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Using reference conditions in ecosystem restoration: an example for riparian conifer forests in the Pacific Northwest

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Abstract. Quantifying the attributes of reference sites is a crucial problem in the restoration of ecosystems, driving both the evaluation of current conditions and the setting of management targets for specific points in the future. Restoration of riparian ecosystems, particularly those dominated by conifers, has become a priority because of the numerous ecosystem services they provide, including a high number of vertebrate species in population decline that utilize these structurally complex forests. By way of example, we illustrate a three-step process to assess the effects of proposed riparian ecosystem restoration efforts: (1) identify reference sites (2) quantify metrics that describe the reference sites, and (3) use models to predict the likely effects of restoration actions relative to reference conditions. To this end, we identified 117 natural, late-successional conifer dominated stands from existing forest inventories in the Pacific Northwest for the purpose of establishing reference conditions. We did this to establish quantitative metrics for structural attributes essential to the maintenance of biodiversity in these forests, and to assess whether there were any important quantitative differences between upland and riparian forests or whether upland and riparian forest reference sites could be used interchangeably. Both forest types were generally similar, but riparian stands had higher average live tree wood volumes and basal areas, suggesting they may be growing on sites that are more productive. Both riparian and upland forests had abundant large diameter (>50 cm) live trees and snags. Collectively, our data suggest that mature, late-successional conifer dominated forests have well developed structural characteristics in terms of abundant large trees in the overstory, abundant large snags, and a well-developed understory of shade-tolerant trees. We modeled the growth of young conifer stands to assess whether a common restoration treatment would accelerate development of structural characteristics typical of reference conditions. We found that left untreated, the stands followed a trajectory towards developing forest structure similar to the average reference condition. In contrast, the restoration treatment followed a developmental trajectory along the outside range of reference conditions.

Key words: applied ecology; biodiversity; conifers; dead wood; ecosystem models; ecosystem restoration; Pacific Northwest; *Pseudotsuga menziesii*; reference conditions; restoration ecology; riparian forests.

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INTRODUCTION

Quantifying reference conditions is a crucial challenge in the restoration of ecosystems, driving both the evaluation of current conditions and the setting of management targets (Palmer et al. 1997, Harris 1999, Hughes et al. 2005). "Reference conditions" refers to ecosystem conditions in the absence of human intervention (Stoddard et al. 2006) and to the range of natural variability in structural attributes, ecosystem functions, and biota (Landres et al. 1999, Moore et al. 1999). Reference conditions are commonly used to evaluate levels of degradation in ecosystems, set ecosystem restoration targets, or evaluate the success of ecological restoration treatments (Stoddard et al. 2006). In the context of ecosystem restoration, reference sites are needed to assess whether degraded ecosystems are moving along a trajectory that will lead to the recovery of desired ecosystem services, or if management is needed to accelerate recovery or to move the ecosystem in a new direction (Pickett and Parker 1994, White and Walker 1997, Beauchamp and Shafroth 2011). Restoration of riparian ecosystems has become an international priority (Palmer 2005, Lake et al. 2007, Richardson et al. 2007). An important function of riparian ecosystems is the high levels of biodiversity they support, yet they are also subject to degradation from a variety of sources such that they are now endangered across much of the Earth (Sala et al. 2000). Because of the important services riparian ecosystems provide, efforts to restore their structure and function are common (Peterken and Hughes 1995, Webb and Erskine 2003, Shafroth et al. 2008, Bunn et al. 2010).

In much of North America and particularly in western states, extensive forest reserves have been established for the purpose of protecting or restoring riparian ecosystems to maintain biological diversity and to benefit numerous aquatic and terrestrial species which are in population decline (Nehlsen et al. 1991, USDA and USDI 1994, Gregory 1997, Riccardi and Rasmussen 1999). In such forests, key structural attributes are large live trees and abundant large dead wood in the form of snags, wood on the forest floor and wood in streams, and a multi-storied canopy (Harmon et al. 1986, Spies et al. 1988, McWinn and Crossley 1996). Large dead wood provides important habitat for a range of taxa, including fishes, amphibians, mammals, birds and invertebrates (Angermeier and Karr 1984, Raphael and White 1984, USDA and USDI 1994, Floyd et al. 2008). For example, large down wood on the riparian forest floor provides breeding habitat and cover essential for herpetofauna (Whiles and Grubaugh 1993, Welsh and Ollivier 1998, Semlitsch and Bodie 2003). Similarly, standing dead trees increase the structural complexity of a forest and provide nesting, roosting and feeding habitat for a suite of cavity nesting birds and mammals (Maser et al. 1988, Loeb 1994, Carey 2000, Erickson and West 2003). For aquatic species, instream wood is essential to the maintenance of habitat because it forms pools, traps and sorts gravels, increases hyporheic exchange, moderates stream temperature, provides cover and increased habitat complexity (Montgomery et al. 1995, Beechie and Sibley 1997, Moore et al. 2005). In both riparian and upland forests, the bole, rootwad and pit created when a tree falls increases topographic and substrate heterogeneity, creating microsites for the establishment of certain trees and shrubs, helping to enhance species richness (Harmon et al. 1986, Harmon and Franklin 1989, Pollock et al. 1998). These studies suggest that in streams and riparian ecosystems, dead wood in the form of snags and down logs is essential to maintain biological diversity and thus should be important structural attributes to quantify when describing forest reference conditions.

Throughout much of the northern hemisphere, old, complex and biologically diverse forested ecosystems have been cleared and replaced by young, structurally simple, species poor forests (Spies et al. 1988, Bunnell and Houde 2010). Riparian forests have been particularly impacted because they are often the most accessible areas due to their location on low gradient ground and because transportation routes are often built within river corridors (Sedell and Duval 1985, Meehan 1991, Naiman et al. 1993, Naiman et al. 2000). Because of the number of species that rely on large snags and down wood in stream, riparian and upland environments, there have been recent experimental efforts to restore complex forest structure by treating young stands to accelerate the development of large trees and large dead wood (Swanson and Franklin 1992, USDA and USDI 1994). One key to ensuring that such restoration activities achieve the intended goal of accelerating a return to natural conditions found in older forests is to quantify the structural and functional attributes of natural reference stands (Fule et al. 1997). Once such reference stand attributes are quantified, then forest growth models can be used to determine if restorative treatments of young forests will help accelerate development of a more complex forest structure within the typical range of natural variation (Taylor 2004, Goebel et al. 2005).

In this paper we describe how we used existing data sets and models to: (1) identify reference conditions, (2) quantify key structural characteristics and (3) assess the potential effect of restoration prescriptions intended to accelerate the development of structurally complex (sensu Oliver and Larson 1996) late-successional Douglas-fir (*Pseudotsuga menziesii*) forests from early seral stands. We also compare riparian and upland Douglas-fir forests for the purposes of assessing whether there are any important structural differences and if it is necessary to distinguish between reference stands for these two forest types. We expect our results to be applicable in the context of assessing whether active restoration is needed in conifer forests or whether the desired future habitat structure can be obtained through natural processes. We also expect our results to have general applications to reference site selection in other ecosystems and to contribute to the larger debate as to the conditions under which active restoration improves ecosystem function (Nekola and White 2002).

Study area

Western Washington and Oregon are bounded to the east by the Cascade Mountain range and to the west by the Pacific Ocean (Fig. 1). A second mountain range, comprised of the Olympic Mountains and the Coast Range, parallels the Cascade Range 150 km to the west, with the north-south trending Puget Sound-Willamette Valley trough set between the two ranges. Elevations in the Cascade and Olympic Mountains exceed 3000 m, whereas the Coast Range is typically less than 1000 m in elevation. Bedrock slopes of the major mountain ranges are steep with relatively thin soils, but extensive terraces fill the Puget-Willamette trough and extend up the main river valleys (Booth et al. 2003).

In the forests of western Washington and northwest Oregon, the dominant tree species is Douglas-fir. In these forests, the main successional pathway is characterized by Douglas-fir colonization after fire, Douglas-fir dominance during the first 200 to 300 years, and then slow succession to a "climax" forest dominated by the shade tolerant (but fire intolerant) western red cedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) as the stand ages (Munger 1940). However, because the historic fire return interval in these forests averaged between 180–270 years (Agee 1993, Long and Whitlock 2002), many of these stands were continually dominated by Douglas-fir, since stands were often reset by fire prior to succeeding to western hemlock and western red cedar dominance. Such forests occupy a wide range of soil moisture conditions, from mesic sites in valley bottoms to more xeric sites on ridgetops, but generally are not found in the more hydric conditions typical of floodplains. Floodplain forests tend to be dominated by a mix of hardwood and conifers, such as Sitka spruce (*Picea sitchensis*), western red cedar, big-leaf maple (*Acer macrophyllum*) and black cottonwood (*Populus trichocarpa*), with an understory that includes red alder (*Alnus rubra*) and vine maple (*Acer circunatum*) (Gannett 1899).

Thus along streams and rivers, there are two broad types of riparian forests as defined by landscape position and the hydrologic conditions that affect them: (1) Hydric or floodplain riparian forests are those that are regularly disturbed by fluvial processes such as flooding and sediment transport (Fig. 2). They are most common along streams flowing unconfined through broad valleys, are dominated by a mix of hardwood and conifers, and often contain evidence of fluvial scour and deposition. (2) In contrast, more mesic riparian forests are found in valley bottoms along streams and rivers flowing through more confined terrain, where hillslopes or terraces are in close proximity to the channel and floodplains are relatively narrow (Fig. 2). Relative to floodplain forests, these mesic riparian forests are more elevated, rarely disturbed by floods, and tend to be dominated by Douglas-fir. Other than their landscape position, they are hard to distinguish from more xeric Douglas-fir forests further upslope, suggesting that these forests may essentially be upland forests growing next to streams.

Though these valley bottom riparian forests are rarely affected by fluvial processes, they provide important goods and services to aquatic systems such as dead wood, shade, nutrient inputs and the maintenance of microclimate, and

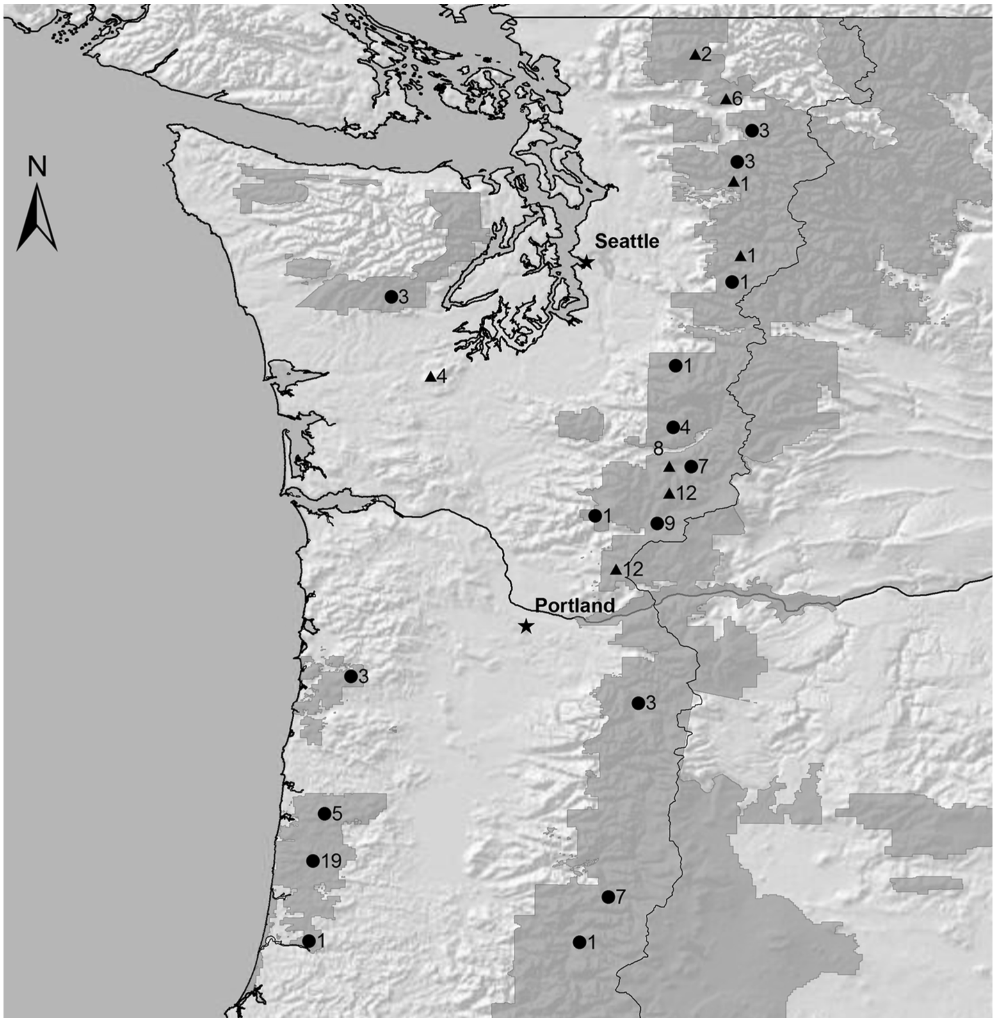

Fig. 1. Map of western Washington and Oregon showing general locations of reference sites analyzed in this study. The triangles represent riparian reference stands and the circles represent upland reference stands, with the adjacent number indicating the number of stands that were utilized in a particular area within a National Forest (shaded areas) or other public lands (see Appendix for site details). The irregular, dark vertical line running through the middle of the figure is the crest of the Cascade Range, the dividing line between the western, "wet" side of Oregon and Washington and the drier east side, while the dark horizontal line just above Portland is the Columbia River, which is the Oregon-Washington state boundary.

buffer against upland activities that are detrimental to aquatic systems. Beyond a horizontal distance from a channel equal to the maximum height that a tree can grow at a given site, there are few services provided by such riparian forests to streams. Thus the horizontal width of riparian forests is frequently defined as the distance from the stream equal to the site potential tree height (Fig. 2).

Methods

Data sources

We obtained data for estimating reference ranges for stand attributes from two primary data sources; The Cooperative Monitoring Evaluation and Research Program (CMER) data (see Schuett-Hames et al. 2005) and the United States Forest Service Federal Forest Inventory and

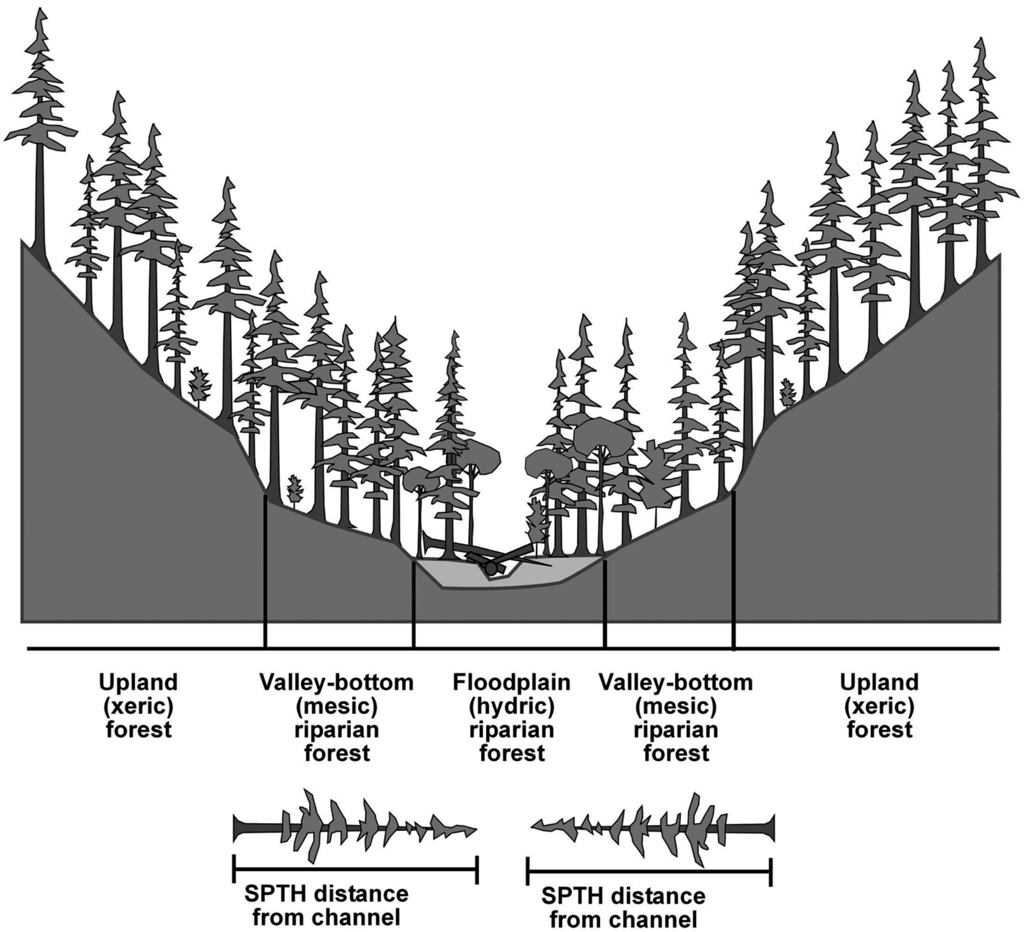

Fig. 2. An illustration of the relative landscape position of forest types for a small stream in a confined valley; (1) hydric, mixed conifer-hardwood floodplain forests, (2) mesic, valley bottom Douglas-fir dominated riparian forests, and (3) more xeric, Douglas-fir dominated upland forests. On federal lands in the Pacific Northwest, forests are considered riparian if they are within a horizontal distance to the stream that is less than or equal to the site potential tree height (the average maximum potential size of the dominant trees at a site), regardless of landscape position. In larger and less confined streams, the floodplain riparian forest tends to be wider, and valley-bottom riparian forests narrower. In the Douglas-fir dominated riparian and upland forests, soils are generally well drained and the major disturbance process is fire, with a stand replacement interval of 180–270 years. In floodplain riparian forests, water tables are often near the surface and the major disturbance process is flooding, with a disturbance return interval of 2–3 years that is usually not stand replacing.

Analysis Program (Hiserote and Waddell 2004), which uses a relatively consistent methodology to regularly inventory private and federal forests across the landscape throughout the United States.

The CMER site selection and sampling protocols were specifically designed for use in quantitatively estimating reference conditions of mature conifer-dominated riparian forests in western Washington (Schuett-Hames et al. 2005). Individual tree data for both live and dead trees are included. All sites are riparian forest stands and exclude non-forest features such as roads, landslides, rocky outcrops, cliffs, and wetlands. The sites were randomly chosen from a large pool of potential mature forest sites and then examined to ensure that the sites were in fact intact, mature forests that had no evidence

Table 1. Filters applied to the databases to select sites representative of mature Douglas-fir dominated riparian forests in western Washington and Oregon.

Filter	Plots were included if:	CVS	CMER	FIA
Elevation ≤3000	Elevation of plots were ≤3000 ft	X	X	X
Site Class = 2, 3 or 4	Calculated Site Index at 50 years is between 75-135 ft	X	X	X
Age ≥80 years old	The average tree age is between 80-200 years.	X	X	X
DF Basal Area ≥ 0.5	The basal area of Douglas-fir in the stand is ≥50% of the total basal area	X	X	X
Forest Type = DF	The USFS forest type classification is Douglas-fir	X		X
Site Index Species = DF	The site species used to calculate the site index is Douglas-fir	X	X	X
Harvest	Harvest activity is absent or light	X	X	X
Fire >80 yrs ago†	No fires occurred in the last 80 yrs	X		
Roads†	No roads in the plot	X	X	
Windthrow†	No windthrow or windthrow was light	X		
Cliffs†	No cliffs in the plot, or cliffs were a minor feature in the plot	X	X	
Rocky/Ridgelines†	Rock outcrops, ridgelines, rocky soils, boulders and/or talus were non-existent or minor features in the plot	X	X	
Unstable†	No slopes were described as unstable, failing, landslides or avalanches	X	X	
Other†	Miscellaneous disturbance or related problems such as plots in ball fields, wetlands, water courses, mines, powerlines etc.	X	X	
Uneven Aged	Dominant trees in subplots were approximately the same age (average within 50 years of each other, and no more than one subplot <80 years old)	X		X
Harvest year	No harvest in plot since 1920			X
Adjacent to streams	Selected sites adjacent to streams		X	
	Sample size before filtering	3408	113‡	3407
	Sample size after filtering	71	46	15§

†From the CVS notes column.
‡CMER randomly selected sites from a pool of 4771 possible sites. Each site was visited, and sites were rejected if they did not meet CMER qualifying criteria. CMER visited 976 sites, and rejected 863 sites during screening. Stand attributes were measured at the 113 selected sites a sample size that was deemed statistically adequate for the purposes of the study.
§Because it could not be determined if there were roads or other non-forest conditions within these sites, ultimately, they were not included in the analysis.

of recent logging activity (Table 1). Plots were fixed and ranged from 0.1 ha to 0.2 ha, depending on stream size. All live and standing dead trees >10 cm diameter breast height (dbh) were inventoried (Schuett-Hames et al. 2005).

The US Forest Service Current Vegetation Survey (CVS) Databases are designed for an ongoing landscape scale inventory of Forest Service lands in western Washington and Oregon and are part of the larger Forest Inventory and Analysis (FIA) program (Hiserote and Waddell 2004). The CVS data are inclusive of stands in the Cascade, Coast Range, Willamette Valley and Puget Trough Ecoregions (Omernik 1987). We used this dataset to delineate upland reference conditions. We did not include FIA plots found in the floristically unique and diverse Klamath Mountain Ecoregion in southwestern Oregon where mixed conifer-hardwood forests are common. Data in the FIA program are collected within 1 hectare plots at specific points on a fixed grid that covers federal lands in western Washington and Oregon, and thus includes forested, non-forested and partially forested sites. The plots can also include forest stands of different ages. Individual tree data for both live and dead trees are included. It is not specifically designed to quantitatively estimate the condition of stands of mature forest. The CVS data contain notes that describe each plot and can be used to identify sites that contain non-forest features such as roads, mines, powerlines, recent disturbances, and whether there has been any timber harvest activity. There is some variation in the quality of the notes both within and between states, with the Oregon notes generally being more comprehensive and detailed. The FIA data set also includes inventories of private land in western Washington and western Oregon. We initially included these in our analysis, but ultimately had to exclude them because these stands lacked information on the existence of roads or other non-forest features in the plots (Table 1).

Rationale for choosing to identify reference conditions for mature forests

After examining the existing data sets, we chose to identify reference conditions for mature forests (80–200 yrs) instead of old-growth forests (>200 years) for several reasons, prime among them was that: (1) quantitative descriptions of mature forest structure were available, whereas such data were limited for forests >200 years; (2) Attainment of mature forest characteristics is a common restoration objective throughout the region (USDA and USDI 1994, Washington Forest Practices Board 2000, Washington Department of Natural Resources 2006); (3) Since the historic fire return interval in these forests was 180–270 years, there were many mature forests across the landscape, (4) commonly used forest growth models such as Forest Vegetation Simulator (USFS 2010*a*) and Organon (Hann et al. 2009) have been calibrated using stand data up to 120–140 years and thus can make reasonable predictions of structural development for specific stands up to this age range; and (5) the transitional period from a young to a mature forest is when most mortality occurs. This is the period in a forest's development when the highest number of large snags and large wood are provided and thus it is key period in terms of the ability of a forest to develop these structural elements (Oliver and Larson 1996, Beechie et al. 2000).

Preparation of the data sets

Because the CMER and CVS data are designed for different purposes, they contain, to varying degrees, plots that are not representative of the same types of forests. Therefore we filtered each data set so that the plots from each data set for which we estimate reference conditions is representative of approximately the same type of forest, one that was once common throughout the region: a typical mature Douglas-fir dominated forest that developed after a stand replacement event (e.g., a fire) growing in soil conditions typical of mesic riparian forests, that had not been subsequently impacted by management activities or severe disturbances. The stands had at least 50% basal area in Douglas-fir, a site class of 2, 3 or 4 (highly productive and highly unproductive sites were not included), no record or evidence of timber harvest, a mean age between 80–200 years old, and a uni-modal age structure for the dominant and co-dominant trees (Table 1). The CMER data were already filtered to only include intact, unharvested mature riparian forest stands that were (relatively) even aged, but we needed to filter them further for Douglas-fir dominated forests since they include some floodplain forests and other riparian forest types.

The CVS data required extensive filtering to identify appropriate reference stands. The CVS data were collected in 5 variably sized subplots within a 1 ha circular plot at fixed points on a grid ranging in size from 0.85 to 3.4 miles (1.4 to 5.5 km) (USFS 2001). They include many sites that were only partially forested or contain stands of different ages. Stands with subplots of different ages are often indicative of timber harvest within one or more subplots, or of an unusual disturbance history. These stands were not representative of a forest that developed after a stand replacement event. Therefore, we removed CVS plots with multi-modal age distributions among subplots. The CVS databases include notes for each site that often describes non-forest features such as roads, rocky ridge tops, cliffs, water courses, baseball fields, mines, powerlines, etc. (and thus describe forest conditions at a landscape scale). We removed sites that contained these non-forest features because we could not use such sites to quantitatively describe forest reference conditions at the stand scale. We chose the stand scale of analysis rather than a landscape scale analysis because forest practices regulations in the study area assess, regulate and set desired future forest conditions at the stand level. Further, such filters are consistent with the filters used in developing the CMER database (Schuett-Hames et al. 2005). Finally, we used the CVS notes to remove sites where there was evidence of other recent disturbances such as fire, windthrow and pests. Some of these disturbances may be natural, but others may not. For example, fires are often started by human activity, windthrow in intact forests is often the result of adjacent clearcuts and climate change is altering the natural frequency of pest and disease outbreaks. Further, in terms of using reference conditions to set stand level management targets (e.g., live tree densities) at a specific age, undisturbed sites are required to set the targets so that when disturbances occur in some of the stands, the average stand condition at the target age will approximate average reference conditions.

We examined 3408 CVS plots in western Oregon and Washington and identified 71 that met our criteria for reference conditions for mature forests, 32 from western Washington, and 39 from northwestern Oregon (Table 1, Fig. 1). Because they are on a grid spread evenly over the landscape, the CVS data is dominated by upland sites that are not associated with riparian areas, and we refer to them as the upland stands, to distinguish them from the riparian stands (the CMER data). We identified 46 of 113 stands in the CMER data that met our criteria for reference conditions for mature Douglas-fir dominated forests (Table 1, Fig. 1). The higher percentage of acceptable sites from this data set stems from the fact that it was prefiltered and already met most of our reference stand criteria (Schuett-Hames et al. 2005). For stands examined, the diameter, height and species of each live and dead tree in the stand was extracted from the data. This allowed us to estimate stand parameters used to characterize the stand such as live and dead tree biomass, density, height and diameter. The age of the dominant trees in each stand was used to estimate stand age. For all quantitative metrics of reference stands, the Kolmogorov-Smirnov two-sample test was used to determine if any statistically significant ($p < 0.05$) differences existed between the mesic valley bottom riparian references stands and the more xeric reference stands upslope.

Model parameterization and simulations

To project long-term changes in stand structure, we used the model Forest Vegetation Simulator and the post processor FFE (USFS 2010*a*). FVS is a distance-independent, individual-tree forest growth model that has been used to project forest stand growth in the Pacific Northwest and elsewhere (Bragg 2000, Wilhere 2003, Anderson et al. 2005, Crookston and Dixon 2005). The key parameters affecting model behavior are tree growth rates and mortality rates. We used a maximum stand density index of 1250, which is typical for the area, to project competition mortality rates in young stands. We set a minimum background mortality rate of 0.7% for all stands, a somewhat conservative estimate relative to Douglas-fir mortality rates in older stands or thinned stands (Munger 1946, Bible 2001). Maximum tree height was set at 76 m because that is the typical site potential tree height in the study area. To ensure that simulated changes in diameter, stand density and height were consistent with local conditions, the model was calibrated against 66 Douglas-fir dominated stands from the area ranging from 23–139 years in age, which were extracted from the FIA database. Comparison of our model outputs with these stands showed that our projected changes in diameter, height and stand density all followed patterns consistent with the stands, suggesting that the model was appropriately calibrated. The model output includes both live tree parameters and tree mortality. To convert tree mortality into estimates of the size and density of snags and down wood, we used the Fire and Fuel Extension of FVS, which projects the number and longevity of snags and down wood after mortality occurs, based on the work of Mellen and Ager (2002). Details of the equations used to estimate snag and down wood production are provided in Mellen and Ager (2002).

We did not model the sensitivity of FVS to various site parameters (e.g., aspect, slope, and elevation) because those sensitivities are well documented for FVS (Wykoff et al.1982). Importantly, these sensitivities are mostly quite small for a given site index and stocking, indicating that they will not have large effects on modeling of stand characteristics. The sensitivity of Douglas-fir growth to elevation is relatively small (only $\pm 2\%$ over an elevation range of 700 m, Wykoff et al. 1982). Slope and aspect also influence growth rates, and the sensitivity of each is dependent on the value of the other. Douglas-fir is more sensitive to slope, with diameter growth varying by $\pm 11\%$ over slopes from 0.0 to 0.8 on a north aspect, and $\pm 12\%$ over slopes from 0.0 to 0.8 on a south aspect. Sensitivity to aspect for Douglas fir is essentially zero on flat ground, but increases to about $\pm 5\%$ for Douglas fir when slope is about 75%. Because these parameters have relatively small effects on stand growth, we did not model a wide range of stands to evaluate the influence of those parameters. Rather, we modeled a relatively simple example stand to illustrate how the model can be used in the three-step planning process.

Initial stand conditions.—The USFS provided detailed data on seven 30–40 year old Douglas-fir dominated stands in the Siuslaw River basin from a group of 130 stands thinned for the

Table 2. Comparison of average characteristics of mature, Douglas-fir dominated upland and riparian forests. L(D)BA = Live (dead) Tree Basal Area. LQMD = Live quadratic mean diameter, L(D)DBH = live (dead) diameter breast height, LTV = Live tree Volume, L(D)TPH = live (dead) trees ha^{-1}. Means and standard deviations are for all trees >10 cm dbh unless otherwise stated. Significant differences (t-test for unequal variances, $p < 0.05$) between the riparian and upland stand totals are noted with an asterisk.

Parameter	Riparian Mean (SD)	Upland Mean (SD)
Age (yr)	115.5 (18.3)	112.1 (18.2)
LTPH	372.8 (97.3)	385.5 (253.5)
LBA (m^2/ha)*	88.4 (20.3)	75.0 (21.2)
LTV (m^3/ha)*	1314.9 (316.9)	1057.7 (313.1)
Live Ht (m)	31.8 (5.1)	33.0 (7.8)
LQMD (cm)	55.6 (7.3)	55.0 (13.9)
LDBH (cm)	48.3 (6.9)	49.6 (13.6)
LTPH >50 cm dbh	154.1 (37.6)	153.0 (56.7)
DBA (m^2/ha)*	13.5 (12.7)	19.8 (16.1)
DQMD (cm)	47.4 (15.2)	44.7 (16.9)
DDBH (cm)	42.4 (12.3)	40.3 (15.3)
DTPH*	74.9 (40.0)	115.2 (67.8)
DTPH >50 cm dbh	21.0 (19.4)	23.6 (19.0)
LBA+DBA (m^2/ha)	101.8 (22.7)	94.7 (31.8)
Number of plots	46	71

purposes of restoring forest functions (USFS 2010*b*). Most of the stands originated 30–50 years ago, when Douglas-fir was planted following clearcut harvest of the original forest. The average stand age (n = 130) was 35 years (sd = 9.0) and ranged from 14-64 years. Pre-treatment stand densities averaged 558 trees ha^{-1} (range = 210–1087 trees ha^{-1}) and post treatment averaged 147 trees ha^{-1} (range = 111–296 trees ha^{-1}). The proposed treatment is typical of recent Forest Service and Bureau of Land Management plans to restore biologically diverse forests (BLM 2010, BLM 2011, USFS 2011).

Restoration treatments.—We used the data from the stands to project the average mortality, size and abundance of large diameter live trees, snags and down wood under a common restoration treatment of thinning to 150 trees ha^{-1} and compared this to untreated stands. The treatment is representative of the average restoration treatment within the project (USFS 2010*b*). Because the restoration thinning is intended to accelerate the development of large diameter trees, all the thinning treatments removed the smaller diameter trees until the target density was reached, such that the largest trees remained. All thinned trees were assumed to have been removed from the site and were not included in mortality counts.

Results

Reference stand structure

Tree densities.—Live trees per hectare (LTPH) >10 cm dbh averaged 373 for the 46 riparian reference stands and 386 for the 71 upland reference stands, a difference that is not significant ($p > 0.05$), (Table 2). The high density of trees in both the upland and riparian stands reflects the fact that many of the stands had significant amounts of understory regeneration of shade tolerant trees and were well on their way towards developing a multi-tiered canopy, an important structural characteristic of older forests (Fig. 3). Both the riparian and upland stands show a bimodal size distribution, with an understory canopy centered around 20 m in height and dominated by western hemlock and red cedar and an overstory canopy dominated by Douglas-fir that is centered around 40 m in height for the upland stands and 60 m in height for the riparian stands (Fig. 3). For both riparian and upland stands, tree densities were about evenly split between the understory and the overstory, though the species composition was quite different. While the overstory was almost entirely Douglas-fir, the understory was dominated by western hemlock and western red cedar, both shade-tolerant species. Notably, shade-intolerant Douglas-fir is also present in the understory of both the upland and riparian stands, and is found in all size classes. The upland reference stands in particular had high densities of small Douglas-fir.

The size range of mortality trees was also quite broad. Though most of the mortality was in the smaller size classes, there were a number of mortality trees in the larger diameter classes (Fig. 4). This suggests that though competition is likely an important mortality agent, not all mortality is related to competition. With stands of this age, other agents such as fungus, insects, floods and wind breakage must also be contributing to tree mortality (Oliver and Larson 1996, Lutz and Halpern 2006). The riparian stands averaged 75 standing dead trees per hectare

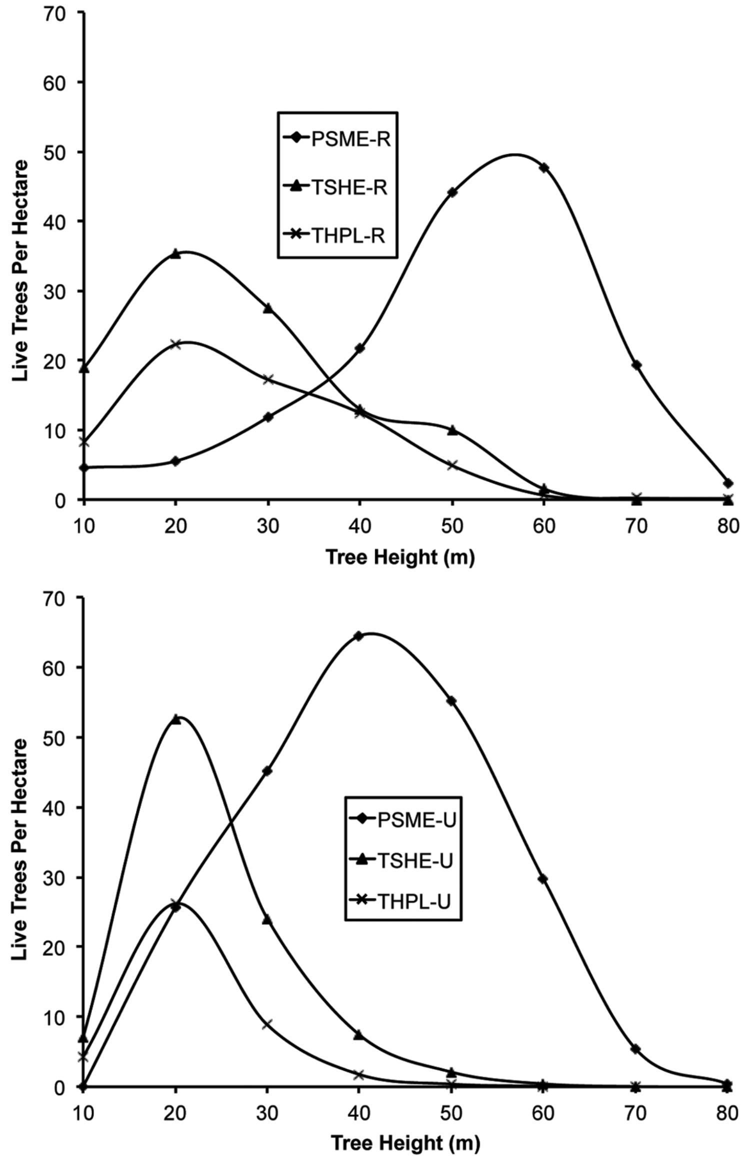

Fig. 3. Comparison of the abundance by tree height of live Douglas-fir, western hemlock and western red cedar trees species among (top) all riparian (R) and (bottom) all upland (U) forest plots. These data show a multilayered canopy with an overstory dominated by Douglas-fir (PSME) and the understory dominated by the shade-tolerant western red cedar (THPL) and western hemlock (TSHE).

(DTPH), which was significantly ($p < 0.05$) lower than the 115 DTPH for the upland stands (Table 2). Both riparian and upland forests had overstories with high densities of large diameter (>50 cm) live trees and large diameter (>50 cm) snags (Table 2, Figs. 4 and 5).

Tree diameters.—Riparian live trees quadratic mean diameter averaged 56 cm while the upland live tree quadratic mean diameter averaged 55 cm (Table 2). Dead tree quadratic mean diameters averaged 47 cm for the riparian stands and 45 cm for the upland stands. For both data sets, the average diameters of the dead trees was less than that of the live trees, a pattern typical of Douglas-fir dominated forests in this age range, where many of the deaths are likely a result of

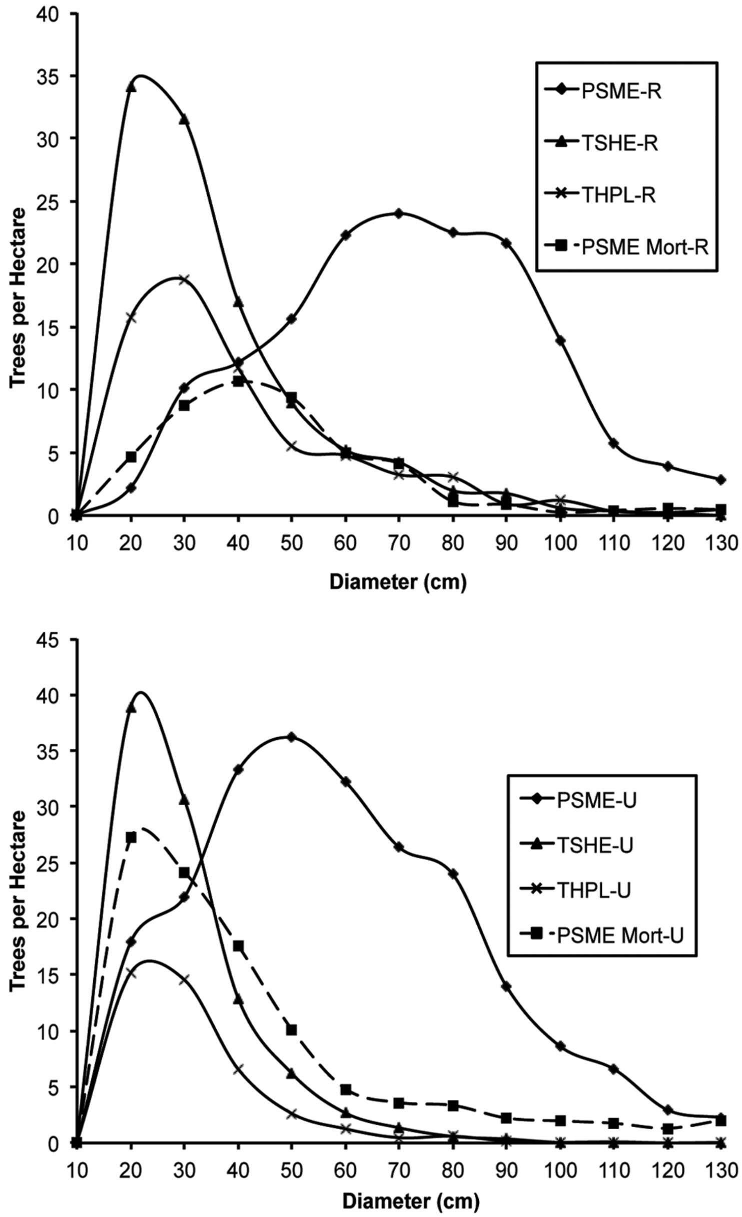

Fig. 4. Comparison of the abundance by diameter class of live Douglas-fir (PSME), western hemlock (TSHE) and western red cedar (THPL) and Douglas-fir mortality trees (PSME-Mort) among (top) all riparian (R) and (bottom) all upland (U) forest plots. There are few standing dead trees of western hemlock and western red cedar and for clarity their diameter distribution curves are not shown.

competition mortality (Fig. 4). Though the average diameter of live and dead trees was higher in the riparian stands, the number of large diameter live and dead trees was not all that different (Fig. 5). Both riparian and upland forests have overstories with high densities of large diameter (>50 cm) live trees and snags (Fig. 5, Table 2).

Almost all of the standing dead trees were Douglas-fir. In the riparian stands, the modal dead tree diameter in Douglas-fir was 40 cm dbh, about 20–50 cm smaller than the broad peak of

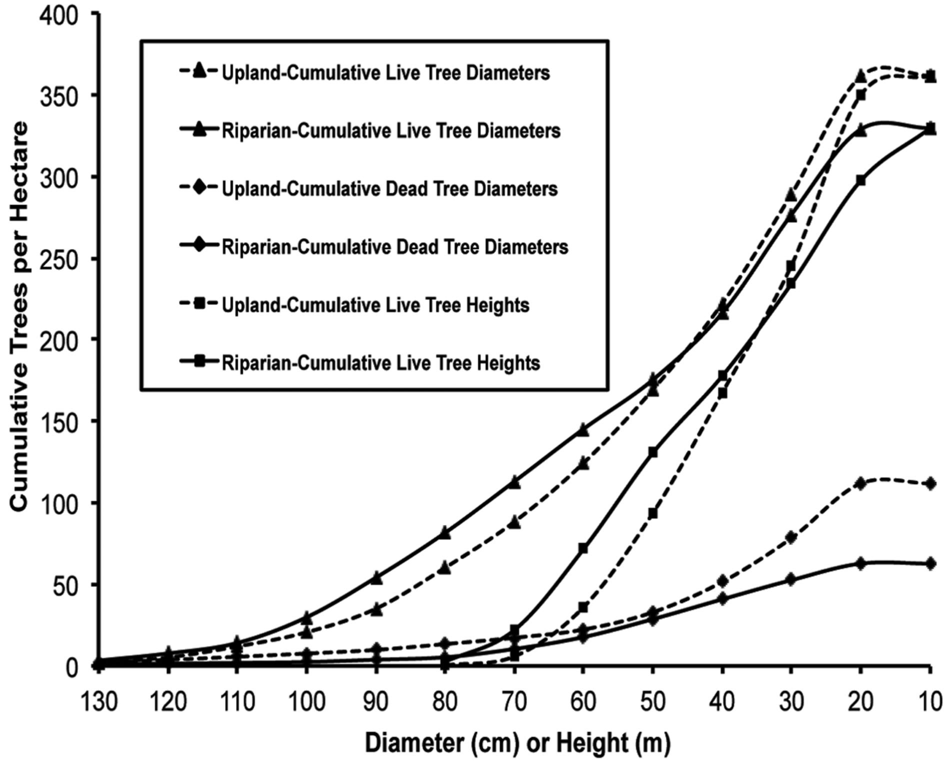

Fig. 5. Cumulative abundance by height and diameter class of live and dead Douglas-fir, western hemlock and western red cedar among all riparian and upland forest plots. These data show that there are abundant large diameter live trees and snags in both riparian and upland plots.

live Douglas-fir diameters between 60–90 cm (Fig. 4). The size distribution of dead Douglas-fir trees ranged from 20 to 130 cm, and as expected, most of the dead trees were in the smaller size classes. However, there were a number of dead trees $>$ 50 cm dbh. In contrast to the riparian stands, the mortality peak for Douglas-fir in the upland stands was around 20 cm dbh, whereas the live Douglas-fir diameter peak was around 50 cm (Fig. 4). The Douglas-fir mortality curve in the upland stands also showed a wide range of size in tree mortalities (Fig. 4).

Wood volumes and basal areas.—The riparian forests had significantly ($p < 0.05$) higher wood volumes than the upland forests. The wood volume of live tree stems was 1315 m^3 ha^{-1} for the riparian stands, while upland wood volumes averaged 1058 m^3 ha^{-1} (Table 2). Comparisons of snag volumes between riparian and upland stands could not be made because data on riparian snag heights were not available.

The riparian stands averaged live tree basal areas (LBAs) of 88 m^2 ha^{-1} and were significantly ($p < 0.05$) higher than the upland stands 75 m^2 ha^{-1} (Table 2). The riparian stands averaged significantly ($p < 0.05$) lower dead tree basal areas (DBAs) of 13 m^2 ha^{-1}, relative to the upland stands DBA average of 19 m^2 ha^{-1}. The higher live tree volumes and basal areas of the riparian forests were primarily due to the higher density of large diameter Douglas-fir in the overstory (Fig. 5).

Trees species composition and richness.—Both the riparian and upland stands were dominated by conifers (Table 3). In terms of overall species abundances, Douglas-fir comprised 41% of the riparian trees and 55% of the upland trees (Table 3). Western hemlock and western red cedar were the next most abundant trees. These three species comprised 88% and 93% of all individuals found in the riparian and upland plots, respectively. Red alder and bigleaf maple were the most common hardwoods. These two species and the three most common conifers accounted for 93%

Table 3. Average tree species richness and tree species abundances of the five dominant species in riparian and upland plots; C = conifers, D = deciduous trees, DF = Douglas-fir, WC = western red cedar, WH = western hemlock, RA = red alder, BM = bigleaf maple.

				Tree species abundance									
	Species richness			Percentage of all trees in all plots					Percentage of plots where found				
Stand type	C	D	All	DF	WH	RC	RA	BM	DF	WH	RC	RA	BM
Upland	2.7	0.8	3.5	55.3	26.4	11.6	2.9	1.6	100.0	78.9	53.5	46.5	26.8
Riparian	3.6	1.1	4.7	41.0	30.1	17.1	2.2	2.8	100.0	97.9	78.7	51.1	40.4

and 98% of all the trees found in the riparian and upland stands, respectively.

The riparian stands were very consistent in terms of species composition. All stands contained Douglas-fir, 98% contained western hemlock, 79% contained western red cedar, 40% big leaf maple and just over half (51%) contained red alder. In contrast, the upland forests had fewer stands with western hemlock (79%), western red cedar (54%) and bigleaf maple (27%). Tree species richness was not particularly high for either the riparian or upland stands (Table 3). The riparian stands averaged 4.7 species (3.6 conifers and 1.1 hardwoods), while the upland stands averaged 3.5 species (2.7 conifers and 0.8 hardwoods).

Assessing effects of restoration treatment on stand structural development.—We used FVS to assess the growth trajectory of a typical Douglas-fir dominated stands thinned to accelerate the development of complex forest structure. We compared the structural development of the treated stands to the development of the stands if left untreated (Table 2, Figs. 6 and 7). Our simulations suggest that a typical young Douglas-fir dominated stand, left untreated, rapidly attained overstory live tree densities and average live tree diameters typical of the reference stands. Beginning around age 100, the untreated stand was within one standard deviation of both the average live tree diameter and overstory density of our average reference stand and continued a trajectory towards average reference conditions throughout the simulation (Fig. 6). In contrast, treating the same stand by thinning to 150 trees ha^{-1} moved the developmental trajectory away from reference conditions, primarily because there were so few overstory trees. For dead trees, both the treated and untreated stands fell within reference conditions for much of the time period examined (Table 2, Fig. 7). The developmental trajectory of the untreated stand put it immediately on course to develop higher snag densities that is typical of reference condition characteristics for dead wood densities and diameters. It exceeded typical densities from about year 60–90, then trended back toward average reference conditions. The treated stand also rapidly achieved snag densities typical of reference conditions, and remained within a standard deviation of the average reference conditions through the length of the simulation. However, the snag densities of the treated stand were on the very low end of the range of natural conditions and generally 3–4 times lower than the snag densities found in the untreated stand. The average diameter of the snags in the treated stand was higher than the untreated stand.

Collectively, our empirical data and model results suggest that mature riparian and upland Douglas-fir dominated forests have well developed structural characteristics in terms of abundant large trees in the overstory, abundant large snags and down wood and a well-developed understory of shade-tolerant trees. The valley bottom riparian forests appear to develop complex forest structure more rapidly than the upland forests, presumably because they are growing on more productive sites with deeper soils.

Discussion

By way of example, this study illustrates a three-step process to assess the potential effects of proposed restorative actions (1) identify reference conditions (2) quantify metrics that describe the reference conditions, and (3) use models to predict the effects of management actions in the context of restoring degraded sites

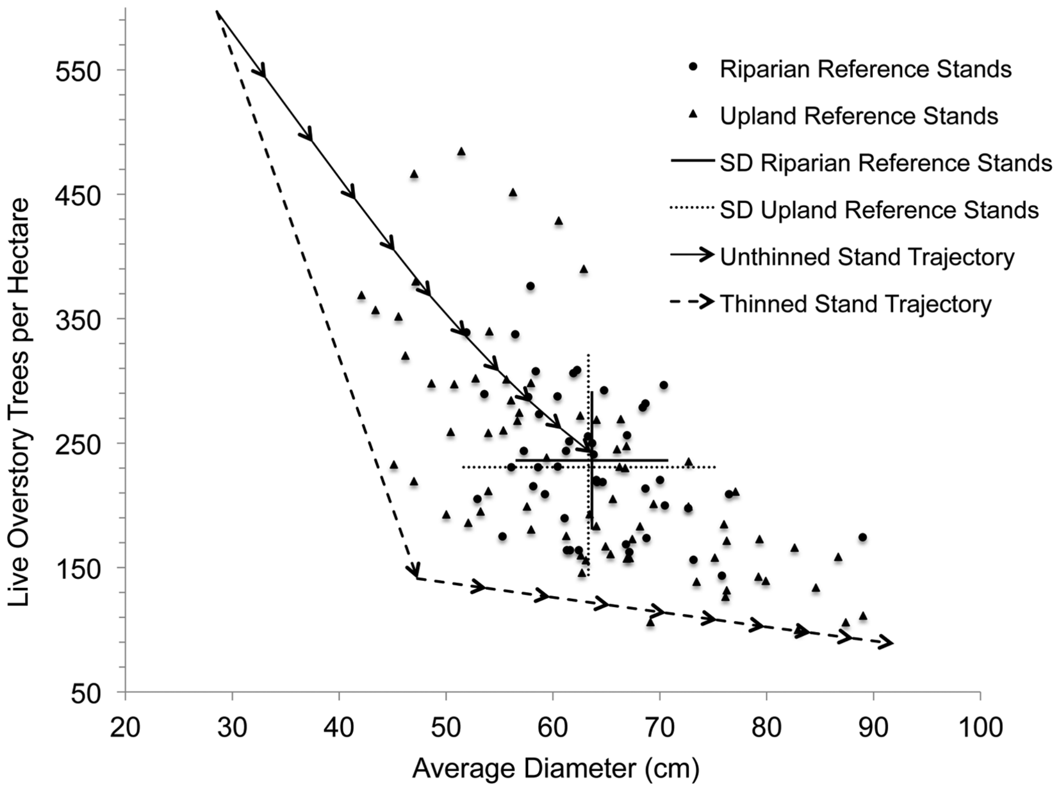

Fig. 6. Distribution of riparian and upland reference stands by average live tree overstory density (trees ha^{-1}) and diameter (cm) Superimposed on these data are the projected changes in the average live tree overstory density and diameter of a 30 year old Douglas-fir stand as it ages to year 130, under two scenarios (1) thinned from an original density of 600 trees ha^{-1} down to 150 trees ha^{-1} at year 30 and (2) an unthinned control. Each arrowhead represents a 10 year increment as the stand ages to 130 years.

to reference conditions. Additional steps in the restoration process, which we do not discuss here, include implementation, monitoring and adaptive management (e.g., see Pollock et al. 2005, Beechie et al. 2008).

A key finding of our study is that with careful analyses, we were able to identify reference sites in the FIA-CVS database, a national inventory of all forest lands. This suggests widespread applicability of our approach for identifying forested reference conditions. Another key finding was that numerous metrics were needed to quantify reference conditions and to more accurately predict the effects of management actions, and that looking at the distribution of values (e.g., Figs. 3 and 4), was much more insightful than a simple examination of averages. We also found that subtle changes in landscape position (e.g., riparian versus upland) of a specific forest type lead to quantifiable differences in some reference metrics, but that for many metrics there was considerable overlap and that there was a wide range of variability for most metrics. Finally, another key finding was that by using a model we were able to examine how restoration thinning, a widespread practice intended to restore the diversity and complexity of forested ecosystems, may actually move the developmental trajectory away from rather than towards the natural range of variability found in reference conditions. This last point illustrates the importance of all three steps in the evaluation of a proposed restoration action. Simply identifying and quantifying reference conditions does not ensure that a restoration treatment will accelerate recovery. A key step is assessing whether the proposed restoration treatment is likely to move the ecosystem towards conditions reflective of

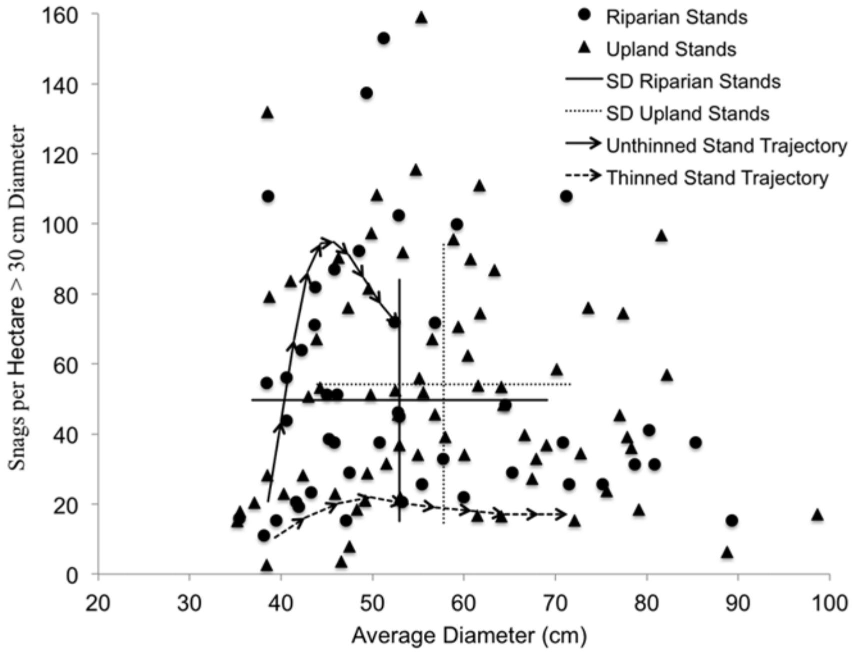

Fig. 7. Distribution of riparian and upland reference stands by average density and diameter of large (>30 cm diameter) snags. Superimposed on these data are the projected changes the average large snag density and diameter of a 30 year old Douglas-fir stand as it ages to year 130, under two scenarios (1) thinned from an original density of 600 trees ha^{-1} down to 150 trees ha^{-1} at year 30 and (2) an unthinned control. Each arrowhead represents a 10 year increment as the stand ages to 130 years.

the natural range of variation, and in particular, for structural attributes that are important to the maintenance of biodiversity and other ecosystem services.

Both riparian and upland forests generally had overstories with high densities of large diameter (>50 cm) live trees and large diameter (>50 cm) snags, with a wide range of natural variation for both these metrics (Table 2 and Figs. 4 and 5), which are structural attributes important to a number of species. Dead trees ≥50 cm are large enough to be stable in most streams, are a size preferred by many cavity nesting birds, and generally are large enough to form snags and large wood that are long-lived structural elements in forest and stream ecosystems (Mannan et al. 1980, USDA and USDI 1994, Beechie and Sibley 1997, Meleason et al. 2003, Fox and Bolton 2007). While snag sizes are important, the density of snags may also be important for some species (e.g., birds that forage on snags prefer nesting sites in areas of high snag density (Raphael and White 1984)).

Mature Douglas-fir forests are generally transitioning from the stem exclusion phase, where there is intense competition among the canopy dominants for light and subsequent high mortality rates and little in the way of understory regeneration, to the understory reinitiation phase, where dominant mortality rates decline and shade tolerant understory species began to emerge, creating a more complex forest (Oliver and Larson 1996). The riparian and upland reference stands are reflective of both of these states, but most stands had a healthy understory of shade tolerant western hemlock and red cedar and a multi-tiered canopy was already well developed, particularly in the riparian stands (Fig. 3). Many stands also had remnants of early successional hardwoods such as red alder, and some included longer-lived hardwoods such as big leaf maple and black cottonwood. Other species that are a minor canopy component of some stands include dogwood (*Cornus nuttalli*), madrona (*Arbutus menziesii*), western white pine (*Pinus monticola*), silver fir (*Abies amabilis*) and

Table 4. Comparison of reference condition metrics from the upland Douglas-fir dominated forests in study with other studies that produced comparable metrics. L(D)DBH = live (dead) diameter breast height, L(D)TPH = live (dead) trees ha^{-1}, DF = Douglas-fir, nd = no data. Means, standard deviations (our study) and ranges (all other studies) are for all trees >10 cm dbh unless otherwise stated.

Study	Age	LTPH-T	LTPH-DF	LDBH	DTPH	DTPH >50 cm
This study	112 (18.2)	386 (254.0)	226 (156.0)	50 (13.1)	115 (67.8)	24 (19.0)
Spies and Franklin 1991	nd (80–195)	452 (373–548)	243 (171–346)	34 (30–39)	100 (nd)	14 (10–20)
Bible 2001	123 (109–148)	nd	255 (181–335)	nd	nd	nd
Winter et al. 2002	nd (110–140)	nd	190 (135–223)	nd	nd	nd
Winter et al. 2002	nd (140–170)	nd	124 (107–143)	nd	nd	nd

grand fir (*Abies grandis*). Neither the upland nor riparian forests were particularly diverse in tree species, which is typical for conifer forests of the Pacific Northwest (Franklin and Dyrness 1973).

Comparison with other studies

This study is relatively unique in that it provides a number of quantitative metrics for dead wood (as well as live trees) in mature Douglas-fir forests in the age range of 80–140 years. A lack of quantitative metrics for this forest type is due to the fact that there are few such forests left. Because of their economic value, most Douglas-fir forests have been harvested at least once in the past 80 years. Out of 3408 stands in the CVS database we could only find 71 that were suitable as reference stands, which speaks to the rarity of this forest type.

The study that provided data most comparable to ours was that of Spies and Franklin (1991), who compared the structural characteristics of young, mature and old-growth conifer Douglas-fir forests in western Oregon and Washington. Their mature stands were more variable than ours in that they included both a wider range of disturbance histories and stand ages (80–195 yrs). Comparable metrics for their mature stands include an average of 452 trees ha^{-1}, 243 shade intolerant trees ha^{-1} (primarily Douglas-fir), a mean dbh of 34 cm, a basal area of 59 m^2 ha^{-1}, mean species richness of 5.1, mean total snag densities of 100 ha^{-1} and large snag (>50 cm dbh) densities of 14 ha^{-1} (Table 4). Their means for tree densities, species richness and total snag densities were similar to but higher than our study, while their means for live tree dbh, live tree basal area and large snag densities were similar to but lower than what we found in our study. They also had relatively high variability around all of these means (reported as confidence limits) and most of their means for comparable metrics were within a standard deviation of our means for both the riparian and upland stands.

Bible (2001) reported Douglas-fir densities of 181–335 trees ha^{-1} (mean = 255 trees ha^{-1}) in five long-term study sites in National Forests throughout western Oregon and Washington containing mature forests ranging in age from 109-148 years (mean = 123 yr). Both the stand ages and the Douglas-fir densities were similar to our study (Table 4). In western Washington Winter et al. (2002) reported mature forest stands (age range = 110-140 yr) with live Douglas-fir densities averaging 190 trees ha^{-1} (range = 135–223 trees ha^{-1}) and slightly older mature stands (age range = 140–170) with live Douglas-fir densities averaging 124 trees ha^{-1} (range = 107-143 trees ha^{-1}), which is lower than the densities found in our study (Table 4). Poage and Tappeiner (2002) examined 505 old-growth Douglas-fir stumps in western Oregon to estimate age-diameter relationships. They found diameters varied considerably at year 100, ranging from 10-90 cm. This is consistent with our findings, though our stands were slightly older and contained some trees larger than 90 cm diameter.

Overall, comparison with these studies suggests that the mature conifer forests range widely in structural characteristics, which is consistent with our observations. Because of this variability, we suggest that mean values do not adequately represent reference conditions and that it is critical to include measures of the range of variability in any description of target reference conditions, as illustrated in Figs. 6 and 7. This further suggests that in the context of restoring forest complexity over areas larger than a single stand, it is essential that a range of desired future conditions be targeted and that multiple metrics be evaluated, particularly those that are relevant to the maintenance of biodiversity and other important ecosystems functions.

Implications for management

Quantifying the natural range of older forest structure allows target conditions to be set for young forests. Forest growth models can be used to project the growth of young forests as they mature and these projections can then be compared to reference conditions. Assessments can then be made to determine when management actions such as thinning will accelerate the development of complex forest structure. Because much of the structure of forests important to the maintenance of biodiversity is composed of large dead wood in its various stages of decomposition (e.g., snags and down logs), assessing the effects of any restorative treatments on dead wood production is especially important (USDA and USDI 1994). Riparian restoration efforts intended to enhance biodiversity are likely to be more successful if they set future targets that include a wide range of variation in the density not just of live trees, but also dead wood (e.g., snags, down wood on the forest floor, and wood in streams).

As an example, we analyzed a typical restoration program intended to accelerate the development of structural complexity in young conifer stands. The simple example we provided suggests that the restorative treatment may delay rather than accelerate the attainment of a structurally complex forest and push the developmental trajectory near the edge of the natural range of variation, at least for large live trees and dead wood (Figs. 6 and 7). In contrast, the untreated forest appears to be heading towards conditions that are well within the range of variation observed in our reference sites and in particular, creating abundant large dead wood, a structural element missing from many riparian forests and essential to the maintenance of biodiversity. Though we provided a simple comparative example for illustrative purposes, we suggest that a more comprehensive assessment of potential thinning effects relative to reference conditions should be undertaken by comparing with more of the metrics provided in Table 2 and the distributions illustrated in Figs. 3–5. While our data suggest that the example of a restoration treatment we provided does not create forest structure typical of the reference conditions, more moderate thinning of young stands with higher densities than those we examined may accelerate development toward reference conditions. Future research should focus on assessing the effect of a wider range of restoration actions on a wider range of stand conditions, so that landscape-level management plans can be designed to create future forests containing the full range of reference conditions.

Conclusions

We conclude that reference stands of mature Douglas-fir dominated riparian and upland forests are generally quite productive, have a well-developed structure in terms of abundant large live and large dead trees, a multi-layered canopy and are not particularly rich in tree species. Relative to upland forests, mesic riparian forests on average are more productive and therefore more advanced in the development of structural characteristics important to numerous species. However, there is a large degree of overlap in the two data sets and for many descriptive metrics the differences are not large. While we examined the differences between riparian and upland forests, others may want to explore different divisions (e.g., geographical proximity). To that end, we have provided the complete reference site descriptions in Appendix so that others have the opportunity to explore and utilize the data, to ask questions that we did not pursue.

Multiple metrics (e.g., live and dead tree volumes, species composition, tree height and diameter distributions) are essential to accurately describe reference conditions, to set desired future condition targets and to ensure that silvicultural treatments will lead to achieving desired future conditions. The use of a single metric (e.g., live tree diameters) to define reference conditions can lead to erroneous conclusions about restorative treatments that should be applied to stands to create desired future conditions.

In terms of general conclusions for developing reference conditions, we find that multiple metrics help to greatly increase confidence in the accuracy of reference conditions. If landscape level data such as the FIA-CVS database are used, the careful and judicious use of filters is required to remove sites that are not representative of the target vegetation type and to avoid erroneous conclusions. Data more closely aligned with the target reference conditions (e.g., require fewer filters), are preferable.

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Supplemental Material

Appendix

Table A1. Summary of characteristics of individual sites analyzed in this study. L(D)BA = Live (dead) Tree Basal Area (m^2 ha^{-1}), L(D)DBH = live (dead) diameter breast height (cm), Ht = height (m) LTV = Live tree Volume (m^3 ha^{-1}), L(D)TPH = live (dead) trees ha^{-1}. Means and standard deviations are for all trees >10 cm dbh unless otherwise stated. Location legend: numerator refers to federal or state forest and denominator refers to county or Water Resource Inventory Area (riparian sites only), as follows. 1 = Mt. Hood National Forest, 2 = Siuslaw National Forest, 3 = Willamette National Forest, 4 = Umpqua National Forest, 5 = Gifford Pinchot National Forest, 6 = Olympic National Forest, 7 = Mt. Baker-Snoqualmie National Forest, 8 = Capitol State Forest. Oregon Counties: 1 = Clackamas; 2 = Lane; 3 = Douglas; 4 = Lincoln, 5 = Tillamook. Washington Counties: 6 = Cowlitz; 7 = Jefferson, 8 = King; 9 = Lewis; 10 = Pierce; 11 = Skagit; 12 = Skamania; 13 = Snohomish.

Location	Site no.	Age	LBA	LDBH	Live Ht	LTPH	LTV	LTPH >50 cm	DBA	DDBH	DTPH	DTPH >50 cm
Upland sites												
1/1	1	84.3	48.6	34.3	24.5	403.4	593.5	130.9	13.4	29.6	142.2	9.9
1/1	2	88.2	52.9	42.1	26.9	284.4	711.9	130.3	26.0	40.0	151.3	34.1
1/1	3	97.6	55.6	43.1	30.0	293.9	784.4	142.4	10.5	46.4	38.1	15.7
2/2	4	91.7	85.7	48.0	33.5	409.1	1210.8	246.2	16.8	34.4	134.6	27.2
2/3	5	126.1	85.8	64.7	39.5	230.9	1262.3	147.7	35.8	73.6	76.1	57.7
2/2	6	116.5	92.8	56.0	38.8	306.9	1514.4	162.4	27.4	39.2	157.8	30.2
2/2	7	91.7	76.3	48.3	33.2	353.5	1082.2	170.2	20.4	66.5	46.0	25.6
4/2	8	150.8	139.3	32.9	21.9	1151.8	1717.5	242.3	23.1	32.6	196.2	43.7
3/2	9	106.1	79.1	53.2	36.9	321.0	1111.8	259.3	5.2	30.3	62.5	5.2
2/2	10	108.3	59.1	56.9	38.6	196.7	908.7	133.6	34.9	42.2	169.1	46.6
3/2	11	151.1	54.2	38.4	26.7	348.6	734.7	124.1	5.9	26.3	55.7	6.2
3/2	12	99.6	78.9	34.3	26.2	706.2	1006.8	196.4	19.4	23.5	308.2	23.6
3/2	13	107.2	62.9	53.3	35.1	216.8	940.4	116.2	2.3	20.7	47.4	2.6
3/2	14	121.3	41.7	48.8	34.0	165.5	627.6	85.8	1.3	17.9	42.2	0.0
2/2	15	110.9	58.5	67.0	41.8	136.4	920.0	98.3	11.1	46.3	53.9	23.6
2/2	16	88.6	86.9	42.1	27.8	466.3	1208.6	149.3	31.9	41.6	127.7	24.4
2/2	17	130.7	95.4	54.0	36.1	328.6	1417.3	186.7	18.5	37.3	111.2	17.7
2/2	18	116.1	76.2	83.0	52.0	133.9	1252.7	131.3	35.3	65.7	76.6	44.4
2/2	19	110.3	58.3	70.1	44.6	131.8	929.2	98.9	9.4	48.1	44.0	15.7
2/2	20	94.3	56.4	58.2	33.3	145.6	851.9	54.3	55.7	76.4	106.7	86.3
2/2	21	96.0	88.6	47.7	34.6	383.4	1377.3	212.1	43.2	54.0	140.6	43.4
2/2	22	110.7	84.8	62.7	39.4	205.4	1329.6	129.8	28.3	60.7	65.1	24.4
3/2	23	106.6	79.7	62.2	40.8	230.7	1186.2	183.3	7.1	36.6	51.6	11.5
2/2	24	106.0	102.9	71.4	46.5	235.1	1626.6	217.4	51.2	49.1	198.5	57.1
2/2	25	102.8	86.1	65.8	42.6	214.4	1368.9	159.1	20.2	47.6	87.8	27.2
2/2	26	139.9	55.8	80.6	50.5	99.9	916.6	92.0	15.9	58.3	42.7	17.1
2/2	27	105.1	71.0	65.1	40.5	172.2	1122.8	98.0	36.7	45.4	155.9	43.4
2/2	28	124.5	88.2	57.7	39.0	279.3	1367.3	193.8	15.0	36.3	114.8	16.7
3/2	29	106.9	51.9	38.2	27.9	323.7	716.7	107.1	6.9	32.3	56.3	11.5
2/2	30	119.3	106.7	61.4	39.8	290.0	1666.2	197.8	37.2	42.9	174.7	35.9
2/2	31	131.7	88.5	72.7	46.7	199.0	1389.4	188.6	11.8	67.4	27.2	11.5
2/4	32	107.0	66.3	65.4	41.8	150.9	1077.3	101.5	22.3	67.3	49.0	31.2
2/4	33	102.2	75.6	50.0	36.0	333.7	1119.2	227.9	25.0	34.7	180.3	22.4
2/4	34	98.2	70.9	74.8	48.5	149.1	1139.7	139.2	20.5	41.1	103.3	33.5
2/4	35	108.7	71.7	60.9	39.1	191.3	1101.6	114.5	5.7	29.3	67.8	5.2
2/4	36	97.2	137.9	57.7	38.0	439.4	2069.3	209.5	110.6	64.7	241.8	99.6
2/5	37	82.1	41.8	47.3	30.9	202.5	576.6	65.5	15.6	59.7	46.6	26.2
2/5	38	92.0	69.5	61.3	42.7	202.5	1109.7	144.0	18.0	52.6	59.5	22.0
2/5	39	96.0	61.2	62.4	38.9	176.9	902.2	120.5	38.9	77.4	74.5	58.7
5/6	40	105.1	58.0	44.2	29.8	288.3	842.0	128.3	32.5	49.6	135.2	42.0
6/7	41	93.3	58.5	27.2	20.0	763.0	631.8	73.3	15.5	25.5	152.1	15.7
6/7	42	105.7	107.0	30.3	22.0	1117.2	1171.6	259.7	11.6	17.0	295.4	15.3
6/7	43	95.3	46.3	33.2	21.9	467.5	460.8	104.8	6.2	25.8	84.7	3.3
7/8	44	100.4	64.5	30.1	22.4	784.1	689.1	178.1	5.7	21.3	126.5	0.0
5/9	45	124.1	69.3	40.7	29.6	406.4	987.1	91.7	31.0	33.8	222.7	43.0
5/9	46	140.0	74.4	37.0	26.7	539.2	1042.1	128.3	12.9	40.7	82.1	34.1
5/9	47	145.6	78.0	43.2	30.6	345.7	1225.0	114.0	9.2	38.8	56.5	13.1
5/9	48	105.4	67.8	44.9	31.5	331.6	1015.1	165.0	19.8	51.8	76.9	41.4
7/9	49	132.2	64.3	29.3	22.5	801.7	752.2	102.1	15.6	25.4	238.4	10.5
5/9	50	99.4	71.2	45.0	31.1	376.7	958.9	214.8	12.6	34.2	116.4	18.4

Table A1. Continued.

Location	Site no.	Age	LBA	LDBH	Live Ht	LTPH	LTV	LTPH >50 cm	DBA	DDBH	DTPH	DTPH >50 cm
5/9	51	98.7	63.2	37.4	26.0	400.4	874.4	114.0	14.3	32.1	138.6	8.9
7/9	52	126.0	71.8	48.6	32.4	327.3	985.5	214.8	27.5	35.5	200.6	34.1
5/9	53	93.8	61.9	51.9	34.2	229.9	917.0	111.0	9.0	38.6	61.1	10.5
7/9	54	138.7	68.7	37.8	27.7	504.9	904.6	217.4	19.3	32.5	211.1	10.5
7/9	55	112.3	88.9	44.3	27.1	407.1	1188.6	107.8	28.2	43.8	110.1	20.7
7/10	56	107.3	72.9	47.1	31.2	311.6	1035.7	143.8	4.5	19.0	119.2	0.0
7/11	57	124.7	49.6	39.0	27.6	330.9	634.5	117.9	6.7	29.2	65.8	13.1
7/11	58	133.3	67.1	29.7	19.7	753.1	718.4	115.2	7.4	24.0	109.9	2.6
7/11	59	88.6	53.0	43.3	28.0	300.5	655.1	162.4	5.4	26.1	94.2	2.6
5/12	60	157.4	61.6	55.5	37.6	197.9	949.7	115.6	6.8	39.2	48.6	15.7
5/12	61	87.2	61.1	35.1	27.2	537.8	781.7	199.0	20.4	31.9	145.6	14.5
5/12	62	123.3	57.7	50.8	35.5	248.5	843.8	157.1	16.4	42.1	105.7	23.6
5/12	63	95.2	71.5	29.8	20.6	792.1	787.3	163.7	15.5	34.8	113.2	19.4
5/12	64	118.0	64.4	50.2	34.8	289.8	877.7	206.9	4.9	28.1	67.8	5.2
5/12	65	146.8	82.4	75.2	40.8	168.4	1112.7	150.7	1.0	18.9	23.4	1.0
5/12	66	126.6	125.0	36.4	26.9	1057.6	1512.0	379.8	15.8	26.5	232.0	17.5
5/12	67	137.3	85.7	48.4	30.7	311.1	1285.8	75.5	17.1	72.8	34.5	26.6
5/12	68	95.7	109.9	33.6	23.2	941.7	1244.7	165.6	25.3	29.6	214.0	33.7
7/13	69	128.1	133.3	33.2	23.0	1095.9	1780.2	242.3	23.4	27.4	250.9	18.9
7/13	70	127.6	92.6	46.9	28.5	410.5	1242.0	110.4	21.6	37.4	105.3	17.1
7/13	71	119.4	77.2	47.3	28.6	323.6	1037.6	123.8	4.9	28.6	57.9	2.6
Riparian sites												
7/01	72	110.5	69.0	40.5	26.7	40.5	980.2	133.5	11.1	46.5	52.3	23.2
7/04	73	102.4	59.2	41.0	29.2	41.0	944.2	107.6	3.2	21.6	66.6	5.1
7/04	74	119.6	74.2	45.5	25.5	45.5	1086.8	82.0	2.8	25.6	66.6	5.1
7/04	75	115.5	76.5	52.9	30.8	52.9	1253.6	107.6	12.0	52.0	30.8	10.3
7/05	76	68.8	75.2	40.9	27.8	40.9	1214.9	106.2	27.5	54.3	68.7	31.2
5/26	77	112.7	109.6	51.3	36.2	51.3	1553.4	205.5	2.2	28.8	31.6	0.0
5/26	78	102.1	101.9	41.3	36.8	41.3	1848.8	187.4	8.0	34.2	81.2	6.2
5/26	79	94.6	96.8	40.9	27.7	40.9	1575.2	156.2	8.6	32.1	81.2	6.2
5/26	80	111.8	77.2	42.2	28.7	42.2	1053.4	143.7	19.2	48.7	68.7	18.7
5/26	81	108.3	84.3	50.3	35.7	50.3	1340.2	162.5	19.5	70.3	37.5	18.7
5/26	82	98.7	61.5	38.4	25.9	38.4	702.9	82.0	31.4	55.9	66.6	25.6
5/26	83	92.0	73.0	40.8	30.4	40.8	1152.8	112.8	8.0	40.6	46.1	10.3
5/26	84	149.3	100.8	59.2	39.1	59.2	1615.3	169.1	11.0	46.9	56.4	20.5
5/27	85	104.0	52.7	37.5	27.7	37.5	751.9	98.4	7.8	30.1	120.3	10.9
5/27	86	127.0	91.1	39.7	26.3	39.7	1455.0	197.6	12.0	36.0	102.8	15.8
5/27	87	147.3	108.9	47.9	33.3	47.9	1772.2	174.3	18.5	48.5	92.3	35.9
5/27	88	112.8	99.9	41.7	30.5	41.7	1526.0	128.1	6.0	30.6	61.5	15.4
5/27	89	114.5	87.9	56.6	34.1	56.6	1374.2	153.8	12.3	63.5	30.8	20.5
5/27	90	129.3	120.3	61.7	27.7	61.7	1485.5	189.6	19.9	56.9	71.8	46.1
5/27	91	123.8	94.0	56.8	30.6	56.8	1329.1	128.1	21.9	52.8	102.5	51.3
5/27	92	123.9	77.9	39.2	29.0	39.2	1265.8	162.5	31.1	42.2	181.2	43.7
5/27	93	105.9	84.7	42.0	24.4	42.0	1089.0	131.2	8.6	57.7	32.8	32.8
5/27	94	131.3	93.5	55.1	24.2	55.1	867.9	161.8	56.7	63.3	125.8	71.9
5/27	95	114.7	77.3	41.1	31.9	41.1	1181.9	164.0	7.3	26.8	96.5	9.6
5/27	96	111.8	98.7	50.0	32.3	50.0	1353.9	161.8	15.3	32.9	161.8	9.0
5/29	97	127.6	89.2	38.8	24.2	38.8	1160.5	174.9	30.6	48.4	174.9	98.4
5/29	98	122.3	69.7	58.7	40.2	58.7	1135.0	144.7	2.7	41.9	19.3	0.0
5/29	99	130.5	83.7	54.9	41.0	54.9	1371.4	174.9	1.5	27.3	21.9	0.0
5/29	100	101.5	74.0	56.0	33.8	56.0	1097.9	125.0	33.3	54.1	118.7	50.0
5/29	101	140.8	111.5	53.1	34.0	53.1	1566.2	212.3	8.7	57.2	57.9	38.6
5/29	102	103.5	114.1	47.0	28.8	47.0	1455.9	241.2	8.7	31.3	96.5	9.6
5/29	103	126.9	68.9	49.9	32.9	49.9	1039.4	118.7	9.1	39.7	62.5	18.7
5/29	104	123.5	62.1	49.2	36.2	49.2	925.4	143.5	10.8	42.3	61.5	10.3
5/29	105	96.7	57.2	46.7	32.4	46.7	842.5	117.9	3.5	33.3	35.9	0.0
5/29	106	139.6	53.4	53.4	42.0	53.4	925.8	117.9	12.8	43.8	82.0	15.4
5/29	107	140.3	67.8	55.9	40.3	55.9	1061.1	153.8	9.8	36.4	82.0	20.5
5/29	108	161.5	91.9	45.6	28.3	45.6	1277.6	164.0	6.2	59.9	21.9	21.9
7/04	109	116.8	109.6	58.2	40.5	58.2	1883.2	174.2	4.2	27.9	52.3	5.8
8/23	110	85.2	113.4	46.3	28.3	46.3	1556.5	193.7	8.4	31.3	93.7	6.2
8/23	111	87.8	92.5	48.6	39.9	48.6	1615.8	191.6	11.0	35.6	98.7	17.4
8/23	112	105.3	133.2	56.0	27.7	56.0	1891.1	153.8	0.2	21.3	5.1	0.0
7/03	113	116.6	120.0	43.5	27.5	43.5	1722.2	206.7	19.6	43.5	98.9	18.0
7/07	114	105.9	90.2	43.7	25.4	43.7	1252.0	131.2	19.0	57.9	50.0	25.0
7/01	115	137.2	132.5	57.2	34.8	57.1	1976.1	242.7	11.7	40.9	71.9	18.0
8/23	116	96.8	88.4	48.2	34.5	48.2	1385.1	143.5	7.2	41.0	66.6	20.5
7/04	117	112.8	95.0	54.2	38.1	54.2	1572.2	156.8	17.5	35.8	139.3	29.0