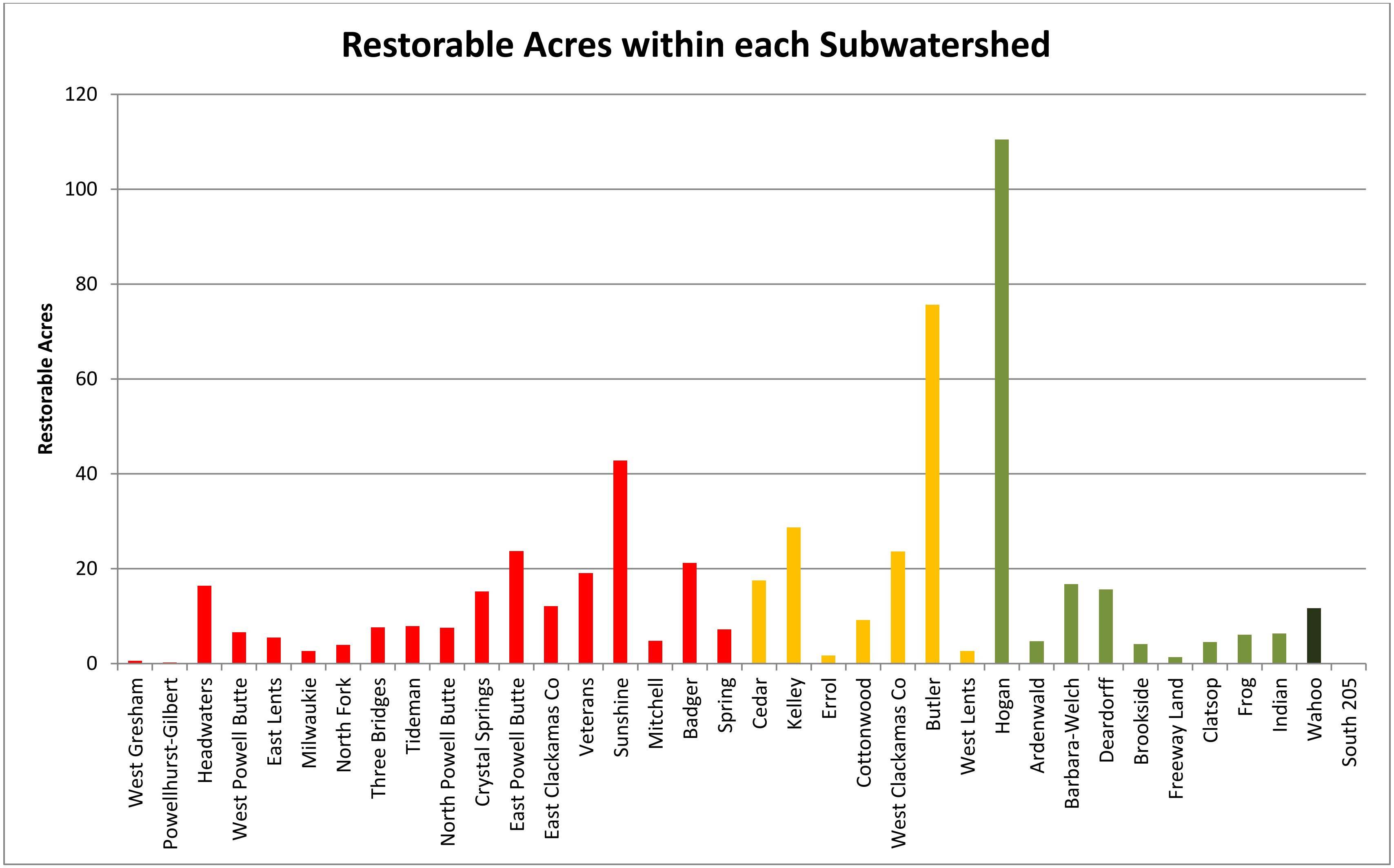


Figure 15: Restorable acres within each subwatershed are presented with the priority ranking for each indicated by its color. While some subwatersheds are bigger in size than others, it is important to consider the percentage of total acres within each subwatershed that are restorable when evaluating the restoration potential of each (see Figure 16).

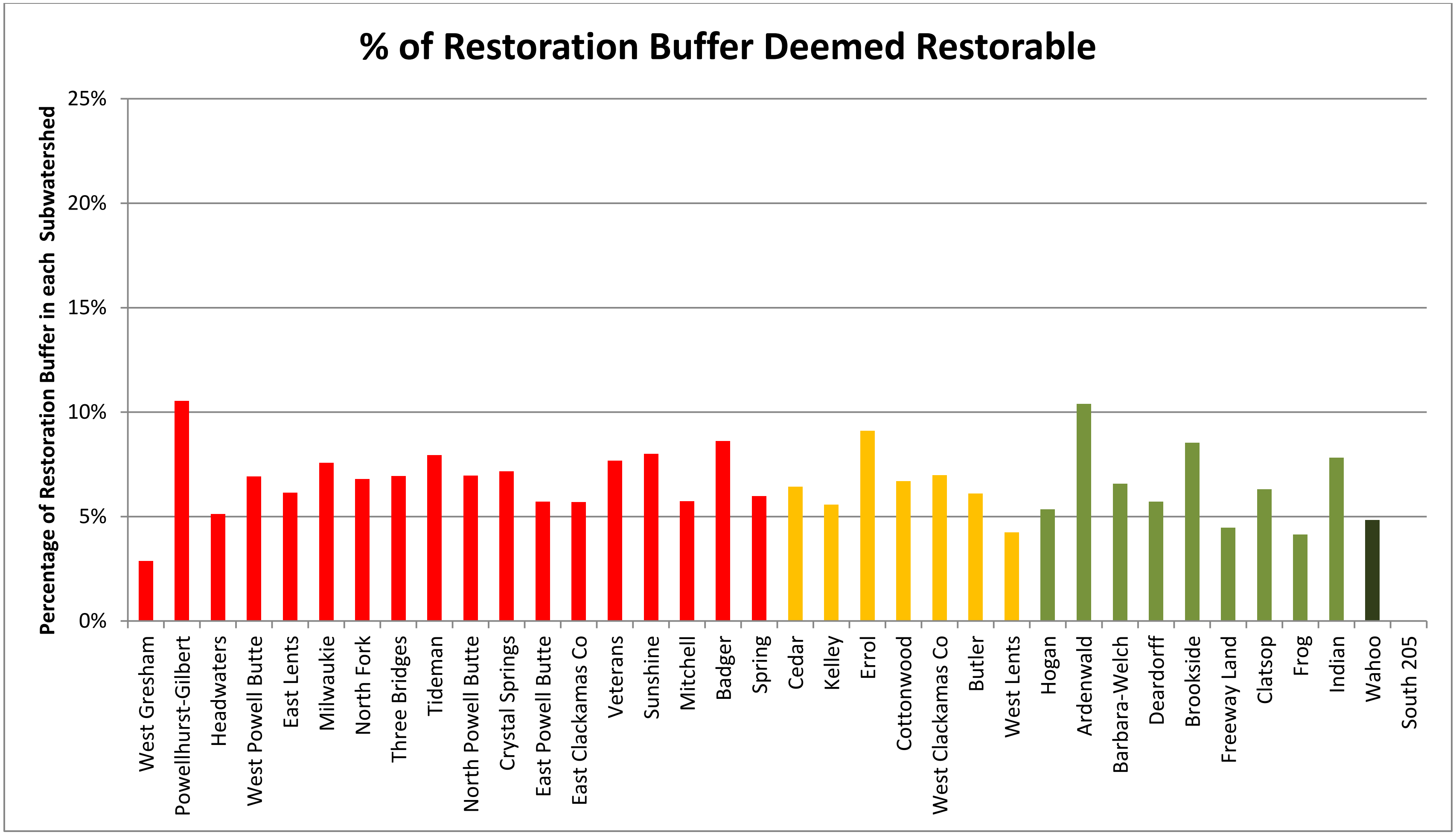


Figure 16: Percent of each subwatershed's restoration buffer that is deemed restorable. The restoration buffer extends 15m out from the stream channel and represents the area in which restoration activities are likely to occur. Restorable acres are those that both fall within the restoration buffer and contain vegetation currently <4m in height; under a restoration scenario the maximum vegetation height in all restorable areas is set to equal 27m.

3.4 Priority Rankings by Jurisdiction

The jurisdictions can be grouped into three size categories: large, medium and small. The two largest jurisdictions are the cities of Portland and Gresham, which each make up over 30% of all taxlots that intersect the restoration buffer (see Figure 17). The portion of the study area located in unincorporated land is primarily concentrated in the eastern headwaters of the watershed; these taxlots fall under the broader jurisdictions of Multnomah and Clackamas counties. These county jurisdictions, as well as the city of Damascus are “medium” in size, making up about 6-11% of all taxlots intersecting the restoration buffer. The smallest jurisdictions are the cities of Milwaukie and Happy Valley, which comprise only 3-4% of all taxlots.

3.4.1 Priority Rankings across Jurisdictions

The following information describes the relative contribution of each jurisdiction to *all* taxlots, subwatersheds, and restorable acres within each priority ranking.

For each priority ranking group, the percentage of taxlots that fell within each jurisdiction tended to reflect the size of the jurisdiction. The largest jurisdictions, Gresham and Portland, which comprise approximately 30% of all taxlots intersecting the restoration buffer also comprised between 27-37% of the taxlots within each priority ranking group. The medium sized jurisdictions, Clackamas and Multnomah counties (unincorporated) and Damascus, comprised between 5-16% of the taxlots within each priority ranking group. The smallest jurisdictions, Milwaukie and Happy Valley, only accounted for 2-6% of the taxlots in each priority ranking (see Figure 19).

For each priority ranking group, the percentage of restorable area that fell within each jurisdiction also tended to reflect the size of each jurisdiction. Gresham and Portland accounted for 19-

33% of restorable area within each priority ranking. Damascus, Clackamas and Multnomah counties (unincorporated) made up 10-22% of restorable area within each priority ranking. The smallest jurisdictions, Milwaukie and Happy Valley comprised between 1-5% of restorable area within each priority ranking (see Figure 18).

Table 5 provides taxlot counts for each jurisdiction within the study area, while Figure 17 displays the relative extent, or percentage, of each jurisdiction within the study area. Due to differences in the size and current condition of vegetation within taxlots, calculations of the percentage of each jurisdiction contained within the study area are inconsistent between different units of measurement (ex: some jurisdictions are larger in terms of acreage vs. # taxlots due to large sized taxlots).

3.4.2 Priority Rankings within Jurisdictions

The following information describes the allocation of only the restorable acres and taxlots within each jurisdiction to each priority ranking group.

In terms of taxlots, all jurisdictions had, on average, 5% of *their own* taxlots ranked as high priority, 9.8% of their own taxlots ranked as medium priority, 22.4% ranked as low priority, and 62.8% ranked as “maintain” (see Figure 22). In terms of restorable area, all jurisdictions had, on average, 20.9% of *their own* restorable area within the high priority ranking group, 34% within the medium priority group, 34.7% within the low priority group and 10.5% categorized as “maintain” (see Figure 23).

Table 5: The number of taxlots that intersect the restoration buffer within each jurisdiction are presented. All taxlots that intersect the restoration buffer come within 15m of any stream in the watershed. Study area is defined as all taxlots intersecting the restoration buffer and the acreage within the restoration buffer as well.

Jurisdiction	# taxlots within restoration buffer	Restorable Acres	Av. Taxlot Area (acres)
Portland	1,234	144.6	2.1
Gresham	1,205	121.2	1.8
Milwaukie	132	10.9	0.9
Happy Valley	121	8.8	2.1
Damascus	237	61.8	6.5
Clackamas County (uninc.)	417	90.4	3.9
Multnomah County (uninc.)	376	107.1	5.2
Whole Study Area	**3,722**	**544.9**	**2.8**

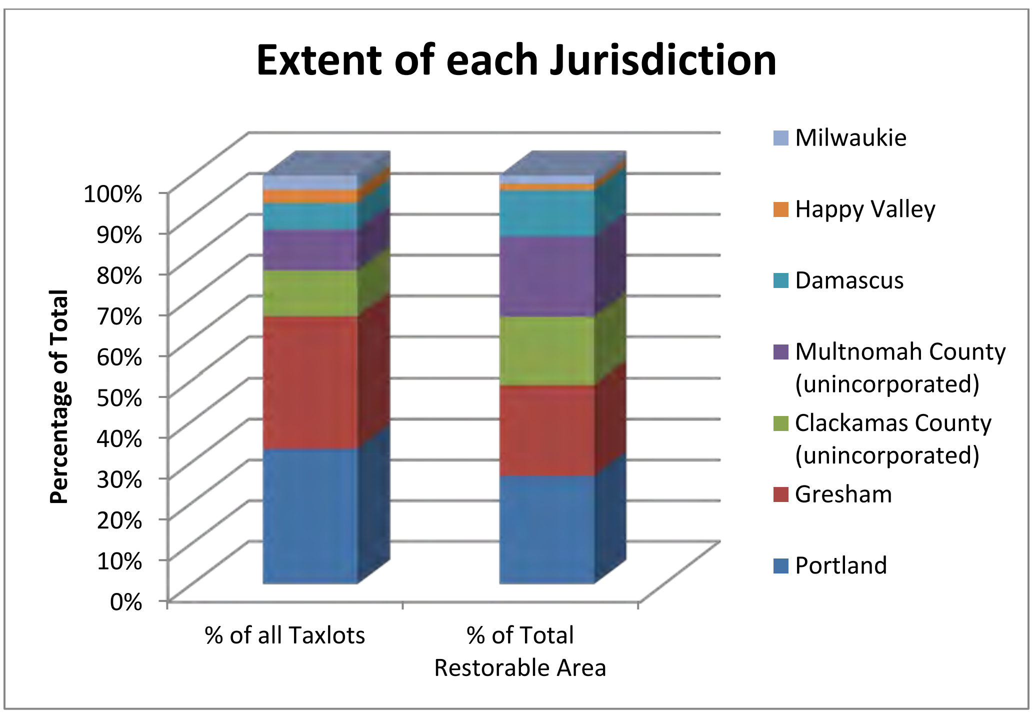


Figure 17: The relative geographic extent of each jurisdiction in terms of their percent contribution to all taxlots that intersect the restoration buffer and the total restorable area.

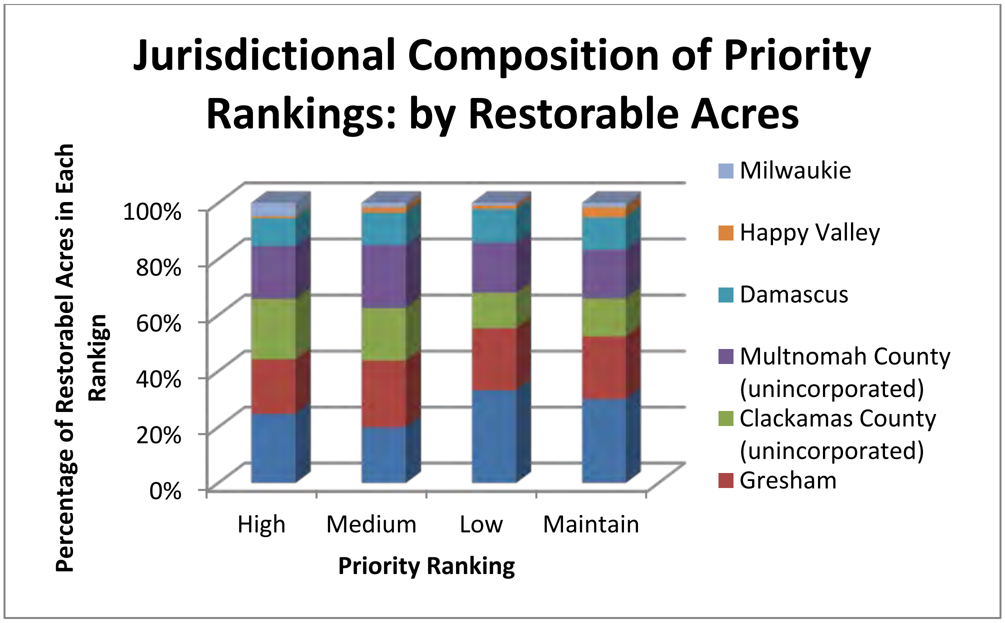


Figure 18: Each priority ranking group is broken down by the percentage of total restorable area that falls within each jurisdiction. The acreage of restorable area within each priority ranking group is included in Table 3.

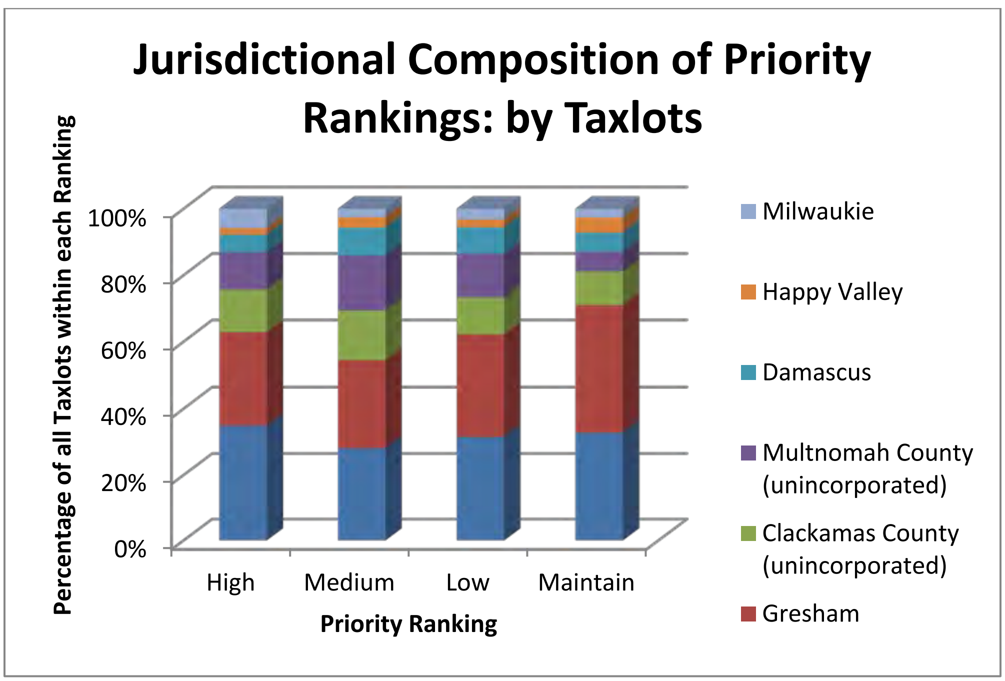


Figure 19: Each priority ranking group is broken down by the percentage of taxlots that fall within each jurisdiction. The number of taxlots within each priority ranking group is included in Table 3.

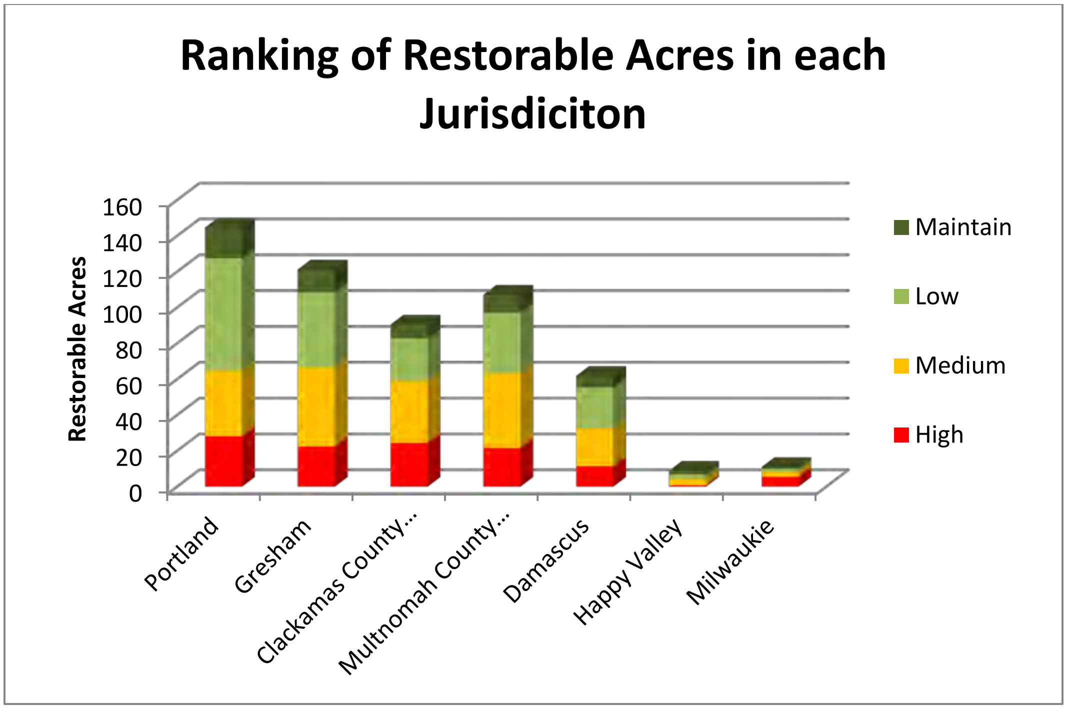


Figure 20: Restorable acres within each jurisdiction are further broken down in terms of their priority ranking.

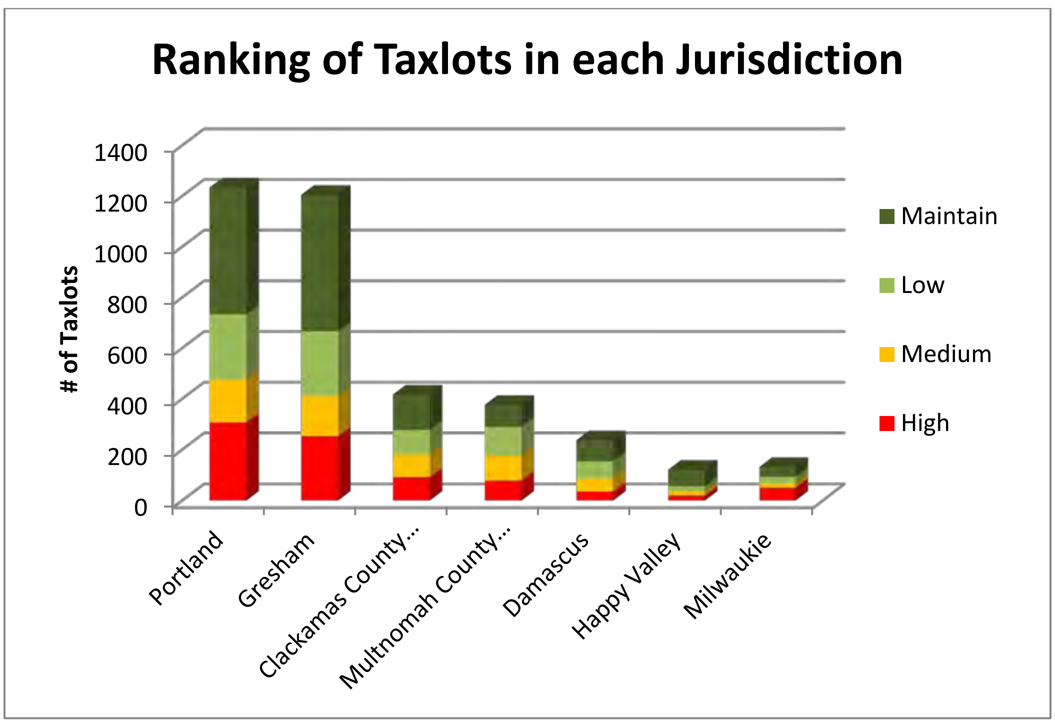


Figure 21: The number of taxlots within each jurisdiction are further broken down in terms of their priority ranking.

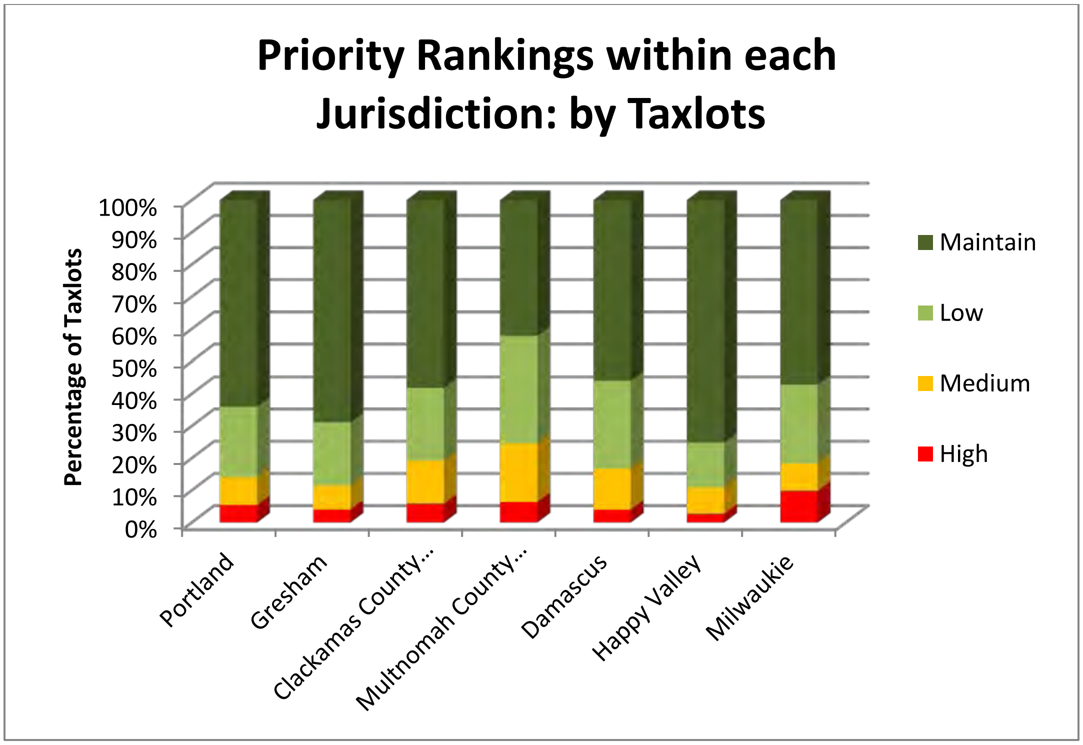


Figure 22: The percentage of each jurisdiction's taxlots that fall within each priority ranking. The number of taxlots within each jurisdiction can be found in Table 5.

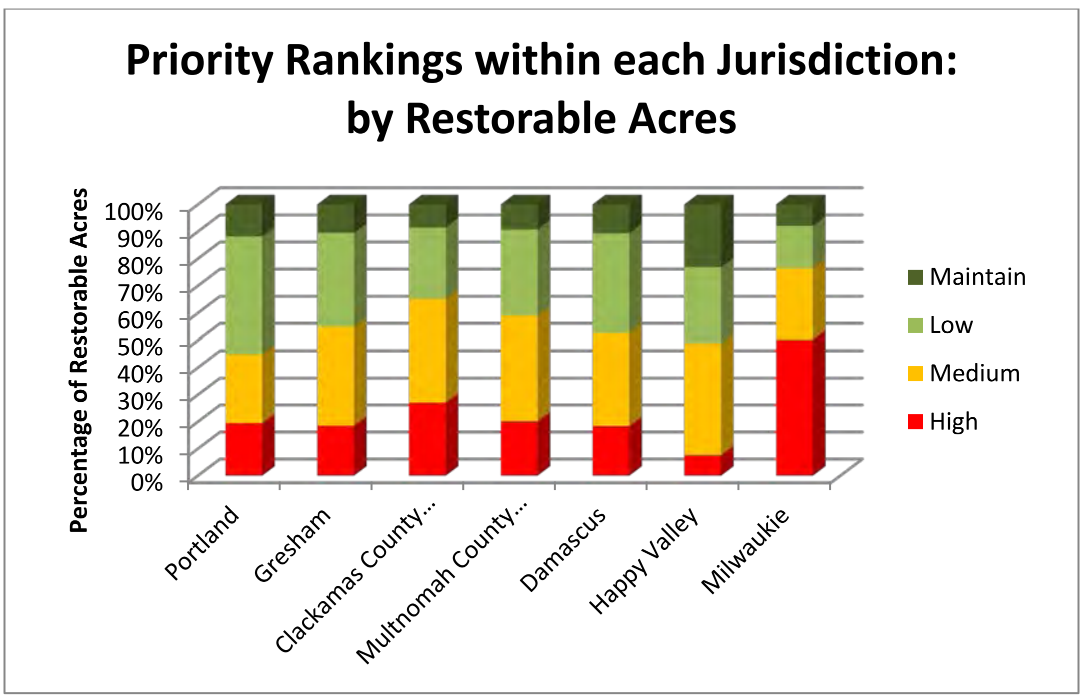


Figure 23: The percentage of total restorable acres for each jurisdiction that falls within each priority ranking group. Total restorable area in each jurisdiction can be found in Table 5.

4.0 Discussion

4.1 Summary of Findings

Effective shade was modeled under current and restored conditions as a function of geographic location, time of year and limited near stream vegetation and channel morphology attributes. Taxlots and subwatersheds were prioritized according to the potential increase in solar flux attenuation they would provide if all vegetation within 15m of the stream channel that is currently less than 4m in height were restored. While the true solar flux attenuation provided by restored vegetation at maturity would be influenced by the surrounding, unrestored vegetation, this study did not account for the growth of unrestored vegetation in an effort to isolate the signal, or effect, of restoration efforts on solar flux attenuation from that of naturally occurring growth of near stream vegetation. Also, accounting for the growth of unrestored vegetation would have involved various assumptions regarding species composition and age, which would have introduced additional sources of modeling error.

Prioritization at the taxlot scale reveals that restoring only 22% of all taxlots or 21% of all restorable acres in the watershed would achieve 50% of the total solar reduction target. Similarly, restoring only 55% of all taxlots or 38% of all restorable acres would achieve 90% of the total solar reduction target. These results suggest there is potential for targeted restoration efforts to produce a high rate of returns, in terms of shade enhancement and ultimately, reduced stream temperatures, per unit restored.

Prioritization at the subwatershed scale reveals that restoring 50% of all subwatershed or 38% of all restorable acres in the watershed would accomplish 50% of the total solar reduction target. Suimilarly, restoring 69% of all subwatersheds or 67% of all restorable acres in the watershed would achieve 90% of the total solar reduction target. These results suggest that restoration efforts prioritized and targeted at the scale of subwatersheds is not very efficient and will not produce a large amount of returns per unit restored.

4.2 Model Limitations

4.2.1 Modeling Error

While it is unreasonable to rely on direct measurements of effective shade when dealing with large spatial extents, estimates derived from high resolution data sources are far more convenient and practical. Consequently, modeling effective shade using data derived from high resolution spatial data sources has become a popular tool for prioritizing riparian restoration projects aimed at reducing stream temperature. As with all modeling endeavors, this technique may be limited in its ability to provide accurate estimates of stream shading due to DEM grid detail, averaged measures of channel azimuth and riparian condition, or a general lack of understanding of stream temperature dynamics and influences (Johnson 2003; Li et al. 2012). Over time, however, technological advances in satellite image production and processing techniques are expected to allow for data to be more easily extracted from high spatial resolution imagery and incorporated into shade models (Gergel et al. 2007).

The sources of modeling error specific to this project include the LiDAR derived raster data and model assumptions. Input parameters concerning physical attributes and vegetation height were sampled from raster data collected between 2004 and 2007. Any changes to bare earth and/or vegetation in the last 6 years are not considered in the model. The impact of riparian restoration projects that have taken place in the watershed since 2007 on stream shading are not reflected in the modeling results. Similarly, the accuracy of the digitized stream channel was verified using aerial photos from 2010. Assuming that the stream channel has not migrated is fairly safe, considering the extent and magnitude of stream channelization that has occurred throughout the watershed. In addition, model assumptions related to the height of restored vegetation and density estimates are potential sources of error and are discussed in detail in the following Section (4.2.2).

4.2.2 Model Assumptions

Restored conditions were coarsely defined and uniformly applied to all near-stream vegetation throughout the study area. In reality, the width, density and height of riparian vegetation required for adequate stream shading will vary according to localized stream conditions such as tree overhang, channel width, gradient and stream flow. Many advanced models exist that are capable of determining restored conditions more discerningly, including modules (not used for this project) within Heat Source (Johnson 2003; Li et al. 2012). For this project, limitations on time and resources meant that a simple model was the most workable option. None the less, it is important to acknowledge the shortcomings of a simplified approach to determining restored conditions. Overall, the main assumptions made in terms of restored conditions that are likely to reduce the accuracy of modeling results relate to the height, width, and density of restored vegetation.

The maximum height of vegetation under restored conditions was derived from the average height at maturity (~20 years) for six of the most common coniferous and deciduous riparian trees species in the study area. Should the actual tree species planted deviate from this chosen assemblage, the average height at maturity would also be subject to change. Also, it is assumed that all tree species planted will successfully reach a mature age unimpeded by natural processes such as flooding or erosion. In an attempt to acknowledge the possibility of unsuccessful tree plantings or stunted growth rates, the *mean* vegetation height of near stream vegetation under restored conditions was used rather than the *maximum* height (27m). As a result, both under- and over- estimating vegetation height under restored conditions are possible sources of error.

For this project, the quality of near stream vegetation was evaluated in terms of height, density, and extent (buffer width) exclusively while ignoring species composition. All vegetation that was currently ≥4m was not considered within the restorable area, with no regard to the species composition or overall quality of habitat provided by this vegetation. In some circumstances, where near-stream vegetation is overrun with invasive species for instance, vegetation currently ≥4m in height would, in fact, be considered worthy of restoration by natural resource managers. Instead, it is assumed that the shade provided by this low quality vegetation would overshadow any sense of urgency in restoring these areas. Conversely, some vegetation currently less than 4m in height may be comprised of native shrubs and herbaceous grasses that would not be considered worthy of restoration as the model assumes. In these areas, it is assumed that the provision of shade overshadows the importance of native understory vegetation. In reality, these areas would still be targeted for restoration in an effort to increase shade, but measures would be taken to avoid disturbing native understory shrubs and grasses.

Density estimates were derived from a single equation, which is subject to an unknown level of error, and uniformly applied to all near stream vegetation. While the density of near stream vegetation is likely to vary with species composition, age, and understory growth these factors were not considered in density estimates.

4.3 Prioritization Scheme

4.3.1 Restored Conditions

A common approach to the prioritization of riparian restoration efforts involves comparing current conditions to reference, or system potential, conditions (Harris & Olson 1997; Landers 1997; Tompkins & Kondolf 2000). In many situations, reference or system potential conditions are used to determine restoration objectives and the composition of restored conditions. Developing reference conditions typically requires an examination of one or more regional geomorphological, hydrological, geographical, ecological, and/or socio-economic aspects that relate to the site suitability criteria (Landers 1997). Reference conditions can be derived from historic and current data sources (aerial photos, visual assessments, water quality data and flow measurements, etc.) concerning aspects of either the system in question, or a functionally equivalent system (Harris & Olson 1997; Landers 1997; Palmer et al. 2005; USGS 2007).

While traditionally, restoration has often emphasized a return to historic conditions, this target is challenged by modern circumstances (Palmer 2005; Seavy et al. 2009). Most notably, socioeconomic factors will inevitably challenge a complete return to historic conditions. Additionally, climate change is expected to alter many of the natural processes that once defined riparian habitats. Increased air and surface water temperatures, changes in the timing and intensity of precipitation and snowmelt, and shifting phenology and distributions of native species will in some cases make a return to historic conditions unfeasible and unwarranted (Palmer 2005; Seavy et al. 2009).

The site suitability criterion for this study was effective shade, and aspects related to shade that were evaluated in the design of restored conditions included the species composition, height and density of riparian vegetation and the typical limitations placed on restoration actions (i.e. typically, vegetation greater than 4m, or beyond 15m from the stream channel does not get restored). Information related to these aspects was derived from current data sources and did not involve an examination of historic conditions. In the Johnson Creek watershed, a return to historic conditions is unlikely and unfeasible for the most part. In determining restored conditions, the typical limitations placed on restoration efforts were considered to accommodate modern day socioeconomic challenges.

An important distinction to note for this study is that restored conditions did not truly represent reference, or system potential conditions. Instead, restored conditions reflected the system potential conditions within restored areas only, while holding unrestored areas constant and below their true potential. This approach was employed to be able to compare restoration sites to each other, while controlling for the unpredictable influence of the surrounding vegetation. The system potential of unrestored areas is unknown and cannot be satisfactorily estimated without knowing which species occupy those spaces; however the system potential of restored areas can be accurately estimated since the tree species planted and their height/age at maturity are known.

4.3.2 Site Suitability Criteria

Site suitability criteria are the variables used to identify areas within the spatial extent of a project that are most deserving of riparian restoration. Criteria can be ecologically based or opportunistic. Opportunistic criteria are primarily driven by socio-economic limitations rather than ecological suitability. Cost effectiveness and landowner willingness are the two most common opportunistic criteria used for riparian restoration prioritization, especially in watersheds with high cost restoration needs or a disproportionate amount of privately owned land (Landers 1997; Holmes et al. 2004). Ecologically based criteria serve as synthetic, or surrogate, indicators of ecological function that represent an integration of multiple riparian processes instrumental in achieving the restoration objectives. For example, the type and extent of riparian vegetation is a commonly used ecologically based criteria because it both influences and is influenced by multiple essential riparian processes such as sedimentation and erosion rates, temperature and disturbance regimes, LWD recruitment and stream flow (Landers 1997; Opperman & Merenlender 2004; Watanabe et al. 2005; Fullerton et al. 2006). In addition, environmental attributes more directly related to climate, hydrology or channel morphology, and less with riparian vegetation, can be used for site suitability criteria as well such as hyporheic exchange, flow, air temperature, stream width and depth, channel slope, floodplain width and connectivity, frequency of natural disturbances, substrate and soil moisture content (Kentula 1997; Landers 1997; Opperman & Merenlender 2004; WSDOE 2007).

For this project, the site suitability criteria used was effective shade, or the amount of solar insolation at the stream surface. Although effective shade is a commonly used indicator of healthy riparian systems, there are many other criteria that are were not considered in this prioritization scheme that will likely influence the outcome of restoration efforts. For example, the continuity of the riparian buffer or proximity to intact riparian habitat, although not included as a site suitability criteria, is believed to enhance the ability of riparian buffers to regulate stream temperature and should be pursued where appropriate and feasible. In addition, prioritizing riparian areas for restoration without considering the social, political, and economic aspects will inevitably challenge and constrain the implementation of those projects (Kentula 1997). While socioeconomic criteria were not incorporated into the prioritization scheme for this project, it is assumed that future restoration efforts will be informed by a combination of socioeconomic aspects and ecological knowledge. From a management perspective, it is important to acknowledge and consider these additional factors when interpreting the results and implementing restoration efforts.

Partnering agencies involved with this project have indicated an interest in using the results for their own prioritization schemes. The Johnson Creek Watershed Council for example, intends to incorporate the results from this study into their 2013 Riparian Restoration Strategy, a document that will outline their strategy for prioritizing areas throughout the watershed for riparian restoration. In other words, results from this project will ultimately serve the same purpose as a site suitability criterion and will be considered in conjunction with many other criteria such as stream flow, riparian buffer continuity, and opportunistic prospects (i.e. landowner willingness). In sum, the taxlots prioritized in this project will be subject to additional screening criteria that will account for many important factors not considered in the modeling or prioritization process presented here.

4.3 Priority Rankings

4.3.1 Taxlot Outcomes

Restoring a small percentage of all taxlots and restorable acres (~20% for each) resulted in a disproportionately large amount of increased solar flux attenuation (50% of the solar reduction target). The restoration efficiency, as measured by the increase in solar flux attenuation per acre of restored area, is highly variable between taxlots. As such, using taxlots as the minimum restoration unit is not only appropriate but also promotes a high level of efficiency in the allocation of restoration efforts.

For the most part, each priority ranking is evenly dispersed throughout the study area, with very few clusters or “hot spots” of any one priority type occurring. Minor differences in the average size and proportion of restorable area within taxlots were observed between different priority rankings (Table 3). All rankings (except the high priority ranking group) comprised a smaller percentage of the total restorable area than they did the percentage of all taxlots; as you go from high to low priority, the amount of restorable area contained in each taxlot diminishes. Slight variations in the average size of taxlots within each ranking group were also apparent. High priority taxlots tended to have a comparatively higher proportion of restorable area within them and were smaller in size. By contrast, low priority taxlots had a comparatively low proportion of restorable area within them and were larger in size. Medium priority taxlots fell somewhere in between high and low, while maintain taxlots were both small in size and had a low proportion of restorable area within them. In sum, taxlots that exhibited the largest amount of change between current and restored conditions were those in which the largest percentage of riparian vegetation was deemed restorable.

4.3.2 Subwatershed Outcomes

Prioritizing at the subwatershed scale resulted in a lower level of efficiency in the allocation of restoration efforts compared to prioritization at the taxlot scale. Restoring only 22% of all taxlots achieved the same amount of solar reduction as restoring 50% of all subwatersheds. Similarly, 39% of all taxlots were categorized as “maintain” whereas only 6% of subwatersheds received this ranking. In part, this is due to a reduced “signal” of landscape heterogeneity that resulted from using a coarser scale, or larger minimum restoration unit. For example, the difference between the percent of all subwatersheds and restorable acres in each ranking was much less pronounced compared to taxlot rankings. Similarly, the percentage of restoration buffer deemed restorable within each subwatershed is relatively uniform across them all; meaning they all exhibit similar conditions and there is less variation to aid in the prioritization of restoration efforts.

When prioritization is performed at the comparatively coarser scale of subwatersheds, the fine scaled variation of current vegetation condition and physical attributes within them is lost during the process of aggregating total solar flux attenuation in these large areas. Using the finer scaled restoration unit of a taxlot can apparently increase the efficiency of restoration efforts by high-lighting aspects of landscape heterogeneity and using that knowledge to refine the site selection process.

4.3.3 Jurisdictional Outcomes

For the most part, the number of taxlots or total restorable acres within each priority ranking was generally uniform across all jurisdictions, with a few minor exceptions. Milwaukie contained a higher percentage of high priority taxlots and restorable acres and, conversely, Happy Valley contained a slightly lower percentage of high priority taxlots and restorable acres compared to other jurisdictions. This could partly be a symptom of their size; they are the two smallest jurisdictions and, as such, are more vulnerable to the presence of outliers. However, the portion of Johnson Creek that is contained within the jurisdictional boundary of Milwaukie may also be subject to unique stressors that inhibit the ability for riparian restoration to occur (for example, more development near the mouth). Similarly, Happy Valley has a relatively high percentage of taxlots and restoreable acres classified as “maintain” meaning that the current condition of near stream vegetation in this jurisdiction is healthier compared to other jurisdictions.

The relative contribution of each jurisdiction to the total taxlots and restorable acres within each ranking group generally remained proportionate to the size of the jurisdiction, with similar exceptions regarding Milwaukie and Happy Valley. Milwaukie is more weighted towards the high priority ranking group whereas Happy Valley is weighted towards the “maintain” group.

For all other jurisdictions, the percent they contribute to each ranking group, in terms of taxlots of restorable acres, is relatively even across all rankings; they do not lean towards one ranking or another. This provides further support for the observed homogeneous dispersion of priority rankings throughout the study area, with no apparent spatial patterns or trends.

4.3.4 Maintain Ranking Group

The number of taxlots and acreage found to contribute 0 watts/acre to the total solar reduction goal was unexpected. For some of these taxlots, all near-stream vegetation is currently ≥4m and, as such, there is no difference between current and restored conditions which comes as no surprise. However, the majority (65%) of these taxlots had restorable area that, when restored, did not reduce heat loading to the stream. In other words, 68 acres of restorable area would not contribute to the solar reduction target if restoration occurred here. While this ranking group was labeled as "maintain" it should not be assumed that restoration in these areas would lack any sort of ecological benefit. In addition to shade, restoring riparian vegetation provides numerous ancillary benefits, including erosion control, flood mitigation, water purification, improved channel complexity, formation of instream and riparian habitat and general ecosystem resilience (Chen et al. 1998; Gebhardt & Fischer 1999; Holmes et al. 2004; Niemi et al. 2006; ODEQ 2006; Teels et al. 2006; Johnson et al. 2007; Kentula 2007; Li et al. 2012). Some of these benefits may even lead to reduced stream temperatures indirectly (i.e. LWD recruitment and stream bank stability). In sum, the taxlots classified as "maintain" are currently providing an adequate level of shade but in no way should this determination imply that all other ecological processes that occur within the riparian complex are functioning properly as well.

5.0 Conclusion

5.1 Management Implications

All taxlots within the study area have been prioritized based on the amount of solar flux reduced per acre of restored habitat. Regardless of the priority ranking they fall into, most taxlots are in need of riparian restoration to some extent and ultimately, the restoration of all taxlots should be pursued in order to achieve the maximum level of stream temperature reduction. Although the priority rankings assigned to the taxlots is indicative of their ability to provide shade to the stream, it is not indicative of their overall worth in terms of habitat or opportunity. All taxlots should be further screened for opportunistic prospects such as landowner willingness, community support or proximity to existing restoration projects, and fundraising opportunities. Taxlots classified as “maintain” may still provide ancillary benefits when restored and, as such, should still be included in additional screening efforts.

Taxlot data concerning solar insolation and priority ranking can be used, at the discretion of each jurisdiction, to encourage landowner cooperation, community support, or fundraising prospects. In terms of monitoring overall watershed health, this data will also provide a snapshot of the current status of riparian shade within the watershed.

5.2 The Evolving field of Restoration Ecology

The National Resource Council broadly defines restoration as "...re-establishment of pre-disturbance functions and related physical, chemical and biological characteristics." Given the broad definition of restoration, coupled with the inherent variability and stochasticity of physical, biological, and chemical phenomena, there is no universal formula for successful riparian restoration. To further compound the issue, restoration ecology is a relatively young interdisciplinary field and, as such, the literature tends to lack consensus and resolve on many issues. In general, the relative effectiveness of individual prioritization and implementation strategies is both highly debated and difficult to assess given the existing body of literature, making it difficult to choose strategies with confidence (Roni et al. 2002, 2008, 2010; Palmer et al. 2005; Palmer 2009). For most, however, a combination of socio-economic and informational limitations demands a careful, calculated consideration of trade-offs. Regardless of which limitations are encountered, restoration efforts are inherently risky endeavors; examples of both successes and failures abound (Landers 1997; Beechie & Bolton 1999; Roni et al. 2002, 2008, 2010). Given this high level of uncertainty, natural resource managers are encouraged to take an experimental approach to restoration and acknowledge the value of their contribution, whether a success or failure, to the body of knowledge surrounding restoration ecology (Landers 1997).

To assist natural resource managers in the prioritization of areas for riparian restoration efforts, more research is needed that evaluates the relative effectiveness of restoration techniques and prioritization schemes. Suggested topics for future research include: the influence of stream order, adjacent land use, land ownership, floodplain width, continuity and width of riparian buffers, hydrographic setting, channel slope and substrate, and soil moisture content on the long term effectiveness of riparian restoration efforts. Furthermore, monitoring the response of multiple indicators including macro invertebrates, fish and wildlife, nutrient and sediment regimes, and even community perceptions will help to advance our understanding of the functional relationships that take place within the riparian complex and will capture more of the benefits received from our efforts. In turn, this knowledge can also help to advance our understanding of the relative effectiveness of restoration techniques and help managers choose their prioritization schemes more wisely.

A growing number of managers have begun to recognize the shortcomings of a piecemeal (ex: uncoordinated efforts or failure to recognize and protect the inter-relationships between ecological processes) approach to riparian restoration and have instead adopted a more refined, holistic approach that acknowledges the importance of many ecological processes at multiple spatial and temporal scales in maintaining the riparian complex (Harris & Olson 1997; Chen et al. 1998; Beechie & Bolton 1999; Roni et al. 2002, 2008; Fullerton et al. 2006). These types of projects establish objectives that concern both biological resources and hydro-geological processes at broad spatial and temporal scales, such as enhancing regional ecological resiliency and habitat heterogeneity, or restoring the natural processes (i.e. disturbance regime or LWD recruitment) that maintain healthy ecological function of the riparian complex (Beechie & Bolton 1999; Roni et al. 2002, 2008; Palmer 2005; Seavy et al. 2009). While these holistic approaches, often referred to as "process-based restoration", are gaining in popularity, they can be prohibitively expensive and socio-economically unfeasible (Palmer et al. 2005; Seavy et al. 2009). Identifying effective, workable restoration strategies that can accommodate the socioeconomic atmosphere of urban watersheds needs to be recognized as an important endeavor in the field of restoration ecology.

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Glossary

Solar Insolation: The amount of energy received by the sun at the earths' surface; on a clear day ~1000 W/m^2 reaches a surface perpendicular to the incoming radiation. This energy varies due to the angle of the incoming radiation and cloud cover.

Restoration Buffer: The restoration buffer is the area in which restoration activities are likely to occur. It extends 15m to either side of the stream channel for Johnson Creek mainstem and all tributary streams.

Study Area: The study area encompasses all taxlots and subwatersheds that intersect the restoration buffer, which extends 15m to either side of the stream channel for Johnson Creek mainstem and all tributary streams.

Restorable Area: All area within the restoration buffer that is currently occupied by vegetation <4m in height and is not occupied by roads or buildings. Under a restoration scenario, all vegetation within restorable area is assumed to reach 27m height at maturity.

Restoration Scenario: As depicted by the restored conditions raster that was used to sample restored vegetation height; the restored scenario is characterized by all restorable area having a maximum vegetation height of 27m.

Solar flux attenuation: The amount of incoming direct beam solar radiation (mass/area*time) that is intercepted by near stream vegetation and prevented from hitting the stream surface. Percent effective shade is a commonly used metric for quantifying solar flux attenuation.

Total Solar Reduction Target: The potential net increase in solar flux attenuation (watts/m^2/d^{-1}) that would occur under a restoration scenario; or the difference between current and restored solar flux attenuation rates, aggregated for the entire watershed.

System Potential Vegetation at Maturity: The maximum height of vegetation is reached at maturity, which typically ranges between 20-30 years depending on the tree species. The system potential vegetation is meant to represent restored conditions after vegetation has had time to reach its maximum height at maturity. Synonymous to "reference conditions", but should not imply a return to historic conditions

Restoration Efficiency: Restoration efficiency is positively correlated with the increase of solar flux attenuation per acre under a restoration scenario; the larger the increase in solar flux attenuation between current and restored conditions, the more efficient, and worthwhile, it is to restore it (it, meaning taxlot or subwatsershed).

Appendices

Appendix A: Heat Source Methodology

Appendix B: Prioritization Calculations